



Abdelrahman Azzuni

**ENERGY SECURITY EVALUATION FOR
THE PRESENT AND THE FUTURE ON
A GLOBAL LEVEL**



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Abstract

Abdelrahman Azzuni

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Energy Security is a universal concern for all stakeholders and achieving energy security is a crucial objective for all societies. Therefore, energy security became a major part of national security with the ability to shape policies and strategies. Its significance sparked questions of what energy security shall be, how to measure it and how to achieve it. Addressing these questions is the purpose of this dissertation. The objectives of this dissertation are to build a coherent, comprehensive and applicable framework for energy security, to test the framework's applicability on present energy systems and future scenarios, and finally, to quantitatively evaluate energy security for all countries globally.

To achieve these objectives, a detailed literature review was used to track previous research about energy security and to collect all important elements to formulate a comprehensive energy security definition and analysis framework. Applying the framework with soft analysis on energy storage technologies was used to validate the framework. Simulating future energy scenarios for a case study was done using the LUT model. The projection of a future scenario was then analysed by the soft analysis method. A novel Energy Security Index was designed to measure all dimensions and parameters of energy security globally, enabling detailed analytical insights for all countries.

Results of the dissertation show the formulation of a generic definition of energy security together with a proper framework. The thermal energy storage (TES) was found to be the best option from the perspective of energy security through the application of this framework on the exemplarily energy sub-system of energy storage technologies. Modelling a future energy scenario for Jordan to achieve a 100% renewable energy system proved its feasibility and benefit for the economy, environment and for energy security, where most of the analysed dimensions are affected positively by such a scenario. Finally, evaluating energy security globally showed, for the first time, a detailed and transparent ranking of all countries; the findings indicate that Germany achieved the highest level of energy security in the world.

It is concluded that this framework for analysing energy security globally is the most generic, comprehensive and applicable to evaluate energy security. It is recommended for policy makers to build strategies that enhance energy security results in their countries.

Keywords: Energy security, Energy Security Index, global, energy transition, 100% renewable energy, energy storage

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September 2020
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*To My Mother and Father, whose favours are endless, I am
the fruit of your plant*

*To my mother who carried me nine months
To my mother whose love is in my heart forever
To my mother, all this success is for you and because of you*

*To my father, who carved my path in life with his bare hands,
and whose unlimited support and thoughtful advice made me
the strong man I am today*

*To Hayat, my love and soulmate, you are the one to travel the
life's journey with*

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Abstract

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List of publications

This dissertation is based on the following papers. The rights have been granted by publishers to include the papers in dissertation.

- I. Azzuni, A. & Breyer, C. (2018) Definitions and dimensions of energy security: a literature review. *Wiley Interdisciplinary Reviews: Energy and Environment*, 7, e268.
- II. Azzuni, A. & Breyer, C. (2018) Energy security and energy storage technologies. *Energy Procedia*, 155, 237-258.
- III. Azzuni, A., Aghahosseini, A., Ram, M., Bogdanov, D., Caldera, U., Breyer, C. (2020) Energy security analysis for a 100% renewable energy transition in Jordan by 2050. *Sustainability*, 12, 4921.
- IV. Azzuni, A. & Breyer, C. (2020) Global Energy Security Index and Its Application on National Level. *Energies*, 13, 2502.

The publications are numbered throughout this dissertation using the Roman numerals above. Reprints of each publication are included at the end of this dissertation

Author's contribution

Abdelrahman Azzuni is the principal author and investigator in Publications I – IV. In publication III, work related to energy transition was done mainly by Mr. Aghahosseini, with contributions of Mr. Bogdanov and Ms. Caldera, in addition, employment results were prepared by Mr. Ram.

Nomenclature

Abbreviations

AHP	Analytical Hierarchy Process
AC	Alternative current
A-CAES	Adiabatic Compressed Air Energy Storage
BPS	Best Policy Scenario
CHP	Combined Heat and Power
CO ₂	Carbon dioxide
CSP	Concentrated Solar Power
DEA	Data Envelopment Analysis
ESI	Energy Security Index
FT-fuel	Fischer-Tropsch – fuel
GIS	Geographical Information System
GT	Gas Turbine
HHB	Hot Heat Burner
HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
$I_{j,r}$	absolute value of the indicator
ICE	Internal Combustion Engine
IEA	International Energy Agency
$\hat{I}_{j,r}$	normalized indicator for corresponding specific parameter (Y_j)
LUT	Lappeenranta University of Technology
MENA	Middle East and North Africa
o	number of indicators
OECD	Organisation for Economic Co-operation and Development
OSGeo	Open Source Geospatial Foundation
PCA	Principle Component Analysis
PHES	Pumped Hydro Energy Storage
PP	Power Plant
PtG	Power-to-Gas
PtH	Power-to-Heat
PtH ₂	Power-to-Hydrogen
PtX	Power-to-X
PV	Photovoltaic
SDG	Sustainability Development Goals
ST	Steam Turbine
TES	Thermal Energy Storage
TWh	Tera Watt Hour
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USChC	United States Chamber of Commerce

V_i	weight of each dimension
WEC	World Energy Council
W_j	weight of each parameter
X_i	value of each dimension
Y_j	value of each parameter

1 Introduction

1.1 Importance of energy security analysis

Energy system development is suggested to be the facilitator of all great historical societal changes (Rifkin, 2011) and the main driver for societies to prosper (Haghighi, 2007). Moreover, energy not only enables social development (Augutis et al., 2011) but also affects all aspects of life (Ciută, 2010). Therefore it is crucial to the endurance of an effective modern society (Bielecki, 2002; Magazzino, 2016; Sovacool, 2011b), since it is viewed as a vital element for economic growth (Bielecki, 2002; Kunz, 2012) and civilization (Asif & Muneer, 2007). Although energy is needed for several purposes such as industry, transportation, residential and other services (IEA, 2016), humans aimed to utilize different types of energies ranging from fossil fuels to renewable options in order to fulfil their basic human needs (Maslow, 1943).

People throughout history realized the importance of energy for their daily activities as food was their primary energy source in their primitive hunter-gatherer societies. But as time passed the definition of energy and energy sources changed and evolved into thinking of materials that can bring heat and light into their societies (e.g. wood as fuel for fire). After that, the nature of their energy sources started to diversify and included other materials. Moving from wood to coal then oil and gas, humans and societies knew the importance of this energy as it enabled them to take on novel actions and accomplish goals which they were unable to previously fathom. The development was so far crowned by electricity as the most developed type of energy.

It is not odd with this long history of human civilization that many concepts related to energy were formed, developed, evolved and conveyed to newer generations. **Energy Security** is one of the earliest considerations of our ancestors and it continues to be for the current generation. The concept of energy security is 'as old as fire' (Valentine, 2011) and for most of our history, discussion regarding energy security has taken place in one way or another.

As any concept that is conceptualized over a long period of time, the concept of energy security evolved and has gone through many advancements. Humans were concerned about building their settlements close to areas with high energy availability (e.g. wood) so that they could use it for fire to get heat and light. The concept of energy security might not have been articulated back then but the analysis of their behaviour clearly shows their motive to secure energy sources. With the societal development and the discovery of new energy sources the concept of energy security became more complex.

Nowadays, as the concept grows in complexity and many aspects are involved in the discussion regarding energy security, the concept is viewed as blurred (Löschel et al., 2010), elusive (Kruyt et al., 2009), abstract and vague (Chester, 2010); in other words, having no common interpretation (Checchi et al., 2009; Winzer, 2012). Therefore, it is

very important to analyse the concept of energy security in order to remove the elusion surrounding it and make it explicit for people to understand as the topic and concept of energy security emerged as one of great importance (Yergin, 2006) in the twenty-first century.

The reasons for this growing significance are attributed to: civilization development (Asif & Muneer, 2007), complex global markets (Chester, 2010; De Vos & Baken, 2004), global energy supply crises (Aparicio et al., 2006), political conflicts (Jonsson et al., 2015), increased energy prices (Vivoda, 2010), climate change (Bang, 2010; Kim, 2014), growing dependence of industrialized economies on energy (Kaare et al., 2013), energy demand and competition (Vivoda, 2010), major disruptions in oil markets (Löschel et al., 2010) related to military upheavals (Constantini & Gracceva, 2004), threats to the energy system (Kanchana & Unesaki, 2015b; Teräväinen et al., 2011) and the view of energy security as equivalent to national security (Phdungsilp, 2015). In addition, countries are ready to overshadow goals of democracy, promotion, and human rights to attain practical cooperation on energy security (Andersson et al., 2011). The impact of energy security on various variables leads to the necessity of having proper energy security analysis and adequate methods on how to approach it.

All these attributes made energy security a universal concern (Ang et al., 2015). Scholars investigated the concept of energy security through many studies (Bielecki, 2002; Jun et al., 2009; Vivoda, 2010) from the fields of: policymaking (Turton & Barreto, 2006; Winzer, 2012), social sciences (Löschel et al., 2010), national energy policies (Franki & Višković, 2015), national security issues (Dyer & Trombetta, 2013), international relations (Kirchner & Berk, 2010), politics (Jonsson et al., 2015) and security strategies (Andersson et al., 2011). Such different approaches resulted in huge disagreements on the concept of energy security. To profoundly understand the origin of these inconsistencies, analysis of energy security concepts and their development through time proves to be very important.

Furthermore, energy security analysis is significant because of its ability to shape policies and countries' behaviours (Kovačovská, 2010). Policy makers strive to ensure consumers' needs of energy (Johnson & Boersma, 2015) in order to achieve freedom of choice towards self-actualization, presented in Maslow's needs hierarchy (Maslow, 1943). Therefore, policy makers address energy security issues when making laws and regulations with urgent priority (Sovacool, 2012).

The last point of importance of energy security analysis lies in the public desire to enhance energy security. Enhancing energy security is a crucial goal for societies (Dunham & Schlosser, 2016; Eaves & Eaves, 2007; Franki & Višković, 2015; IEA, 2007; Jordan et al., 2012; Sovacool, 2011a; Vivoda, 2010). In order to enhance energy security, a full detailed analysis proves important.

All these points make the legitimacy of energy security analysis very clear. However, an anticipated question that may arise targets the type of analyses that is required to answer these questions, which will be addressed in the next section.

1.2 Need for a global perspective

As was detailed in the previous section, there is an obvious importance of energy security analysis. Nevertheless, many types of analyses exist, but then, which one is the most needed approach? Following the principles of globalization where people, nations and countries are more connected than ever, there is a real need to address the challenges of **energy security analysis from the global perspective**.

Nowadays we live in a very connected world (Sachsenmaier, 2011) where countries and people are no longer isolated from what happens internationally. The globe is connected more than ever before in terms of markets, traveling and tourism, education, businesses and work-related trips, and import-export relationships of both raw materials and finished equipment. All these aspects make countries to effect on and be affected by the global energy systems.

The one global system that has been developing for centuries to be a real global system is the energy system (Yergin, 1991; 2011). Reasons for this development defer but two main reasons appear to possess the most influence. The first reason is the uneven distribution of energy resources on a global scale. This was seen in many milestones of the coal, oil and gas development. Although many industrial activities were historically located where coal was available, transportation of coal between industrial activities and its locations of abundance became an important element in later years. This kind of interconnectedness affected different parts of the world, especially if unrests happened in areas of abundant coal reserves. The same trend was observed from oil and gas systems where countries were divided into net exporters and net importers with a more complicated relationship developing between the two sides.

The second reason for the energy system to be a real global system is the investment cost of this system (Broker et al., 2019). Investments moved from rich industrial countries to resource rich countries, in order to import their needed commodities (energy resources). This financial coupling of both sides made international connections strengthen resulting in a real global energy system.

Therefore, such a global energy system needs to be analysed from the global level rather than the very narrow perspective of one territory. One part of the needed analyses for the global energy system is the analysis of **Energy Security**, in which its importance was established in the previous section.

In order to fully understand the energy security aspect of the global energy system there is a demanding need for Global Energy Security Analysis. A global analysis of the energy security is the only way to provide relative results on global levels. Such global energy

security analysis will tackle the energy system as a whole and such an overview will have the power to be mirrored on the globe level. Furthermore, a global analysis of energy security is the only method that can be applied both locally and internationally as its premises originate from the overall energy system and include national perspectives.

In addition, as will be seen in this research, the nature of energy security analysis requires a comparative approach where parts of the system are evaluated against each other. This means it is not possible to have an absolute evaluation of energy security analysis in one country regardless of all other countries. Therefore, a global energy security analysis is needed to be able to provide a meaningful analysis of different countries in comparison to others.

1.3 Motivation and objectives

As this research is done with the idea to cover one of the very important topics of the energy system “energy security”, there are several motivations and objectives to be achieved, together with many research questions. **The main purpose of this investigation is to evaluate and analyse energy security globally in order to provide a useful tool for decision-making processes, especially, when developing policies nationally and internationally.** Providing such an analytical evaluation requires many steps together with measurable objectives. These objectives were achieved in **Publications I-IV**. The details for all research questions and objectives are presented as follows:

1. The first objective is to determine what exactly is being analysed and what is being evaluated. This means to determine and define energy security and breakdown what it consists of. Therefore, the research question of “what is energy security?” took part in **Publication I**.
2. Understanding the nature of energy security and its elements cannot be done without a detailed literature review about how scholars along the history defined and investigated energy security. Therefore, the aim to track energy security definitions to answer the research question “How was energy security scientifically defined throughout history?” was answered in detail in **Publication I**.
3. After tracking the definitions of energy security from previous literature, the formulation of the best and most concise definition for energy security led to the research question of “What should the definition of energy security be?”. This was to be answered in order to construct a suitable definition that can be applied on a global-level analysis. The answer to this question can be found in **Publication I**.

4. It was found by answering the previous questions that energy security is defined by its elements “Dimensions and Parameters”. Thus, it became important to check what dimensions and parameters previous scholars included in their research. A literature review of previous research took place in order to answer the question of “What are the dimensions that were considered for energy security?” with a detailed respond being found in **Publication I**.
5. Considering all the dimensions that were previously included in the research of energy security, it was then important to analyse which research used which dimensions. Also, the analysis of the occurrence frequency of each of these dimensions in literature was done. This analysis was important to provide an answer to the research question “What dimensions were used in previous researches? And how many times was each dimension used?” The answer to these two questions was one of the aims of **Publication I**.
6. Going through all the dimensions that were presented in previous literature, the question of “What dimensions and parameters should be considered for energy security analysis and evaluation?” arose. It was the goal of **Publication I** to answer this question by providing a detailed description of all dimensions and parameters of energy security, together with their respective relationship to energy security.
7. The overall objective of **Publication I** was to formulate and build a comprehensive and coherent framework for energy security analysis.
8. As the framework was ready to be implemented, it was an objective to validate the framework’s ability to deal with all parts and aspects of a global energy system. Energy storage was chosen for this matter in order to answer the question “Is this energy security framework analysis valid for all parts of the energy system?” The answer to this question was presented in **Publication II**.
9. After the validity of the framework was approved, it was aimed to apply this analysis framework on energy storage technologies. The aim was to analyse energy storage technologies from the perspective of energy security. **Publication II** provided an answer to the question “What is the energy security level of different energy security technologies?”.
10. Since the framework was validated and tested on a sub-system, another test for this framework was aimed. The application of energy security analysis on a future energy scenario was the objective of **Publication III**. The answer to the research question of “How will a transition towards a 100% renewable energy system affect energy security?” was investigated.

11. Once the framework was ready, it needed a quantifying approach to be able to evaluate energy security levels with numerical values. The objective of choosing suitable numerical indicators for all parameters and dimensions was achieved in **Publication IV** by answering the question “What are the suitable numerical indicators to measure each and all of the energy security dimensions and parameters and how they relate to energy security?”
12. Then it was the question of “How should all indicators be aggregated to for a global Energy Security Index (ESI)?” which was the objective of **Publication IV**.
13. After all these steps, the jewel motivation and objective for this research was to quantitatively analyse energy security for all countries in the world with numerical representative values. **Publication IV** achieved this objective by answering the question “What are the energy security levels of all countries globally?”

1.4 Scope and limitation of the current research

As no research can cover all fields of science, this current research has its own scope and focuses. As was discussed in detail in the objectives of this research, the main scope is to build, test and apply a comprehensive energy security analysis framework and to evaluate energy security levels of all countries globally. This implies both, a qualitative approach with literature reviews and a quantitative approach with numerical evaluations. However, there are many aspects that are not included in the scope of this current research that can be possible in future research. Also, within the scope of this research some limitations were faced and dealt with accordingly.

This research limited the scope of its literature review on scientific research that was published after 1970, as scientific investigations following systematic and scientific principles only started around 1975 (Augutis et al., 2011). This scientific interest got momentum because of the 1970s oil crisis. Moreover, the documentation of energy security definitions is relatively new, with more than 40% of studies from 2010-onward, see **Publication I** (Figure 1). Furthermore, research publications prior to 1970 were not readily available for review.

As the scope of this research was to formulate a more profound understanding of energy security together with a global view on all of its elements, research confusing energy security with energy security of supply or research with no clear understanding of the nature of energy security were excluded. As Kaare et al. (2013) stated, there is a big difference between energy security of supply and a well-structured concept of energy security, as the former fails to address energy security from all its aspects. Erdal et al. (2015) provided a clear distinction about the two concepts of energy security and security of energy supply. Although, security of supply was discussed by many researchers (Bazilian et al., 2006; Cabalu, 2010; Cohen et al., 2011; Creti & Fabra, 2007; De Joode et al., 2004; Findlater & Noël, 2010; Grubb et al., 2006; Hoogeveen & Perlot, 2007;

Jamasb & Pollitt, 2008; Jansen & Seebregts, 2010; Joskow, 2007; Keppler, 2007; Kruyt et al., 2009; Le Coq & Paltseva, 2009; Löschel et al., 2010), it is not the scope of this research.

Applying the proposed energy security framework on energy storage was intended to validate and provide an example of how the framework can be applied on the sub-system of energy storage. Technologies for energy storage were analysed from the energy security perspective. It is not the scope of this research to provide a detailed analysis of every part of the energy system as the current research uses energy security analysis of energy storage technologies as an example of the framework application and as a test of its validity. Future research can overcome this limitation by applying this framework on all sub-systems of the energy system.

Furthermore, applying energy security analysis on a future energy transition scenario towards a 100% renewable energy-based system was limited to all the assumptions, estimations and projections that took place in modelling and simulating a future scenario. Although, these assumptions and projections have valid justifications and used credible scientific references, they can still be improved in the future. For this, this current research followed a full transparency of all the assumptions and data estimations. Other studies lack such level of transparency, for examples see **Publication III** (page 3). Therefore, the current research endeavours a fully transparent approach.

Moving on, one of the objectives of this research is to build a comprehensive Energy Security Index (ESI) that can be used to evaluate energy security levels quantitatively. However, there were some limitations in such a design. The first limitation is the use of equal weighting of all parameters and dimensions, which can be inaccurate at times. Nevertheless, the choice of equal weights was due to the absence of any valid justification for otherwise. Also, as was concluded by Augutis et al. (2020), equal weighting is similar to the average of different weighting scenarios after a detailed sensitivity analysis. However, to overcome this limitation, future research can investigate improved weighting techniques for all parameters and dimensions.

Additionally, in the ESI design, there is the limitation of static nature of the analysis. Energy security is analysed for a certain time which is mainly attributed to the choice of indicators. Many of these indicators have past records, but future projections of the indicators must be addressed separately in future research. If in future research all indicators have justified projections, ESI can be evaluated for future energy scenarios. The reason why it is difficult to project indicators into the future is due to the energy system changes which vary structurally from fossil bases to renewable bases (Haegel et al., 2019).

The final limitation encountered in this research was the absence of data from some countries. Although best efforts were spent in choosing indicators for which data is available for most countries, some values were absent. To overcome this limitation, some assumptions were made. Moreover, data unavailability for each country was presented in

Publication IV (Supplementary Material) for full transparency. Future research is needed to investigate the reasons of data unavailability from these sources and to build a suitable method to obtain absent data.

1.5 Scientific contribution of this research

The overall contribution of this research is to enable policy and decision makers to build their arguments on solid grounds with quantitative results. This kind of energy security analysis can provide a profound understanding with clear justification of the use of information from inside the energy system. This evaluation then provides a path of how to enhance energy security. This can then be mirrored to adopted policies. However, to achieve this important contribution in the scientific community, many smaller contributions are in need. The contributions of this research are distributed throughout **Publications I-IV**; all smaller contributions are listed below with references to where their details can be found:

1. The novel literature review procedure where energy security definitions were tracked along with their history is a major contribution to scientific knowledge. Prior literature lacked thorough and standardized methods in approaching energy security definition tracking. This research contributes by providing a set of criteria for which definitions are to be included based on what definitions were used by other researchers and scholars since 1970. (**Publication I**)
2. Showing the frequency of which energy security was discussed and defined in the research field with most of the discussion found in recent publications is the second contribution. Such frequency analysis helps the scientific community to form a better understanding of the influence of recent international crises on the energy system. (**Publication I**)
3. Furthermore, this research provides a generic definition of energy security that can be applied in future research about energy security. The novelty of this definition lies in its ability to be applied on all levels of energy systems, both nationally and internationally. Such a definition is necessary as previous researches did not agree on a specific method of how to address energy security. (**Publication I**)
4. In addition, this research shows the approach of previous literature on what dimensions to include while analysing energy security. This was done through a detailed literature review showing the diversity of what dimensions researchers previously included in their studies which contributes to the knowledge that conclusions are determined by the perspectives of scholars. Showing such diversity influences the discussion of motives and approaches of how to address energy security. (**Publication I**)

5. Moreover, the novelty of this research lies in the inclusion of all dimensions that were distributed in previous literature as no research addressed all these dimensions together. In total this research counted 15 dimensions that are related to energy security. These 15 dimensions are collected from previously separated literature with this research combining and consolidating all energy security dimensions into one analytical approach. **(Publication I)**
6. The next contribution is building a comprehensive framework for analysing energy security. In order to build this framework, all dimensions were justified, in addition, all parameters inside each dimension were introduced and discussed in detail. Such a transparent and detailed framework for energy security analysis has no precedent. Furthermore, building this framework sets an example of the methodological procedure for how to build frameworks for other matters. **(Publication I)**
7. This research does not stop its contribution only to providing a detailed framework for analysing energy security, rather, it extends to validating and testing this framework. This contribution was done by applying the energy security analysis framework on energy storage technologies as a representation of one of the sub-systems within the energy system. This contribution shows the validity of the framework and its applicability on all parts of the energy system. **(Publication II)**
8. Furthermore, this contribution provides recommendations for decisions makers for what and how energy storage technologies can affect energy security. Such a contribution is highly needed for energy systems' design and construction. **(Publication II)**
9. Moving on with the framework, this research proves the feasibility of this energy security analysis framework through the application on future energy systems. After the framework was tested for a sub-system, it was applied at the country/national level (Jordan) through the use of the whole energy system. Application of this energy security framework on a future energy scenario in Jordan is an example of how this framework can be applied to any country in the world. **(Publication III)**
10. Another novelty when applying the energy security analysis framework on a future energy scenario for the case of Jordan is the proposal of a 100% renewable energy Best Policy Scenario. Such a scenario contributes to the discussion of the feasibility of a 100% renewable power system for future planning, together with benefits on enhancing energy security. **(Publication III)**
11. The scenario is novel in itself by combining all sectors (power, heat, transport and desalination) with high temporal and spatial resolution. **(Publication III)**

12. Once the framework was prepared, validated and tested, the theoretical qualitative analysis was transposed into a more objective quantitative analysis using numerical values. Each of the parameters were presented with a suitable numerical indicator or a set of indicators. The novel choice of these indicators is one of the very important contributions made by this research to the scientific community. **(Publication IV)**
13. Another novel contribution of this research is the criteria set to be used for choosing indicators. This criteria set is not well established in previous research or, at least, with limited transparency of how these indicators were chosen. **(Publication IV)**. The following criteria are chosen in this research for numerical indicators:
 - a. Indicator values are available for all countries in the world or at least the majority;
 - b. Data used from trusted sources;
 - c. Indicator values can be in absolute or relative numbers;
 - d. Close proxy to the parameters;
 - e. Availability for current and future scenarios;
 - f. Normalization should be possible for the energy security analysis;
 - g. Accounting for sustainability (Child et al., 2018) as much as possible.
14. Furthermore, this research shows a huge contribution for an open data approach through total transparency. The detailed methods of how each indicator is linked to its correspondent parameter and to energy security are presented in a detailed manner to fully track all established relationships between dimensions, parameters and indicators of energy security. **(Publication IV)**
15. In addition to the novelty of the choice of proxy indicators to measure each parameter, this research evaluates each dimension separately on a global level. This research presents the achievement of all countries in the world in each of the dimensions, both numerically and by world maps. **(Publication IV)**
16. The crown contribution of this research is the evaluation of energy security for all countries in the world through a comprehensive index. This energy security evaluation, with all 15 dimensions quantitatively presented, was a missing gap in previous research. Energy security results for all countries are presented quantitatively and in a world map. **(Publication IV)**
17. The last contribution of this research lies in its ability to provide policy recommendations of what supportive policies are, in order to enhance energy security. Decision makers can spot out why energy security is at a certain level and what is needed in order to enhance energy. These recommendations contribute to policies comparisons from different countries. As on a global map, policies differ and thus having a visualized view of which country achieves higher energy

security levels makes other countries willing to learn and develop their strategies accordingly. **(Publication IV)**

1.6 Summary of dissertation structure

With a total of six chapters, the first chapter provides an overview about the background of energy security and the importance of its analysis, together with the motivation and objectives. The scope and limitations together with contributions of this research are all presented in the first chapter. Following, the second chapter addresses the current approaches to study energy security from theoretical frameworks through partial and spatial attempts to the limited applications. At the end of the second chapter the needed solutions are presented. Moving forward to the third chapter, methods for designing own energy security framework, its application on the energy sub-system of storage, a soft analysis of energy security for a future scenario for the case of Jordan, building an energy security index, numerical evaluations of energy security on the global level and visualising the results on global maps are all addressed. Once the reader has gone through these three chapters, the fourth chapter presents the four publications that are used to achieve the goals of this dissertation. Moving to the end, discussion about the obtained results are detailed in the fifth chapter whereas conclusions are presented in the sixth chapter.

2 Current approaches for energy security studies

Studies that addressed energy security have a huge variation in their intakes on the topic. As mentioned earlier in the introduction chapter, energy security was analysed from many different angles, including: policymaking (Turton & Barreto, 2006; Winzer, 2012), politics (Jonsson et al., 2015), national energy policies (Franki & Višković, 2015), national security issues (Dyer & Trombetta, 2013), international relations (Kirchner & Berk, 2010) and social sciences (Löschel et al., 2010). Such different starting points in addressing the topic of energy security resulted in different approaches to the topic. Some scholars approached the topic on the framework level, some do the analysis for a certain location, while others tackle parts of the energy system. In this chapter, current approaches for energy security are presented with the state of the art found in literature.

2.1 Theoretical framework

Since energy security is a concept rather than a strategy or policy (Chester, 2010), it needs to be addressed as such. It was concluded by many researchers that the concept is defined narrowly and disparately (Bohi & Toman, 1993; Kucharski & Unesaki, 2015; Narula & Reddy, 2015), is not defined clearly (Löschel et al., 2010; Winzer, 2012) or is with no common consensus (Checchi et al., 2009; Kruyt et al., 2009). Therefore it was the first step for researchers when designing a theoretical framework for energy security to decide what the definition of energy security is, although the term of energy security was described before by terms such as abstract, elusive, vague, inherently difficult and blurred (Checchi et al., 2009; Chester, 2010; Löschel et al., 2010; Narula & Reddy, 2016; Sovacool et al., 2011). Although, defining energy security is the first step in building a framework, definitions have been context-dependent and polysemic in nature (Chester, 2010; Jonsson et al., 2015; Kruyt et al., 2009; Vivoda, 2010) due to various assumptions (Ciută, 2010). To overcome this dilemma, energy security definitions moved to be more generic, see **Publication I** (pages 3-4).

There were many attempts to identify energy security through research history (Bohi & Toman, 1993; Cherp & Jewell, 2013; Ciută, 2010; Deese, 1979; Dreyer, 2013; Hossain et al., 2016; Hughes, 2009; IEA, 2001; 2007; Jan & Goldwyn, 2005; Jansen, 2009; Jewell et al., 2014; Johansson & Nakićenović, 2012; Kononov, 2014; Lakić, 2013; Lovins & Lovins, 1981; Miller et al., 1977; Müller-Kraenner, 2007; Narula & Reddy, 2016; Ojeaga, 2014; UNDP, 2000; Willrich, 1976; Winrow, 2009; Yergin, 2006). Most studies provided the definition of energy security by some of its elements, for example, energy security is defined as “The continuous availability of energy in varied forms, in sufficient quantities, and at reasonable prices” by UNDP (2000). However, limiting the definition to certain elements deteriorates any further possible framework design. Therefore, many researchers started to add more elements into their definitions of energy security, for example, energy security was defined as “How to equitably provide available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users” by Sovacool (2011) and Sovacool et al. (2013a).

With time, the previous approach of including more elements into the definition proved to be incapable of providing the reality of the energy security concept. Therefore, researchers started to limit the definition by providing a reference to these elements, and then, in a next phase of building the framework, these elements were illustrated. An example of this development was noted in recent years by Kanchana & Unesaki (2014), where they defined energy security as “Access to modern energy services”, with further explanations to the elements of access and what services are. Another example was provided by Jewell et al. (2014), where energy security was defined as “Low vulnerability of vital energy systems.” Afterwards, it was their task to determine what is vital for the energy system and what vulnerabilities are expanded on. However, both attempts did not manage to capture the nature of energy security. As can be seen in **Publication I** (page 5), energy security was defined as “the feature (measure, situation or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats”. This definition was generic enough to account for all elements (dimensions, parts of the system and threats). Afterwards, continuation to identify all these elements can be seen in **Publication I**.

The next step in building the theoretical framework for energy security analysis, after the definition is proposed, is the formulation of what elements need to be included. Although some researchers would call these elements as boundaries and vulnerabilities (Jewell et al., 2014), the vast majority of all researchers prefer the use of dimensions and parameters as the elements of energy security analysis (Ang et al., 2015; Azzuni & Breyer, 2018; Chester, 2010; Sovacool & Brown, 2010; Sovacool & Mukherjee, 2011; Winzer, 2012). A drawback of the approach by Jewell et al. (2014) is the negligence of many important elements of energy security such as environment and military, as well as many others. Their approach lags behind as Yergin (2006) states that energy security discussion should be extended to all possible dimensions that have a relationship to energy security. Further discussion about what dimensions are included in literature are provided in section 2.3. Furthermore, all detailed relationships between parameters and dimensions with energy security are well-established and presented in **Publication I**.

At this point, conceptualisation of the energy security framework is done and some researchers stopped at this depth (Chester, 2010). However, most researchers continued building an analytical framework by proposing numerical indicators to measure, calculate and/or evaluate each of the parameters and dimensions (Ang et al., 2015; Azzuni & Breyer, 2018). The number of proposed indicators varied, some researchers proposed very few indicators (Badea et al., 2011; Radovanović et al., 2017), where only eight and six indicators were used, respectively. The most intensive proposal of numerical indicators was done by Sovacool & Mukherjee (2011) in which hundreds of indicators were purposed. Although it is theoretically possible to propose such a high number of indicators, in order to build an applicable and systematic analysis to evaluate energy security, limiting criteria is needed. **Publication IV** (pages 2-3) provides detailed criteria, which is required when choosing suitable numerical indicators.

Once the set of indicators are ready, researchers start the collection of data for such indicators. When all values are prepared, researchers are faced with three main challenges; and their approaches to overcome these challenges vary. The first challenge is the unequal ranges of differing indicators, therefore normalization techniques are required. Through all previous research, normalization was done by varying techniques: min–max (Gnansounou, 2008; Kamsamrong & Sorapipatana, 2014; Lefèvre, 2010), distance to a reference (USChC, 2012) or standardization (Martchamadol & Kumar, 2012; Sovacool & Brown, 2010). Nevertheless the most common approach is max-min as summarized by Ang et al. (2015).

After normalizations, scholars faced the second challenge of how important each indicator is, how important each parameter is and how important each dimension is. To answer this question, weighting techniques are needed. As found by Ang et al. (2015), the most common technique in literature is equal weighting technique (Onamics, 2005; Sovacool & Brown, 2010; Sovacool et al., 2011). Other researchers tried other weighting techniques: import/fuel share (Sharifuddin, 2014; WEC, 2014), Principle Component Analysis (PCA) (Gnansounou, 2008; Martchamadol & Kumar, 2012), Analytical Hierarchy Process (AHP) (Wu et al., 2012) and Data Envelopment Analysis (DEA) (Zhang et al., 2013); while some researchers did not use any of these analytical techniques but rather relied on subjective evaluations.

Once weighting for all indicators, parameters and dimensions is done, the third challenge of how to aggregate an index is faced by researchers. Mostly this is done by simple addition. Figure 1 summarizes all three steps of building numerical indexes for energy security frameworks that lead researchers to varying approaches of how to present their results, for example by numbers, clusters, or coloured maps.

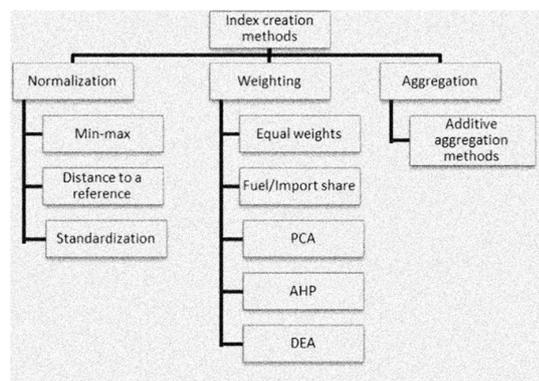


Figure 1: Summary techniques to build an energy security analysis framework, adopted and modified from Ang et al. (2015). Abbreviations: Principle Component Analysis (PCA), Analytical Hierarchy Process (AHP) and Data Envelopment Analysis (DEA).

2.2 Spatial analysis

Previous research has focussed only on certain locations to make the energy security analyses. Such spatial analysis is limited by nature as it focuses on the perspective of individual countries or regions with specific factors, which only interplay inside that location. Such analyses are not very helpful when drawing comparisons of what policies to adopt globally. It is true some researchers have tried to overcome this dilemma by expanding the research to different countries instead of limiting the scope to one national level. However, this approach was not successful to reach the inclusivity of all countries with a true global analysis except with few exception, such as (Wang & Zhou, 2017; WEC, 2019). As will be seen in the next section, all previous attempts to analyse energy security globally did this from a very narrow perspective and partial approach.

Summaries of previous research addressing energy security analyses on the national levels for most countries are presented in Table 1.

Table 1: Summary of previous national energy security analyses.

Country	References
Albania	(Fida et al., 2009; Çukaj, 2015)
Argentina	(Kozulj, 2010)
Algeria	(Seifeddine & Abdeldjalil, 2017)
Armenia	(Hovhannisyian, 2003; Kazarian, 2018; Kosowska et al., 2018; Sarukhanyan, 2011)
Australia	(Gang, 2010; Ralph & Hancock, 2019; Tidemann, 2019; Yates & Greet, 2014)
Azerbaijan	(Aslanbayli, 2013; Senderov et al)
Bangladesh	(Halder et al., 2015; Islam et al., 2014; Islam, 2003)
China	(Lu et al., 2014; Matsumoto, 2015; Ren & Sovacool, 2014; Ren & Sovacool, 2015; Wu et al., 2012; Yao & Chang, 2014)
Croatia	(Franki & Višković, 2015; Tatalović, 2008)
Cyprus	(Karakasis, 2015; Taliotis et al., 2014)
Denmark	(Sovacool & Tambo, 2016)
Egypt	(Atlam & Rapiea, 2016)
Estonia	(Kasekamp, 2006)
Ethiopia	(Guta & Börner, 2017)
Finland	(Helin et al., 2018; Jääskeläinen et al., 2018)
France	(Teräväinen et al., 2011)
Georgia	(German, 2009; Zachmann, 2014)

Germany	(Gillessen et al., 2019; Röhrkasten & Westphal, 2012)
Greece	(Jones et al., 2017; Nomikos, 2016; Vidakis & Baltos, 2013)
Hong Kong	(Holley & Lecavalier, 2017)
Hungary	(Bősze, 2006; Isaacs & Molnar, 2017)
India	(Kunz, 2012; Narula, 2014; 2015; Reddy, 2015)
Indonesia	(Kumar, 2016; Prasetyono, 2008)
Ireland	(Bazilian et al., 2006; Chalvatzis & Ioannidis, 2017a; Glynn et al., 2014; Seebregts & Welle, 2018)
Italy	(Farinosi et al., 2013)
Japan	(Barai & Saha, 2015; Lesbirel, 2004; Matsumoto, 2017; Matsumoto & Shiraki, 2018; Vivoda, 2016; Wahlin, 2006)
Jordan	(Alshwawra & Almuhtady, 2020; Azzuni & Breyer, 2020; El-Anis, 2012; Hammad & Al-Momani, 2013)
Kazakhstan	(Amirov et al., 2018; Baizakova, 2010), North Korea (Von Hippel & Hayes, 2007)
South Korea	(Chung et al., 2017; Kim et al., 2011)
Latvia	(Kochetkov & Yurkovskaya, 2015)
Lithuania	(Janeliūnas & Molis, 2006; Leonavičius et al., 2015; 2018)
Macedonia	(Glavinov et al., 2017)
Malaysia	(Foo, 2015; Sharifuddin, 2014; Sovacool & Bulan, 2012)
Mexico	(Spring, 2020)
Mongolia	(Ryu et al., 2014; Song et al., 2013)
Morocco	(Moore, 2017; Seifeddine & Abdeldjalil, 2017; Vidican-Auktor, 2017), Myanmar (Simpson, 2005)
Nepal	(Herington & Malakar, 2016)
Nigeria	(Okeke & Nzekwe, 2014; Okonta, 2013)
Pakistan	(Aized et al., 2018; Anwar, 2010; 2016; Sahir & Qureshi, 2007)
Philippines	(Brahim, 2014; La Viña et al., 2018)
Poland	(Johnson & Boersma, 2013; Pająk et al., 2017; Wieloński & Machowski, 2008; Ćiković, 2008)
Romania	(Gheorghe et al., 2011)

Serbia	(Bukurov et al., 2010; Lakić, 2013; Pavlović & Ivezić, 2017)
Singapore	(Chang & Lee, 2008; Chang & Putra, 2012)
South Africa	(Bellos, 2018; Nkomo, 2009)
Spain	(García-Gusano & Iribarren, 2018)
Sweden	(Månsson et al., 2014)
Tajikistan	(Akhrova et al., 2014; Laldjebaev et al., 2018)
Thailand	(Kamsamrong & Sorapipatana, 2014; Martchamadol & Kumar, 2012; Phdungsilp, 2015; Selvakkumaran & Limmeechokchai, 2012; Watcharejyothin & Shrestha, 2009)
Turkey	(Biresselioglu et al., 2017; Jones et al., 2017; Kaygusuz et al., 2015; Winrow, 2009)
Turkmenistan	(Boucek, 2007)
Ukraine	(Semenenko, 2016)
United Arab Emirates	(Bahgat, 2012)
United Kingdom	(Abdo & Kouhy, 2016; Cox, 2018; Demski et al., 2014; Mitchell et al., 2013; Rogers-Hayden et al., 2011)
United States of America	(Bang, 2010; Chow & Elkind, 2005; Dunham & Schlosser, 2016; Faeth, 2012; Johnson & Boersma, 2015; Nyman, 2018)

All this previous research was limited to a spatial analysis, addressing challenges and opportunities for specific and targeted countries. Researchers became aware of the need to have a more coherent energy security analysis with robust comparison. Therefore, cluster energy security analysis for bigger regions was started to get more profound insights and applicable results of not only how energy security is in one country, but rather what interactions countries have in one cluster. Since all countries nowadays are connected globally, aspects of energy security interplay across national borders affecting the whole energy system. Summarized in Table 2 are energy security analysis publications clustered for different regions.

Table 2: Summary of regional energy security analyses.

Regions and clusters	References
ASEAN countries	(Kanchana & Unesaki, 2014; 2015a; Tongsopit et al., 2016)

18 countries (United States, European Union, Australia, New Zealand, China, India, Japan, South Korea, and the ten countries comprising the Association of Southeast Asian Nations (ASEAN))	(Sovacool et al., 2011)
China, India, EU, USA	(Jewll et al., 2013)
Asia-Pacific	(Neff, 1997; Sovacool, 2011a; 2013b; Vivoda, 2010)
South Asia	(Mahmud, 2012; Sankar et al., 2005)
East Asia	(Matsumoto & Andriosopoulos, 2016)
Central Asia	(Bahgat, 2006a)
EU	(Chalvatzis & Ioannidis, 2017b; Gracceva & Zeniewski, 2014; Hedenus et al., 2010; Jonsson et al., 2015; Le Coq & Paltseva, 2009; Matsumoto et al., 2018; Scheepers et al., 2006)
Europe	(Bahgat, 2006b; Checchi et al., 2009; Dreyer, 2013; Johnson & Boersma, 2015)
Southeast Europe	(Franki & Višković, 2015; Čehulić et al., 2013)
Central and East Europe	(Onamics, 2005)
Baltic region	(Augutis et al., 2020; Findlater & Noël, 2010; Jääskeläinen et al., 2019; Kaare et al., 2013)
Nordic countries	(Aslani et al., 2012)

Furthermore, most of the previous analyses, whether for national countries or for regions and clusters, lack a detailed quantitative analysis for all aspects of energy security. Many previous researches were carried with a qualitative analysis, similar to **Publication III**. On the other hand, an indicator-based analysis with quantified measures has been used in a very simplified view of energy security, not including all the needed aspects. The next section will address this point in more detail.

2.3 Partial indexes

The current state of the art in scientific research is to analyse energy security by its elements. Scholars choose the elements of energy security to be discussed based on their needs and their energy security perspectives. Studying previous literature through an intensive and comprehensive literature review shows that a total of 15 dimensions were distributed in literature, with no single research to address them all together. Table 3 shows the number of total literatures that were analysed together with the occurrence frequency of all dimensions. The detailed occurrence of each dimension in previous literature is presented in **Publication I** (Supplementary Material).

Table 3: Number of reviewed publications and frequency of dimensions occurrence.

Total Literature	104
Dimensions	Frequency of occurrence
Availability	98
Diversity	83
Cost	93
Technology & Efficiency	70
Location	52
Timeframe	37
Resilience	30
Environment	69
Health	18
Culture	16
Literacy	17
Employment	19
Policy	89
Military	35
Cyber Security	4

Furthermore, not all previous literature provided a quantified indicator-based analysis for these dimensions. Some just addressed the energy security topics from a view of qualitative soft analysis, and some provided numerical indicators.

2.4 Limited applications

After the state of the art has been explained for the spatial analysis and the use of partial indexes, it can be seen that current research lags behind in another aspect when it comes to energy security analysis. That is the focus of the analysis. Many researchers would focus their studies and analyses on parts of the energy system, instead of addressing all interconnected parts or assessing the system as a whole. As was addressed before, many previous researchers analysed the system partially by focusing on the analysis of the security of supply (Bazilian et al., 2006; Cabalu, 2010; Cohen et al., 2011; Creti & Fabra, 2007; De Joode et al., 2004; Findlater & Noël, 2010; Grubb et al., 2006; Hoogeveen & Perlot, 2007; Jamasb & Pollitt, 2008; Jansen & Seebregts, 2010; Joskow, 2007; Keppler, 2007; Kruyt et al., 2009; Le Coq & Paltseva, 2009; Löschel et al., 2010). Such analyses

lag in their ability to evaluate energy security matters related to other parts of the energy system, i.e. refineries, electricity transmitting lines, etc.

Other researchers focused their analyses on specific types of fuels: oil (Colgan, 2014; Gupta, 2008; Zhang et al., 2013), oil and natural gas (Cohen et al., 2011; Selvakkumaran & Limmeechokchai, 2012; Wu, 2014), natural gas (Cabalu, 2010; Cabalu & Alfonso, 2013; Findlater & Noël, 2010; Gillessen et al., 2019; Samrina, 2004; Taliotis et al., 2014), fossil fuels (Le Coq & Paltseva, 2009), and electricity (Cox, 2018; Kamsamrong & Sorapipatana, 2014; Stirling, 2014; Tidemann, 2019). This gap in research is to be covered in this research. **Publication IV** provides a detailed inclusion of all types of fuels into the energy security analysis.

Furthermore, many other limited applications of energy security analysis took place in previous literature in which some researchers focussed on critical energy infrastructure (Farrell et al., 2004), transport (Gillessen et al., 2019; Månsson et al., 2014) or primary energy system (Jansen, 2009; Jansen & Seebregts, 2010; Neff, 1997). The gap of limited application on one part of the energy security system was overcome by Azzuni and Breyer (2020).

2.5 Needed solutions

After going through the journey of different approaches to address energy security, a need for a solution to fill research gaps arises. Theoretical frameworks are different as discussed before; however, the most common approach is to formulate a framework for energy security based on its elements. Although scholars differ in which terms to be used for these elements, most agree on the use of dimensions, aspects and parameters. After that, an analysis is usually done whether qualitatively by studying these elements of energy security, or numerically by assigning suitable indicators. If so, indicators are aggregated in different techniques. Furthermore, scholars must decide on a weighting method in order to produce the aggregation of energy security values; most scholars choose equal weights. Afterwards, results are presented in a way that serve the purpose of the analysis. Throughout the building of the frameworks, researchers choose between which location to hold the analysis, which dimensions and parameters to include and which parts of the energy system the analysis is to be applied on.

The needed solution to cover all these research gaps is to formulate a comprehensive energy security framework that includes all dimensions and parameters, applied with a real global representation on all countries and addresses the energy system as a whole. How to achieve this solution is detailed in the methods, found in the next chapter.

3 Methods of energy security studies

3.1 Designing an energy security framework

The first step in designing a framework for energy security analysis is to determine the nature of the energy security concept and what it is. In order to get a clear understanding of the concept of energy security itself, the definition of energy security is needed. Since the concept of energy security has been addressed as abstract, vague, elusive, or blurred (Checchi et al., 2009; Chester, 2010; Löschel et al., 2010; Narula & Reddy, 2016; Sovacool et al., 2011) a systematic approach is needed to define energy security. Also, such an approach is needed because energy security was defined narrowly (Bohi & Toman, 1993; Kucharski & Unesaki, 2015; Narula & Reddy, 2015) or not clearly (Löschel et al., 2010; Winzer, 2012).

To formulate a definition for energy security, an intensive literature review took place as a first step. Methodologically, scientific publications that provided a definition for Energy Security were listed with their proposed definitions. However, all publications that defined any other term (e.g. security of supply or oil security) were excluded from the review for the reasons mentioned in the previous chapters. **Publication I** provides a detailed list of previous energy security definitions found in literature. Once the previous attempts of defining energy security were analysed, it was clear how researchers obtained these definitions.

The result of this literature review set the path for the methods to formulate a comprehensive energy security definition. Definitions were simple at the beginning, but as time progressed, researchers started including more dimensions into the definition. At the latest stage it became more appropriate to use generic terms for energy security elements and then analyse these elements. This latest method was followed in this work.

The next step to formulate a comprehensive energy security definition was to include the three fundamental parts of the energy system: supply, demand and conversion. As it was suggested by UNDP et al. (2004), security of supply should not be the only focus of an energy security definition. Furthermore, in order to define energy security comprehensively, the concept of sustainability has to be taken into consideration (Von Hippel et al., 2011). The next step was to include the concept of threat or risk, i.e. the degree to which the system is unable to cope with disastrous events (Gnansounou, 2011). Finally, once all these steps are clear, the final step was to track the linguistic meaning for the two sides of the term “Energy” and “Security”. The formulation of energy security definition took place in **Publication I** (page 5). The resultant definition will be presented in the results chapter.

The next level of the framework was to determine all elements of energy security, together with the threats to these elements. Following the established methods of previous research, where elements were addressed as dimensions and parameters, an intensive

literature review was done to capture all these elements. **Publication I** (Supplementary Material) shows the record of all these dimensions.

As this work aims for a global comprehensive energy security analysis framework, all dimensions that were found in the literature were included and analysed. Analysing dimensions and parameters are meant to establish a profound and unique relationship to energy security. All included dimensions and parameters have their independent relationship to energy security; these relationships are established by an inclusive theoretical approach.

3.2 Energy security analysis for energy sub-systems (energy storage)

To analyse energy security for an energy sub-system (energy storage), the first step was to determine the most commonly used energy storage technologies in the world. In consideration of previous literature, five energy storage technologies were identified.

The next step was to study all these five technologies in detail; the state of the art for all of them was provided. Additionally, interplays and interactions between energy security and all aspects from these technologies was analysed qualitatively. The analysis was done by assigning plus and minus (+/-) signs for all dimensions and parameters. The plus sign is given if the aspect of a technology affects energy security positively, while the negative sign is the opposite, where energy security is affected negatively by the aspect in question. A detailed description of all these interactions between energy security dimensions and parameters with each aspect of these five storage technologies was reported in **Publication II**.

After that, a colour coded, soft analysis was done with the following steps:

- **Step 1:** Each technology is explained for all dimensions.
- **Step 2:** Within each dimension, if there is a positive relationship between any of its parameters with this technology, a plus is given.
- **Step 3:** The exact opposite is applied when a negative relation to energy security appears to affect any of the parameters.
- **Step 4:** A technology-dimension matrix table was created to summarize the effects of each technology on parameters from each dimension.
- **Step 5:** If the number of the plus elements in a dimension for the specific storage technology is more than the minus elements, the box was coloured in green.
- **Step 6:** If the number of minus elements is more than the positive signs, the box was given a red colour.

- **Step 7:** If the number of plus and minus elements are equal, the relationship was considered neutral for this dimension and the box was given a yellow colour.
- **Step 8:** The total energy security evaluation for each energy security dimension was calculated in the last column of the technology-dimension matrix table.
- **Step 9:** The green box was allocated a value of +1, the red box a value of -1, and the yellow box a value of 0.
- **Step 10:** The values of the boxes were summed up for each storage technology. If the summation was positive, this technology was considered to enhance energy security. The higher the number, the better the enhancement of energy security.

3.3 Soft analysis of energy transition from the lenses of energy security

A detailed method of how a scenario simulation is done is needed in order to carry out an energy security analysis for any future scenarios. In this section, the detailed methods and data formulation are described. A Best Policy Scenario for the period 2015 to 2050 is defined. The last part of this section details the methods for the energy security analysis.

3.3.1 LUT Energy System Transition model overview

The LUT Energy System Transition model (Bogdanov et al., 2019a; Breyer et al., 2017) was used to explore the feasibility of a transition scenario in Jordan. The LUT model is an optimization model to investigate energy systems under numerous technical and financial assumptions through all sectors of power, heat, transport and desalination. Industry is not singled out as a separate category because electricity, heat and transportation demands for the industrial sector are measured within the respective sectors. The model operates in five-year intervals, with hourly resolution, for the period of 2015-2050. The target function of the model is to achieve a least-cost energy system under given constraints and assumptions.

Figure 2 shows the LUT Energy System Transition model's process flow diagram. More detailed explanation of the model for the four sectors of power, heat, transport and desalination was provided by Ram et al. (2019). The schematic block diagram for the integrated power and heat sectors is shown in Figure 3. The respective block diagrams for transport and desalination sectors are presented in Figure 4 and Figure 5, respectively.

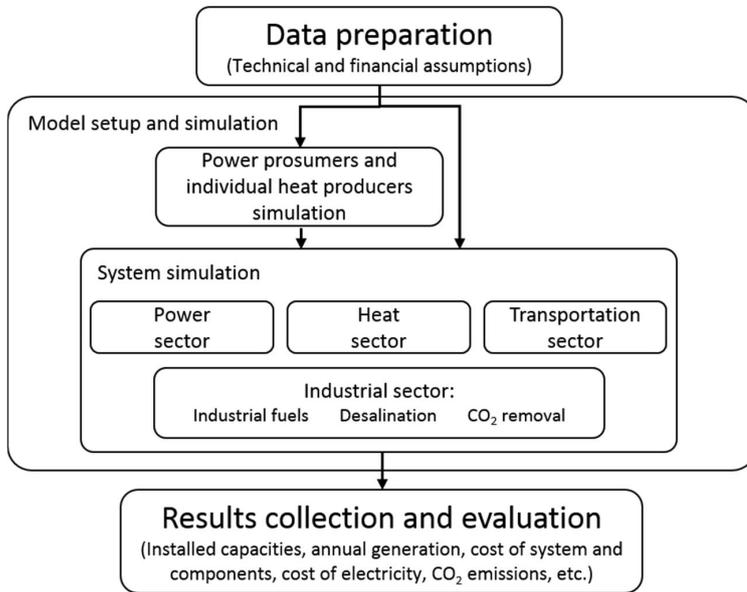


Figure 2: Fundamental structure of the LUT Energy System Transition model (Bogdanov et al., 2019a; Ram et al., 2019).

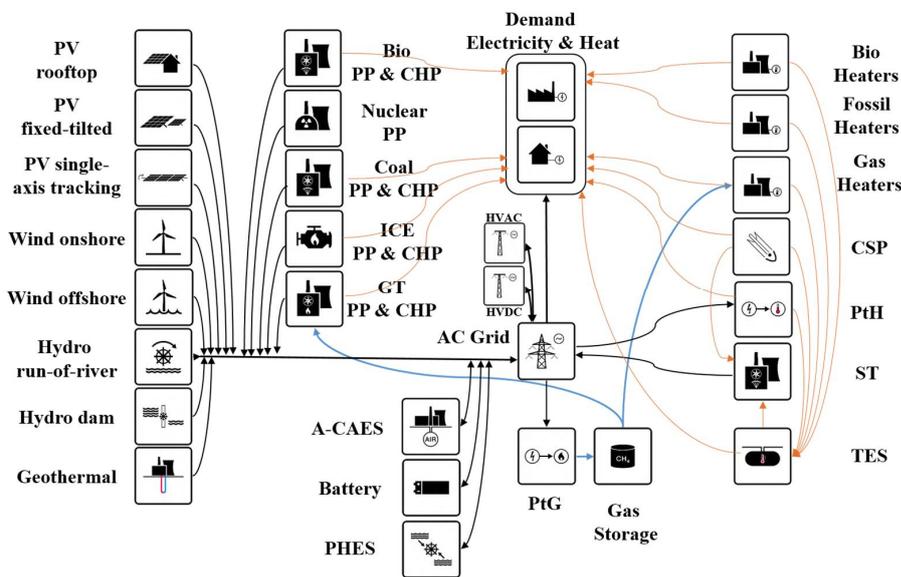


Figure 3: Schematic of the LUT Energy System Transition model for the coupled power and heat sectors (Bogdanov et al., 2019b).

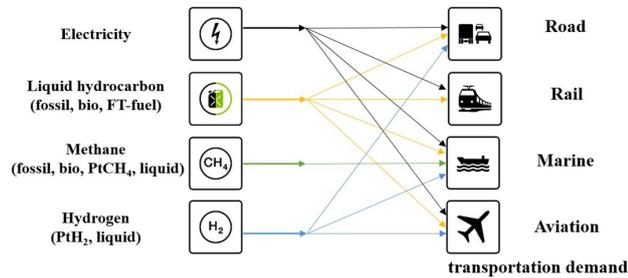


Figure 4: Schematic of the transport modes and corresponding fuels utilized (Bogdanov et al., 2019a; Ram et al., 2019).

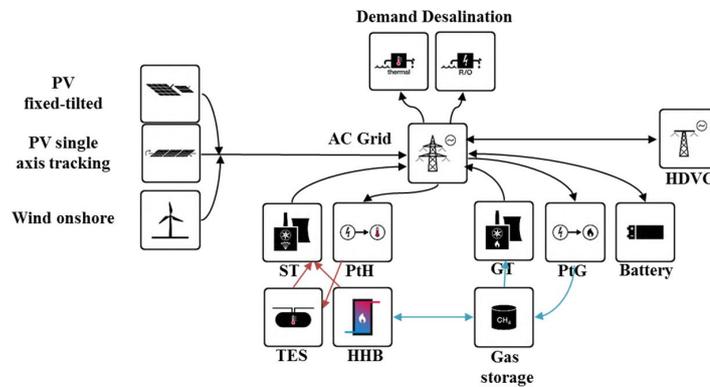


Figure 5: Schematic of the LUT Energy System Transition model for the desalination sector (Caldera & Breyer, 2020).

Optimization was carried out in two stages. First, demand for prosumers must be covered in hourly resolution for commercial, residential and industrial sectors by installed capacities of solar PV, battery storage and individual heating capacities as long as it leads to improved economics for prosumers. The prosumers' demand is limited to 20% of total demand by 2050, whereas up to 50% of the total generation of the prosumers can be fed into the grid.

Second, the demand for all sectors should be met in every hour of the applied year. The optimization was conducted for the power and heat sectors as an integrated case, while the transport and desalination sectors are simulated individually. The installed capacity share of renewables was limited to a maximum growth of 20% every five years to eventually reach a 100% renewable energy system by 2050. Additionally, no new nuclear and fossil-based power plants were assumed to be installed after 2015. The existing capacities, however, were assumed to continue operating until the end of their actual lifetimes. Infrastructure of gas turbines was assumed to be active in the model, as the sustainably produced synthetic natural gas and biomethane can substitute fossil fuels.

3.3.2 Country data and assumptions used in the model

The LUT model was used to build an energy transition scenario for Jordan. Current energy demand was obtained from different references, whereas future demand was projected and extrapolated. The hourly demand profiles were generated and used as input data. The demand profile for each power sector was taken from Toktarova et al. (2019). The heat demand was classified into four categories: space heating, domestic hot water heating, industrial process heat, and biomass for cooking. Furthermore, based on temperature, the heat demand was divided into three categories: low, medium and high. It was projected that biomass for cooking will decline the closer the transition gets to the end. This projection can be justified with the argument that the energy system will become more efficient and all residents in the country will have access to clean energy by 2050. There are four types of transport modes in the system: road, rail, marine and aviation. Each of the transport modes includes passenger and freight as a sub-category. The impact of smart charging and vehicle-to-grid concepts was excluded in this study. The desalination demand is collected from Caldera and Breyer (Caldera & Breyer, 2020). The projected demand of desalinated water was related to municipal, industrial and agricultural sectors. Final energy demands by sectors and by energy for Jordan are presented in Figure 6.

As explained by Bogdanov et al. (2019a), weather data from 2005 was applied. Resource profiles in high spatial and temporal resolutions for solar PV, concentrated solar power (CSP), wind energy and hydropower were prepared. Bioenergy sustainable potential (Bunzel et al., 2009) and geothermal energy (Aghahosseini et al., 2017) were used as an upper limit in the model. Currently-installed power plants capacities were summarised in annual resolution from 1960 to 2015 by Farfan & Breyer (2017).

Further, all detailed data and all the technical and financial assumptions for all technologies were obtained from different sources and were published in **Publication III** (Supplementary Material). Learning curves assumptions for all technologies were included indirectly. Learning curves have a direct and indirect impact on future costs as they are a crucial element for determining cost-optimal energy transition pathways.

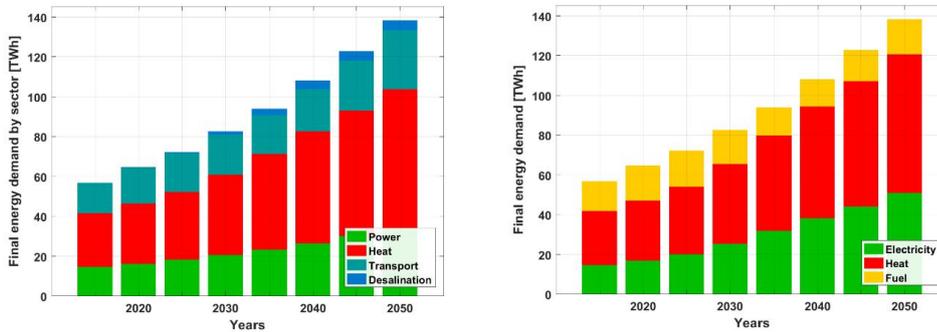


Figure 6: Development of final energy demand by energy form (left) and by sector (right) for Jordan.

3.3.3 Scenario definition

Although the LUT model can be used for wide scenario variations, the choice of this research was to emphasize a transition towards a 100% renewable energy system, which is in line with the Paris Agreement (UNFCCC, 2015) targets, and the United Nations (UN, 2015) Sustainable Development Goals (SDG). The Best Policy Scenario fulfils these criteria, wherein the demand for power, heat, transport and desalination sectors must be met in 2050 only by renewable energies, energy storage and other flexibility options, e.g. power-to-X (PtX) technologies. The transition towards a fully renewable energy system in Jordan was planned from 2015 to 2050. After that, a scenario simulation was carried out using the LUT modelling setup, including all critical aspects of the power, heat, transport, and desalination sectors.

3.3.4 Method for future scenario energy security analysis

Future energy security for a 100% renewable energy system in Jordan was analysed by using a similar method presented for energy storage technologies analysis from an energy security perspective. The first step was to identify the dimensions to be analysed. The choice of dimensions is done based on their importance. For that, six dimensions out of 15 were included in the analysis: availability, diversity, cost, environment, health and employment. The limited inclusion of six dimensions was due to the nature of the LUT model in which many other energy security dimensions were not part of the simulation results.

The analysis was carried out by addressing parameters of each dimension. If a parameter or an aspect of a dimension was affected positively, then this dimension received a plus sign. The same qualitative analysis was carried out for negative impacts of the energy transition on energy security where a minus sign was given for negative impacts. The

overall evaluation of a dimension was represented by a numerical sum of the plus and minus signs.

Colour coding was used to visualise the impact of a 100% renewable energy transition on energy security for each analysed dimension. The colour coding paradigm depends on how many positive or negative impacts each dimension received throughout the analysis. If the total number of positive impacts was higher than the negative ones, then a green colour was given, otherwise it was given a red colour. If the number of plus signs and negative signs were equal, then the colour was designated yellow.

3.4 Indicators and data collections

After all dimensions and parameters were identified and introduced in the process of building an energy security analytical framework, proper numerical indicators were chosen to measure each parameter. Although the most intensive proposal for numerical indicators was done by Sovacool & Mukherjee (2011), most of these indicators cannot be readily used to build a global energy security index that evaluates energy security correctly because of data unavailability for most countries and the interdependence of each indicator. In this work, strict criteria were used for the choice of numerical indicators. Such criteria allowed for the most accurate energy security framework analysis. The criteria for numerical indicators are:

1. Indicator values should be available for all or at least most of the countries in the world.
2. Indicators should have their data obtained from trusted sources.
3. Indicator values can be in absolute or relative numbers.
4. Indicators should have close proximity to the parameters.
5. Normalization should be possible for all indicators.
6. Indicator values should be available for the present with the possibility to be extrapolated to the future.
7. Indicators should be in accordance with the sustainability guardrails (Child et al., 2018) as much as possible.

Furthermore, the methods for choosing suitable indicators are transparent. To fully track all established relationships between dimensions, parameters and indicators, methods

were presented in a maximum level of detail. Following all these criteria resulted in a very well-established list of 76 indicators, see **Publication IV** (Table 1).

The next step in the method was to collect and obtain all needed data for each of the numerical indicators. Collecting data was done from online datasets provided by international organizations such as the United Nations and the World Bank. All countries and all indicators distributed on different parameters and dimensions were put together in Microsoft Excel. All values and their references for all indicators and parameters were included in **Publication IV** (Supplementary Material).

3.5 Numerical evaluation methods of aggregations

Once all the data were collected for all indicators, then the issue of different ranges appears as it was described in Chapter 2. Basically, there was a need to convert absolute numbers into relative percentage values in a normalization step, so that it was possible to have the comparable representations from all the data sets. Some indicators were already normalized, but the ones that needed normalization had to go through this step. Normalization was mainly done by a max-min approach in linear regression to create a percentage indicator relative to all other countries. Equation (3.1) describes the max-min normalization method. Usually, normalization takes place if the original indicator is not already in a percentage value.

$$\hat{I}_{j,r} = \frac{I_{j,r} - \min_r(I_{j,r})}{\max_r(I_{j,r}) - \min_r(I_{j,r})} \times 100\% \quad (3.1)$$

where $\hat{I}_{j,r}$ is the normalized indicator for corresponding specific parameter (Y_j), $(I_{j,r})$ is the absolute value of the indicator, $\min_r(I_{j,r})$ is the minimum value in the world for $(I_{j,r})$ and $\max_r(I_{j,r})$ is the maximum value in the world for $(I_{j,r})$.

However, sometimes the max-min approach was improved by an optimal-worst relationship of an indicator. This was done for the indicators where their relationship to energy security is more complex. Equation (3.2) shows the conversion from Equation (3.1) to an optimal-worst normalization method. Such a choice of optimal-worst normalization was justified separately for indicators that needed such alternations (**Publication IV**).

$$\hat{I}_{j,r} = \frac{I_{j,r} - \text{worst}_r(I_{j,r})}{\text{optimal}_r(I_{j,r}) - \text{worst}_r(I_{j,r})} \times 100\% \quad (3.2)$$

where $(\hat{I}_{j,r})$ is the normalized indicator for the corresponding specific parameter (Y_j), $(I_{j,r})$ is the absolute value of the indicator, $worst(I_{j,r})$ is the worst value in the world for this indicator ($I_{j,r}$) and $optimal(I_{j,r})$ is the optimal value in the world for this indicator ($I_{j,r}$).

After all indicators were normalized, they were used to calculate parameters (Y_j). Some parameters are calculated by one indicator, but many other parameters are linked to two proxy indicators or more. If so, then Y_j was computed by their average. If there was more than one indicator for any parameter, then Equation (3.3) was applied.

$$Y_j = \frac{\sum_{n=1}^o \hat{I}_{j,r}}{o} \quad (3.3)$$

where $(\hat{I}_{j,r})$ is a normalized indicator used for the specific parameter Y_j and o is the number of indicators.

If the relationship between indicators and energy security was directly proportional, then their values were used as-is. If the relationship was reversely proportional (increase in a parameter resulted in a negative impact on energy security), then normalized indicators were subtracted from unity (100%).

The following step was to aggregate all parameters to calculate the value of each dimension (X_i). Such aggregation was done by simple addition of the results after multiplying each parameter by its weight. Weights represent the importance of each parameter within a dimension. Equation (3.4) shows how aggregation is done for each dimension.

$$X_i = \sum_{j=1}^m W_j \cdot Y_j \quad (3.4)$$

where W_j is the weight of each parameter and Y_j is the value of each parameter.

In this work, all parameters were given equal weights (W_j) within their dimension, due to lack of data for individual weighting. Also, equal weighting is used in past work (Cabalu & Alfonso, 2013; Kamsamrong & Sorapipatana, 2014; Wu et al., 2012). Furthermore, as it was discussed in more detail in Chapter 2, equal weights are very similar to the average weight after a sensitivity analysis is done (Augutis et al., 2020).

The last step in aggregation was to formulate the overall Energy Security Index (ESI). This was done in a similar fashion to how parameters were aggregated for each dimension, but now, dimensions were aggregated for ESI. Equation (3.5) represents the aggregation of all dimensions to formulate the ESI.

$$\text{Energy Security Index (ESI)} = \sum_{i=1}^n V_i \cdot X_i \quad (3.5)$$

where V_i is the weight of each dimension and X_i is the value of each dimension.

The same approach of equal weighting used for parameters was again applied on the dimensions' weights (V_i) in the aggregation of the ESI.

Sometimes, the values of indicators do not exist for each parameter, these indicators were set as empty cells, and therefore, did not affect the calculation of the respected parameter. That was in the case of indicators used to calculate a parameter. In the case there was only one indicator for a parameter, then the value of that parameter was set as the worst value (0%). The list of missing indicators for all countries was published in **Publication IV** (Supplementary Material). Furthermore, the detailed methods for formulating each of the dimensions and their corresponding parameters and indicators, the relationships between indicators and energy security and all normalization techniques used for each indicator were provided in **Publication IV** (Appendix A).

3.6 Methods for global presentation of energy security on maps

The last aspect of the methods that were used in this work was the representation of all ESI values for all countries with the performance of each country in each individual dimension. Results were plotted against the world map using QGIS (OSGeo, 2016). Shapefiles for determining the borders of each country were obtained from (DIVA-GIS, 2011). After that, values of the ESI for each country were included in the attribute tables in QGIS. The results were then colour-coded based on their ESI performance, as will be discussed in the next chapter, in section 4.4. All other results for each dimension were presented in **Publication IV** (Section 3.2).

4 Results

4.1 Publication I: Definitions and dimensions of energy security

Aims

The aim of **Publication I** was to perform a detailed comprehensive literature review on previous research focusing on energy security and its dimensions, in order to design a proper framework for energy security analysis, through understanding the nature and the elements of energy security. The literature review that was published in **Publication I** was not the ultimate goal, but a tool to track all previous definitions of energy security that existed in literature and analyse them. This historical analysis was used to achieve the goal of formulating a generic definition of energy security that allows for better understanding of the nature of energy security.

Methods

The primary method used in this publication was a detailed literature review. An extensive literature review was conducted to formulate the energy security definition by analysing previous trends and following the most comprehensive recent approaches. Furthermore, connections between energy security and all dimensions and parameters were noted. Insights from previous researchers about what dimensions to be addressed were considered and resulted in the inclusion of 15 dimensions that were distributed in previous literature into one framework.

Results

Although, this literature review was performed on more than 100 publications, it was found that, most of the publications were published in recent years. Figure 7 shows the trend in publications to address energy security with a clear definition.

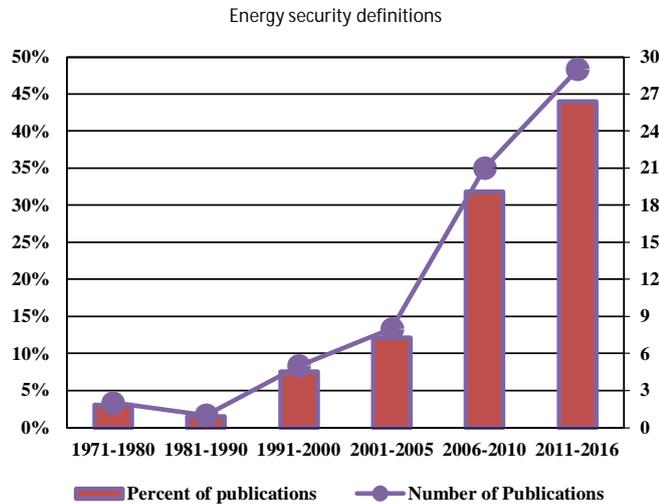


Figure 7: Scientific documents defining energy security and occurrence percentage in time spans from 1970s until 2016.

After that, the objective of this literature review was completed by formulating an energy security definition that can be used in all contexts and fields. Energy security was found to mean “**the feature (measure, situation or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats**”. This definition includes all perspectives and aspects of energy security with all its elements.

In addition to the definition of energy security, the literature review provided deep insights of what dimensions were needed to conduct an energy security evaluation. Tracking previous research concerned with energy security resulted in finding and formulating 15 dimensions and 50 parameters. As can be seen from **Publication I** (Supplementary Material), the 15 dimensions were summarised for the first time in one publication.

The last piece of results from **Publication I** was the formulation of a well-established relationship between all dimensions and energy security and between all parameters and their corresponding dimensions. This showed the importance of all parameters, how they are connected to energy security, what threats for energy security there are in each dimension and some proposals of numerical indicators to measure each parameter.

4.2 Publication II: Energy security and energy storage

Aims

This publication aimed to test and validate the already-developed energy security analysis framework. This framework was applied on one sub-system of the energy system, namely, energy storage. Applying this framework was aiming to evaluate the performance of different energy storage technologies from the perspective of energy security.

Methods

The first step was to determine what the most commonly used energy storage technologies in the world were. Five energy storage technologies were identified and analysed in detail. The state of the art of each technology was provided by an extensive literature review. After that, interactions between any aspects from these technologies with energy security was analysed qualitatively. The analysis was done by assigning plus and minus (+/-) signs for all dimensions and parameters. The plus sign was given if the relationship was positive whereas a negative sign was the opposite and was given if the relationship was negative. The last step in the methods was to build a colour-coded evaluation of all dimensions. If the number of plus signs in a dimension was more than the minus signs, the box was coloured in green. If the opposite was the case, then the box was given a red colour. If the numbers of plus and minus signs were equal, the box was given a yellow colour. Green boxes were allocated a value of +1, red boxes a value of -1 and neutral boxes a value of 0. The boxes were summed up for each technology, if the summation was positive for a storage technology, this technology was deemed to enhance energy security. The higher the number was, the technology resulted in a better enhancement of energy security.

Results

By the detailed analysis of the most common energy storage technologies, it was concluded that all of them have an overall positive relationship to energy security. However, the level of which each technology affects energy security was found to be different. Table 4 summarizes the achievements of each storage technology with all 15 dimensions. The previously described colour coding method is used in this article.

Table 4: Summary of the energy security analysis for storage options. Dimensions are abbreviated: 1 Availability, 2 Diversity, 3 Cost, 4 Technology & Efficiency, 5 Location, 6 Timeframe, 7 Resilience, 8 Environment, 9 Health, 10 Culture, 11 Literacy, 12 Employment, 13, Policy, 14 Military, 15 Cyber Security.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
PHES	++	-+	+++	++	+++	++	-+	+	+++ +	+	+	+	++	-	-	+5
TES	+++++	+++	+++ +++	+++ +-	+++++	+++ -	+	++	+-	++	++	+	++	--	-+	+9
Batteries	+++++	+++	+++ +	++	++++	+++	+	---	-- ++	++	-- ++ -	+	+++	--	+++	+5

A-CAES	+++	--	++ +	+++	--	-+	+	-- ++	-+	+	+	+-	++	-	+-	+2
Gas/ Liquid Storage	+++ +++	+++	+- -	+++	---	- ++	+	+- ++	---	+++	+- -	++	+++	-+	+	+5

4.3 Publication III: Energy security for future scenario in Jordan

Aims

The aims of this publication were to apply the already-developed energy security analysis framework on a future scenario for the whole energy system. The purpose was to analyse the impact of an energy transition towards a 100% renewable energy system in Jordan by the year 2050 on energy security. However, in order to analyse the impact of this transition on energy security, first it was needed to model a future scenario with a Best Policy Scenario approach to reach a fully renewable system, then to apply the energy security framework on the future energy system.

Methods

Applying a Best Policy Scenario was done using the LUT model for simulating future energy systems. The model was used to explore the feasibility of a transition scenario in Jordan towards a 100% renewable energy system by the year 2050. The LUT model is an optimization model to investigate energy systems under numerous technical and financial assumptions through all sectors of power, heat, transport, and desalination. Optimization was carried out with two criteria: first, demand for prosumers must be covered; second, demand for all sectors has to be met in every hour of the applied year. The current energy demand was obtained from different references whereas any future demand was projected.

The energy security analysis was carried out by addressing parameters of each dimension. If a parameter was affected positively, then a plus sign was given, and a minus sign was given for negative impacts. The overall evaluation was dependant on a colour-coding paradigm. The assigned colour depended on how many positive or negative impacts each dimension received throughout the analysis. If the total number of plus signs was greater than the minus ones, then green was used, otherwise red was used. If the number of plus and minus signs was equal, then the used colour was yellow.

Results

The results for scenario modelling showed an increase in primary energy demand from around 90 TWh in 2015 to 140 TWh in 2050, as shown in Figure 8 (left). Although primary energy demand would increase with this future scenario, the implementation of a 100% renewable energy system with all its efficiency benefits would lead to a demand

increase which is less than the demand increase with low electrification (as of today). Figure 8 (right) shows the difference between high electrification and low electrification.

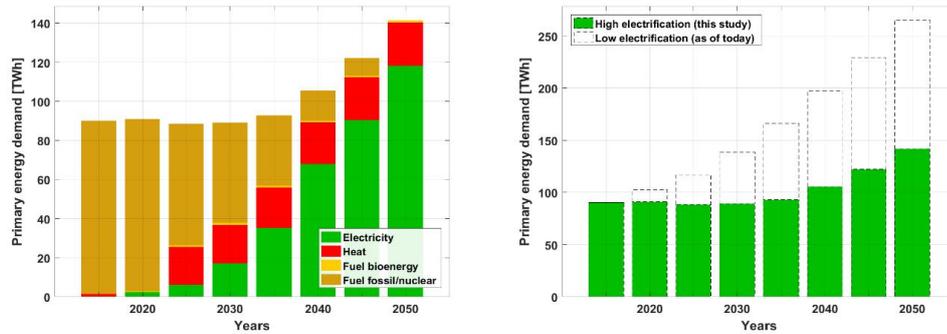


Figure 8: Development of primary energy demand by form of energy (left), and efficiency gain in primary energy demand (right) through the transition for Jordan.

Renewable electricity and renewable heat generation capacities are needed to cover all electricity and heat demands for the year 2050 using renewable technologies. Figure 9 shows the technology mix for generation capacities throughout the transition for both electricity and heat.

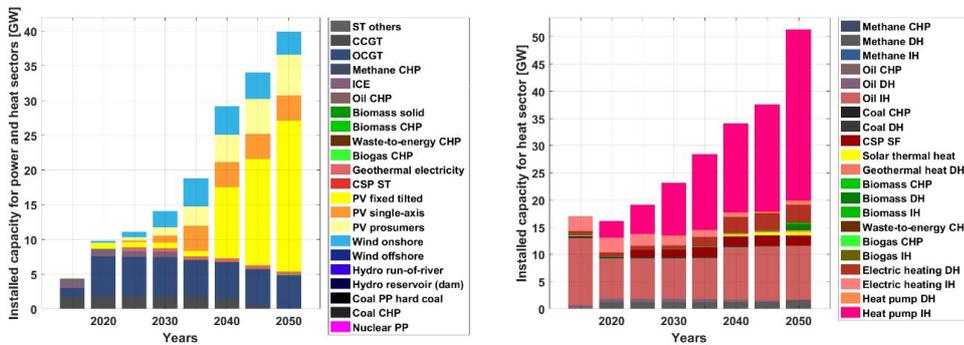


Figure 9: Development of electricity generation capacity (left) and heat generation capacity (right) in the integrated heat and power sector from 2015 to 2050 for Jordan.

Once modelling the future energy system was done with all the needed details, impact of this transition on energy security was analysed. Results suggested a significant positive impact on energy security by the year 2050. Six dimensions from the energy security framework were analysed in detail with all of their corresponding parameters. The impact of energy transition on energy security for each dimension with a detailed soft analysis

was provided in **Publication III** (Section 4.2). The outcome of this soft analysis for each dimension is presented in Table 5.

Table 5: Summary of energy transition impacts on energy security.

Dimensions	Availability	Diversity	Cost	Environment	Health	Employment
Impact	++++	+++-- -	++++ +--	+++++	++	++

4.4 Publication IV: Global Energy Security Index

Aims

The overall purpose of this research was to evaluate energy security quantitatively with numerical indicators. An Energy Security Index (ESI) was modelled and then applied on all national countries globally to achieve the goal of this work.

Methods

To build the ESI, the numerous steps that were followed were detailed in the methods chapter. The result was to correlate 76 numerical indicators to all the 50 parameters and 15 dimensions to quantitatively evaluate energy security. All the proposed indicators for all parameters and dimensions, references, units and normalizations methods were presented in **Publication IV** in detail. After designing a ready-to-use ESI, data for all countries were collected and the ESI was aggregated using the data.

Results

Results of the exact values of the ESI for each country are presented in Figure 10.

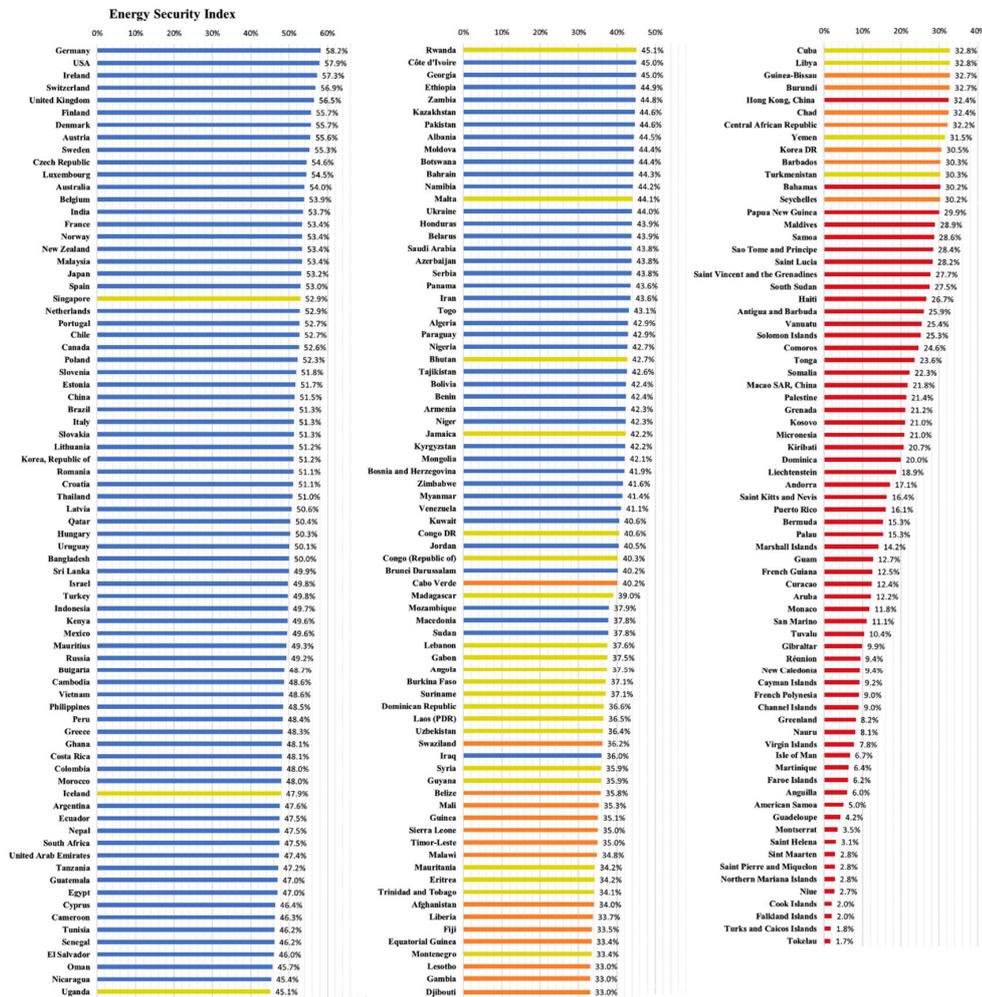


Figure 10: Global energy security levels. The applied colour of the bars indicates the number of missing parameters: blue <= 5, yellow 5 <= 10, orange 10 <= 15, red > 15.

The aggregated ESI is the result of 15 dimensions, **Publication IV** provided detailed results for performance of all countries in each of the 15 dimensions. Additionally, a colour-coded world map for the overall ESI is presented in Figure 11.

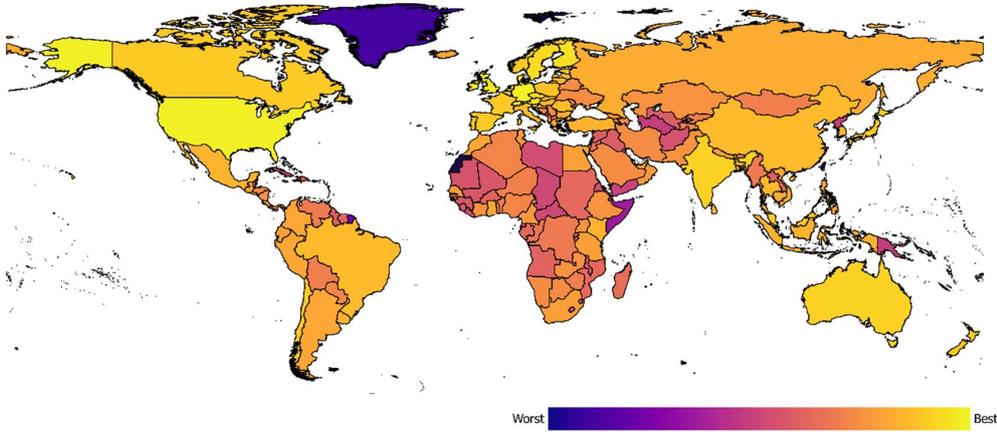


Figure 11: Global view of the Energy Security Index.

One of the best 10 performing countries globally in terms of energy security is Germany with an overall ESI of 58.2%. The detailed achievement of each dimension for Germany is presented in Figure 12.

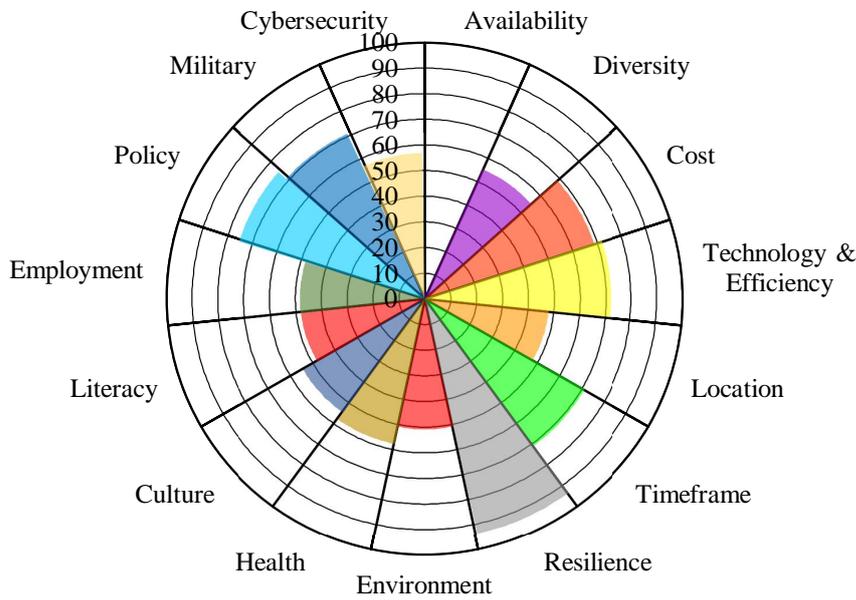


Figure 12: Detailed energy security view for Germany for all dimensions, values 0-100 represent worst to best.

5 Discussion

5.1 General discussion of the presented result

As the results' chapter presented promising outcomes of this research, several points can be addressed and discussed. The first result from **Publication I** showed clearly how energy security can be defined. The formulated definition is as generic as possible in order to be applied on all aspects of energy systems, but as detailed as possible to provide a clear understanding. Further, the proposed definition of energy security from **Publication I** covers all dimensions of energy security and what threats can be imposed against it. This result goes hand in hand with previous research where it is deemed important to provide a definition that is generic in nature (Kirchner & Berk, 2010).

Most of the previous research work was not able to achieve the same results, but some researchers provided similar results. Kanchana & Unesaki (2014) defined energy security as "Access to modern energy services". Although this definition is generic in nature and can be applied on many aspects of energy services, it examines the topic from the end users' perspective, i.e. those who receive the services. Unlike the definition from **Publication I**, this definition will not be able to account for security of demand in the perspective of the producer.

Another similar generic result for defining energy security was provided by Jewell et al. (2014). Their definition of energy security was "Low vulnerability of vital energy systems". This definition lacked simplicity and deviated from the nature of energy security, which is avoided in the results of this research as demonstrated in **Publication I**. Although this definition accounted for many aspects of energy systems, as vital aspects are addressed and analysed, it turned a white spot on other aspects of the energy system that are not as vital but are important for higher efficiency and improved performance. The results of this research, shown in **Publication I**, include all important aspects of energy security whether they are vital or just influential. Furthermore, this definition does not consider energy security as an overall feature of the energy system but rather a susceptibility of being damaged only. The result, as shown in **Publication I**, accounts for vulnerability and threats as part of an overall feature of the system because, as was concluded by Gnansounou (2011), the concept of threat is to be included in the definition. In addition, unlike Jewell et al. (2014) the result of this dissertation accounts for the environment and sustainability, as was concluded by Von Hippel et al. (2011), the concept of sustainability has to be taken into consideration when addressing energy security. Additionally, it was found in previous literature that with environmental climate mitigation policies, energy security is affected positively (Matsumoto, 2015). This proves the need to address the environment and sustainability in the discussion of energy security; this is exactly what was presented in **Publication I**.

After the definition was formulated, dimensions and threats had to be identified. As it has been presented in **Publication I**, this research found 15 dimensions and 50 parameters of

energy security. Unlike other researches, this current research collected and included all dimensions in one analytical framework. The most comprehensive previous literature only included 13 dimensions (Lovins & Lovins, 1981), excluding literacy and cyber security. This can be understood as their analysis was before the widespread use of telecommunication technologies. All other researchers lagged behind in the number of analysed dimensions, for example; 7 dimensions were addressed by UNDP (2000), 8 dimensions by Barton et al. (2004), 3 dimensions by Gawdat (2005), 10 dimensions by Haghighi (2007), 11 dimensions by Pascual and Elkind (2010), 5 dimensions by Čehulić et al. (2013), 10 dimensions by Kucharski and Unesaki (2015), 8 dimensions by Kumar et al. (2016), and 3 dimensions by Matsumoto et al. (2018) and Matsumoto & Shiraki (2018). The whole list of which dimensions are included for each publication is presented in **Publication I** (Supplementary Material).

After formulating the energy security analysis framework, it was applied on energy storage as a representation of energy sub-systems. Results from **Publication II** showed that Thermal Energy Storage (TES) has the lead in comparison to all other storage technologies. This is attributed to the positive relationship between TES and each of the dimensions. As can be seen from the results in **Publication II**, the only dimension that has a negative relationship with TES is the military dimension, since TES can be an easy target for military attacks. The results from **Publication II** are unique as previous literature did not include any energy storage analysis from the perspective of 15 energy security dimensions. Some previous research claimed to address energy security regarding energy storage, but their claim was of limited value as they did not have a clear view of what energy security is. For example, Strielkowski et al. (2016) misleadingly put energy security in the title of their paper but energy security was mentioned only once throughout the article with no evaluation on how energy security is affected by energy storage development. The same misleading flaw can be noted in a research done by Zafirakis & Chalvatzis (2014) where in the title, energy security is claimed to be improved by a proposed energy storage system, but then, energy security is lightly discussed with no analytical framework of analysis and with no comparison between energy storage technologies in perspective to energy security. **Publication II** is the first novel analysis of energy storage technologies from the perspective of energy security with a well-established and detailed analytical framework based on the 15 dimensions of energy security.

In contrast, the current research, as shown in **Publication III**, reached a result of total feasibility of 100% renewable energy system, similar to what was found in previous research that was done for the MENA region (Aghahosseini et al., 2020) Saudi Arabia (Caldera et al., 2018), Turkey (Kilickaplan et al., 2017) and Iran (Aghahosseini et al., 2018; Caldera et al., 2019; Ghorbani et al., 2017; 2020). Although benefits from renewable energy for Jordan were found in this research, as shown in **Publication III**, are similar to benefits found in previous research done by Jaber et al. (2015), **Publication III** continues to provide a clear pathway for how to seize these benefits in reality, not only highlighting its potential as was done before (Anagreh & Bataineh, 2011; Anagreh et al., 2010). The last aspect of the future scenario, unlike earlier studies for desalination options

with a fossil fuel based energy system (Østergaard et al., 2014), this research, as provided by **Publication III**, offers a detailed desalination capacity installation scheme based on 100% renewable energy technologies. Although energy security benefits from renewable energy systems were found by previous researchers (Matsumoto & Andriosopoulos, 2016), results from **Publication III** regarding positive impacts on energy security by a 100% renewable energy system with the detailed results for the 6 dimensions, are not precedented.

The last piece of the results is the global quantitative evaluation of energy security for all countries in the world, as presented in **Publication IV**. As it was shown in the results' chapter, **Publication IV**, energy security levels differ from one country to another. Although previous literature tried to provide global energy security analysis (Wang & Zhou, 2017; WEC, 2019), **Publication IV** of this research overcomes their research gaps. For Wang & Zhou (2017), their research did not include all dimensions and parameters that affect energy security globally, thus their evaluation is imperfect, with remaining defects. In addition, their results were clustered, and countries were grouped when the analysis was completed. Such grouping hindered the applicability of the results on national levels. The results of **Publication IV** are different as they show the achievements of each country individually. The same shortcoming in the results of energy security evaluation can be noticed from the research that was done by WEC (2019), in which a very limited number of parameters are included. Furthermore, unlike results from WEC (2019), where transparency is almost absent, the results of this research as shown in **Publication IV** provide a complete track of all calculations to achieve the ESI values of all countries. For example, results are transparent about the fact that 115 countries have no more than 5 missing parameters, 28 countries are affected by 6-10 missing parameters, 22 countries are affected by 11-15 missing parameters, and 64 countries suffering from more than 15 missing parameters. Parameters are missing mostly due to missing data for non-sovereign countries or the country's population is less than 100,000. In total, there are 44 countries, either non-sovereign or with low populations, in the 64 analysed countries within the lowest category that suffer from more than 15 missing parameters.

The world map representation that is shown in **Publication IV** provides insights on how the energy security performance is different in different countries. Germany and USA are among the highest ranks in the world for energy security levels. This result is different than the results of WEC (2019) where Switzerland and Sweden were on the top. The reason for this difference is the number of used dimensions and parameters. WEC (2019) considered a very limited number of indicators and parameters that do not cover the whole spectrum of aspects affecting energy security. Results from **Publication IV** of this current research are more reliable as they include more aspects in the analysis.

The last point to be discussed is the path Germany and USA followed to achieve high energy security levels. Energy security performance of Germany, shown in **Publication IV**, proves that lacking in natural resources does not hinder energy security if political will exists to advance resilience and regulations. USA has a more balanced distribution

of the dimensions on a high level. Also, results from **Publication IV** suggest that lagging behind in one dimension can be compensated by a higher performance in other dimensions and such a situation should not hinder development. This point confirms the need of a multi-dimensional evaluation of energy security in order to compile a comprehensive analysis.

5.2 Global policy implications

As the results of this research are diverse and on multiple fronts, many utilizations and policy implications can be drawn to provide policy makers with deep insights of how to benefit from these results. As this research is focused on a global-national analysis, so could the policy implication.

The first policy implication for researchers and governments may be to use the formulated definition of energy security in their future research. Although Ang et al. (2015) concluded that it is unlikely to have a commonly accepted procedure to formulate an energy security definition and framework, a widespread adoption of our generic definition, with its ability to be applied on all aspects of energy security, may make energy security analyses more coherent, precise and reliable.

This acceptance can be seen as a reality if governments would start to adopt such a definition in their official publications. Although there are some attempts from international organizations to provide such a definition (IEA, 2001; 2007; UNDP et al., 2004; UNDP, 2000; 2011), their efforts were not successful as their view on the energy security definition were similar to the current situation of vagueness and no-consensus (Checchi et al., 2009; Kruyt et al., 2009). Also, their framework lacked many aspects of energy security, as was discussed in detail in **Publication I**.

Once there is a broader consensus, then a discussion and evaluation of energy security could be more comparable, and it can be evaluated and compared globally. As Aristotle reputedly said, “he who controls the definition, controls the debate.” (Sovacool, 2011b), results from **Publication I** implicate policy adoption of the formulated definition and framework to overcome the complexity of the concept, as was the policy implication from Kirchner & Berk (2010). Similar policy implications may be obtained from adopting the 15 dimensions framework presented in **Publication I**. It makes the elements of energy security well known and thus easier to evaluate and compare. More reliable and comparable evaluation will give policy makers in various countries valuable insights on how to enhance energy security in their territories in comparison to others. In addition, as was concluded by Sovacool (2013c), policies for adopting an energy security definition should have a consistent polycentric approach with emphasis on engaging stakeholders at multiple geographic scales.

The second potential policy implication is the regulations and rules that could be put in place in order to ensure the use of a portfolio of the most secure energy technologies. In

this research in the exemplarily analysis for energy storage, TES, was found to be the most secure energy storage technology, and thus policies to favour this technology may be beneficial for both production and installation. As the magnitude of the energy security benefits depends on the energy security profile of the sub-system (Lefèvre, 2010), policies favouring TES can enhance energy security levels of the whole system. The application of such a policy could be broadened to more categories of energy technologies.

As found by Sovacool (2013c) policies on a carbon tax can be a useful tool for promoting energy security through renewable energy. Similar implications might be noticed from a rare earth metal tax to channel the use of TES. However, Sovacool (2013c) clarifies that even such a tax does not affect the overall economy, he states that this is not the same for all countries. For that, the results from **Publication II** imply that at least policies could propose requirements for energy storage permits. Such requirements make energy security analysis of different storage technologies very valuable. Such regulations and requirements may ensure customers and producers to opt for more secure energy storage technologies. Alternatively, such policy implications might result in more research to improve storage technologies to have higher energy security levels. Although many storage technologies were discussed in detail (Akinyele & Rayudu, 2014; Barnes & Levine, 2011; Evans et al., 2012; Zhao et al., 2015), previous research was not done from the perspective of a detailed energy security analysis. Therefore, this exemplarily energy security analysis for energy storage technologies could encourage governments and policy makers to propose a starting point for a more systematic analysis of all technologies potentially used in comprehensive energy systems.

The third policy implication can be derived from the proposed future scenario for Jordan. On a global level, Jordan can be an example of feasibility and applicability of a 100% renewable energy system. Policy makers in Jordan and elsewhere can draw suitable rules and regulations to transfer the scenario into reality. Also, results imply that an energy transition does not happen overnight, but over a timeframe of 30-40 years. This is the same conclusion of Smil (2010) where he wrote that energy transitions always require much time. Furthermore, results of the scenario did not only show the feasibility and possibility of energy transition, as was mentioned by Sovacool (2013c), but also in particular, the financial benefits together with co-benefits for the environment and employment. Such benefits are regularly a target for policy makers. In addition, impacts on energy security are very positive from the perspective of a 100% renewable energy system. The link between energy security and national security (Dyer & Trombetta, 2013; Phdungsilp, 2015) makes it important for national strategy planners in all countries to adopt regulations that make energy systems more secure, a 100% renewable energy system can serve such needs. Furthermore, the results imply that if the proposed scenario is not preferred by policy makers in any country in the world, but another scenario of their own is preferred, energy security analysis may be an additional tool for advice. Such an energy security analysis linked to the developed framework of 15 dimensions and 50 parameters can provide valuable insights when deciding among scenarios for future energy systems. As Yao & Chang (2014) found, policy makers should adopt policies that reduce carbon dioxide emissions and include as many and as diverse energy supplies as

possible. Such an implication provides policy makers with a tool to choose from different scenarios.

The last implication that can be seen from the results is the need for all countries to enhance their energy security levels. As energy security should be considered when energy policies are formulated (Ang et al., 2015), results from this research imply that policy makers in all countries should better analyse results of the performance of their country and spot the shortcomings and supportive actions for improvement. Numerical results of the ESI show clearly where each country is lagging behind and therefore policy makers in those country can develop suitable policies to improve ESI values. Furthermore, cooperation and exchange between different countries can be one of the policy implications on a global level that are obtained from the results.

5.3 Limitation of the current research and future research prospects

The main limitation of this research is the unavailability of some information and data. The first limitation was faced in **Publication I** when conducting the detailed literature review. Although many previous literature pieces addressed energy security, only a limited number provided a clear definition of energy security. In addition, definitions of energy security are diverse with no consensus. This kind of unclarity and vagueness of the term channelled the current research to formulate a new definition as presented in **Publication I**. Overcoming this limitation could be enabled if future research adopts one definition with consensus. It is encouraged to use the provided definition of this research because of its strict criteria of formation and because of its ability to provide all needed and generic analysis.

The second piece of limitation due to the unavailability of information, comes from the kind of dimensions that are included in literature. Many of the dimensions are not well discussed and addressed in detail when energy security is analysed, as was presented in **Publication I**. For example, cyber security is rarely mentioned in previous studies as an important aspect of energy security. This limited the research and formulation of these dimensions to be built on what is available in previous literature. To overcome these limitations, future research is needed to provide a profound understanding of the relationships between energy security and each dimension, together with relationships between dimensions and their corresponding parameters.

Another limitation that was faced in **Publication II** of the current research is the existence of diverse energy sub-systems. Although energy storage was chosen in this research to represent an exemplarily energy sub-system, and designated as a subject of energy security analysis, other sub-systems can be analysed. Existence of different energy sub-systems on which energy security analysis can be applied on, makes it difficult to decide which sub-system to be analysed, especially, if this application is used as a test and validation for the framework. Future research can overcome this issue by focusing the analysis on applying the energy security framework on all major energy sub-systems, for instance: transportation.

Even after determining one energy sub-system (energy storage) to be the subject of energy security analysis, limitations were faced in **Publication II** because of the diverse technologies that are available in the market. To cope with this limitation, the research in **Publication II** focused the analysis on the five most used technologies. Future research can analyse energy security for a more comprehensive set of storage technologies.

Another category of limitation that was experienced by the application of the energy security analysis framework on an exemplarily future energy scenario for the case country “Jordan” was the limitation of the pre-assumptions that are used in the model, presented in **Publication III**. Although all these assumptions are scientifically accepted and obtained from respected references, there is always room for further improved assumptions that can be provided by future research. For example, the assumption of the building speed of power transmission lines can be limited to the reality of population concentration in big cities with the rest of the country as desert.

Another limitation in **Publication III** of this research was the absence of some aspects of the future energy outlook. This limited the choice of important dimensions to only 6 dimensions of the total 15 dimensions presented in the energy security analysis framework. This limitation shows the complex relationship between qualitative and quantitative analysis. For the qualitative analysis, only the framework is needed, and it is less objective and usually does not require choosing among the dimensions that were developed in the framework. On contrast, the quantitative approach may be more realistic and may provide more concrete conclusions of what needs to be done. This limitation can be overcome in future research by modelling a future scenario that results in more details about all aspects of the whole energy system and its interactions with other systems in the socio-economic or environmental sphere.

Another limitation was linked to the projected future scenario presented in **Publication III**. The goal was to have a Best Policy Scenario which leads to a 100% renewable energy system with more emphasis on what technologies are used, how fast switching to low-cost solutions is possible and how fast one can adopt clean water supply and electric vehicles, etc. This objective is not the same as achieving the most sustainable energy system. Moving towards a fully sustainable energy system can be done by future studies that model an energy system with higher standards of living where electricity consumption per capita is equal to the average OECD consumption per capita. Another example is the studies that compare different scenarios to see their relative impact on energy security, in particular, scenarios describing little to no progress for a sustainable development. Comparing impacts of different scenarios on energy security can provide valuable insights in future research about how sustainable energy systems can be enabled for the case country “Jordan”. Such an analysis can be then expanded to other countries.

The last three limitations are attributed to the main limitation of this research, data unavailability of some indicators’ values, far proximity of some indicators and weighting values. The issues of data unavailability was addressed in **Publication IV**. Although best efforts were applied to choose suitable indicators for which data is available for most

countries, some indicators have a significant unavailability. Future research is needed to investigate the reasons of data unavailability from these sources and build a suitable replacement for the absent values. The second limitation in **Publication IV** was the inaccuracy of some indicators as they are used as a proxy to measure the correspondent parameter. Future research is needed to design more accurate indicators for each of the parameters. Furthermore, the last limitation is the absence of valid justification to use different weights as was described in detail in **Publication IV**. Future research could provide a proper scientific investigation to justify different weights instead of equal weights that were used in this research.

6 Conclusions

Going through this extensive research about energy security provided significant value and additional resources for research communities, policy makers and other stakeholders. The importance of energy security, as a global concern, has been growing rapidly with the current state of globalization and interconnectedness. In order to address these concerns with an objective evaluation that can have implications on policy, this dissertation provides tools and results to be used for existing energy security questions. Key results were obtained from **Publications I-IV**.

The first fundamental development shown in **Publication I** was the formulation of a generic definition of energy security together with a detailed framework of 15 dimensions and 50 parameters to analyse and evaluate energy security. Such a highly detailed framework was concluded to be needed for current and future energy security analyses. Also, it is concluded from **Publication I** that adopting such a generic definition by researchers, policy makers and public audience may facilitate the discussion about energy security, as a common understanding could be established of what is meant with energy security and what it consists of.

The second outcome was the proof of validity and applicability of the formulated framework to evaluate energy security for an exemplarily energy sub-system. This outcome was discussed in detail in **Publication II**. Also, it was found that thermal energy storage (TES) has the best performance from an energy security perspective. Many conclusions can be drawn out from these results. First, it was concluded that energy security analysis with a comprehensive framework is needed whenever a comparison between energy storage technologies is implemented. This is important, particularly for customers who need to make decisions on what energy storage option to choose, if the technical applicability allows various options. Secondly, it was concluded that, for policy makers, developing regulations that enhance energy security with stricter criteria is needed for what energy storage options are allowed to be installed. Also, policy makers can make it a requirement to have an energy security analysis carried out before permits are given to install energy storage facilities. Lastly, it can be concluded that improvement is needed for some energy storage technologies in order to enhance energy security.

The third major contribution was linking the energy security framework to a future energy scenario that aims to achieve a 100% renewable energy system. This contribution was discussed in detail in **Publication III**. A future scenario of the energy system was used to validate the applicability of the formulated energy security framework for assessing future energy systems. The formulated energy security analysis framework was found to be applicable even for future energy systems. Furthermore, it was found that the modelled Best Policy Scenario substantially enhances energy security in the future. From these results presented in **Publication III**, it can be concluded that a 100% renewable energy system is feasible for Jordan and for other countries as well. Additional to the improved energy security levels, it was concluded that such a 100% renewable energy system can present many economic, environmental and social benefits. Furthermore, it was

concluded that policy makers in Jordan should make strategies today for implementations of such a Best Policy Scenario if they want to achieve a higher level of energy security by the year 2050, as presented in **Publication III**. Delaying the start of the transition process will either mean a delayed achievement of higher energy security levels or mean the need of very progressive actions in a shorter period of time.

The fourth major result, as highlighted in **Publication IV**, was the presentation of the global energy security achievement of all countries by a newly introduced Energy Security Index. The first result from **Publication IV** was designating of and collecting data for suitable numerical indicators to measure each of the proposed parameters and dimensions of the energy security framework. It was concluded from this result that measuring dimensions and parameters of energy security is possible by proxy numerical indicators. This conclusion should drive researchers to put more emphasis on reliable sources and trustworthy sets of data. The second major result from **Publication IV** was the design and application of a comprehensive Energy Security Index. Applying this index helped draw many conclusions about diverse performances of different countries in the world. It was concluded that the energy security levels are not the same in all countries but rather, they differ vastly. Also, it is concluded that a high energy security level can be achieved through different pathways, and there is no one recipe. Energy policy makers in each country may investigate the performance of their countries and compare it with other countries. Such a comparison can provide profound insights of what strategies are needed to be adopted in order to achieve higher energy security levels.

On a different note, the methods used in **Publications I-IV** provided conclusions on how the energy security framework can be built and applied. It is concluded that in order to build a comprehensive energy security analysis framework, robust and transparent methods are needed, starting with detailed literature reviews, to testing and validation, and finally, to application and analysis. Such a conclusion invites researchers to adopt methods in this current research work to design an energy security framework.

Furthermore, this dissertation does not contribute only to the discussion of energy security, energy storage, future energy transition projections up to 100% renewable energy systems, and an analytical framework design, but also to the discussion of energy policy and national security. It is concluded that the link between national security and energy security is significant and achieving higher levels of energy security will enhance national security.

Lastly, it is concluded that total transparency of all assumptions, methods and results compensate for limitations faced in this dissertation. In addition, it is concluded that this transparency can encourage future research to fill this gap by providing reasons for the missing data and propose suitable replacement.

References

- Abdo, H. & Kouhy, R. (2016) Readings in the UK energy security. *Energy Sources, Part B: Economics, Planning, and Policy*, 11(1), 18-25.
- Aghahosseini, A., Bogdanov, D. & Breyer, C. (2017) A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions. *Energies*, 10(8).
- Aghahosseini, A., Bogdanov, D. & Breyer, C. (2020) Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030. *Energy Strategy Reviews*, 28, 100466.
- Aghahosseini, A., Bogdanov, D., Ghorbani, N. & Breyer, C. (2018) Analysis of 100% renewable energy for Iran in 2030: integrating solar PV, wind energy and storage. *International Journal of Environmental Science and Technology*, 15(1), 17-36.
- Aized, T., Shahid, M., Bhatti, A. A., Saleem, M. & Anandarajah, G. (2018) Energy security and renewable energy policy analysis of Pakistan. *Renewable and Sustainable Energy Reviews*, 84, 155-169.
- Akhrorova, A., Mukimova, N. & Razykov, R. (2014) The energy security of the Republic of Tajikistan. *Energy Production and Management in the 21st Century: The Quest for Sustainable Energy*, 190, 1213.
- Akinyele, D. O. & Rayudu, R. K. (2014) Review of energy storage technologies for sustainable power networks. *Sustainable Energy Technologies and Assessments*, 8, 74-91.
- Alshwawra, A. & Almuhtady, A. (2020) Impact of Regional Conflicts on Energy Security in Jordan. *International Journal of Energy Economics and Policy*, 10(3), 45-50.
- Amirov, A., Kozhukhova, M., Koshebaeva, G., Biryukov, V., Zhiyenbayev, M. (2018) Economic and energy security of the Republic of Kazakhstan. *International Journal of Energy Economics and Policy*, 2018, 8(6), 16-21.
- Anagreh, Y. & Bataineh, A. (2011) Renewable energy potential assessment in Jordan. *Renewable and Sustainable Energy Reviews*, 15(5), 2232-2239.
- Anagreh, Y., Bataineh, A. & Al-Odat, M. (2010) Assessment of renewable energy potential, at Aqaba in Jordan. *Renewable and Sustainable Energy Reviews*, 14(4), 1347-1351.

- Andersson, J. J., Brattberg, E., Häggqvist, M., Ojanen, H. & Rhinard, M. (2011) The European Security Strategy: Reinvigorate, Revise or Reinvent? Swedish Institute of International Affairs, Stockholm, Sweden.
- Ang, B. W., Choong, W. L. & Ng, T. S. (2015) Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews*, 42, 1077-1093.
- Anwar, J. (2010) An analysis of energy security using the partial equilibrium model: the case of Pakistan. *The Pakistan Development Review*, 925-940.
- Anwar, J. (2016) Analysis of energy security, environmental emission and fuel import costs under energy import reduction targets: A case of Pakistan. *Renewable and Sustainable Energy Reviews*, 65, 1065-1078.
- Aparicio, G., Pinilla, V. & Serrano, R. (2006) Europe and the international agriculture and food trade, 1870-2000. Finland: IEHC Helsinki session.
- Asif, M. & Muneer, T. (2007) Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews*, 11(7), 1388-1413.
- Aslanbayli, B. (2013) Critical Infrastructure Aspects Of Energy Security: Azerbaijan And Regional Context. *Energy Security in the Wider Black Sea Area–National and Allied Approaches*, 110, 10.
- Aslani, A., Antila, E. & Wong, K.-F. V. (2012) Comparative analysis of energy security in the Nordic countries: The role of renewable energy resources in diversification. *Journal of Renewable and Sustainable Energy*, 4(6), 062701.
- Atlam, B. M. & Rapiea, A. M. (2016) Assessing the future of energy security in Egypt. *International Journal of Energy Economics and Policy*, 6(4).
- Augutis, J., Krikštolaitis, R., Martišauskas, L., Urbonienė, S., Urbonas, R. & Ušpurienė, A. B. (2020) Analysis of energy security level in the Baltic States based on indicator approach. *Energy*, 199, 117427.
- Augutis, J., Krikštolaitis, R., Pečiulytė, S. & Konstantinavičiūtė, I. (2011) Sustainable development and energy security level after Ignalina NPP shutdown. *Technological and Economic Development of Economy*, 17(1), 5-21.
- Azzuni, A. & Breyer, C. (2018) Definitions and dimensions of energy security: a literature review. *Wiley Interdisciplinary Reviews: Energy and Environment*, 7, e268.
- Azzuni, A. & Breyer, C. (2020) Energy security analysis for a 100% renewable energy transition in Jordan by 2050. *Sustainability*, Forthcoming

-
- Badea, A. C., Tarantola, S. & Bolado, R. (2011) Composite indicators for security of energy supply using ordered weighted averaging. *Reliability Engineering & System Safety*, 96(6), 651-662.
- Bahgat, G. (2006a) Central Asia and energy security. *Asian Affairs*, 37(1), 1-16.
- Bahgat, G. (2006b) Europe's energy security: Challenges and opportunities. *International affairs*, 82(5), 961-975.
- Bahgat, G. (2012) Energy security: The United Arab Emirates. *Asian Affairs*, 43(2), 268-279.
- Baizakova, K. I. (2010) Energy security issues in the foreign policy of the Republic of Kazakhstan. *American Foreign Policy Interests*, 32(2), 103-109.
- Bang, G. (2010) Energy security and climate change concerns: Triggers for energy policy change in the United States? *Energy Policy*, 38(4), 1645-1653.
- Barai, M. K. & Saha, B. B. (2015) Energy security and sustainability in Japan. *Evergreen*, 2(1), 49-56.
- Barnes, F. S. & Levine, J. G. (2011) Large energy storage systems handbook. *Mechanical engineering series*, p. 244.
- Barton, B., Redgwell, C., Rønne, A. & Zillman, D. N. (2004) *Energy security: Managing risk in a dynamic legal and regulatory environment*. Oxford, UK: Oxford University Press.
- Bazilian, M., O'Leary, F., O Gallachoir, B. & Howley, M. (2006) *Security of supply in Ireland 2006*. Ireland.
- Bellos, E. (2018) Sustainable energy development: How can the tension between energy security and energy transition be measured and managed in South Africa? *Journal of cleaner production*, 205, 738-753.
- Bielecki, J. (2002) Energy security: Is the wolf at the door? *The Quarterly Review of Economics and Finance*, 42(2), 235-250.
- Bireselioglu, M. E., Yildirim, C., Demir, M. H. & Tokcaer, S. (2017) Establishing an energy security framework for a fast-growing economy: Industry perspectives from Turkey. *Energy research & social science*, 27, 151-162.
- Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A. S., de Souza Noel Simas Barbosa, L. & Breyer, C. (2019a) Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nature Communications*, 10(1), 1077.

Bogdanov, D., Toktarova, A. & Breyer, C. (2019b) Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan. *Applied Energy*, 253, 113606.

Bohi, D. R. & Toman, M. A. (1993) Energy security: Externalities and policies. *Energy Policy*, 21(11), 1093-1109.

Boucek, C. (2007) Energy security implications of post-Niyazov Turkmenistan. *Central Asia—Caucasus Analyst*(1), 6-8.

Brahim, S. P. (2014) Renewable energy and energy security in the Philippines. *Energy Procedia*, 52, 480-486.

Breyer, C., Bogdanov, D., Aghahosseini, A., Gulagi, A., Child, M., Oyewo, A. S., Farfan, J., Sadovskaia, K. & Vainikka, P. (2017) Solar photovoltaics demand for the global energy transition in the power sector. *Progress in Photovoltaics: Research and Applications*, 26(8), 505-523.

Broker, T., Durr, D. & Smith, L. M. (2019) Analysis of the global energy industry, climate change and financial matters: the need for effective corporate governance. *International Journal of Corporate Governance*, 10(3-4), 185-208.

Bukurov, M. Z., Babic, M. J. & Ljubicic, B. (2010) Finding the balance between the energy security and environmental protection in Serbia. *Thermal science*, 14(suppl.), 15-25.

Bunzel, K., Zeller, V., Buchhorn, M., Griem, F. & Thrän, D. (2009) *Regionale und globale räumliche Verteilung von Biomassepotenzialen*. Leipzig.

Bösze, B. (2006) Security of energy supply in Hungary. *Regio-Minorities, Politics, Society-English Edition*, 9(1), 191-202.

Cabalu, H. (2010) Indicators of security of natural gas supply in Asia. *Energy Policy*, 38(1), 218-225.

Cabalu, H. & Alfonso, C. (2013) Energy Security in Asia: The Case of Natural Gas, in Dorsman, A., Simpson, J. L. & Westerman, W. (eds), *Energy Economics and Financial Markets*. New York, USA: Springer Berlin Heidelberg, 13-30.

Caldera, U., Bogdanov, D., Afanasyeva, S. & Breyer, C. (2018) Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. *Water*, 10(1), 3.

Caldera, U., Bogdanov, D., Fasihi, M., Aghahosseini, A. & Breyer, C. (2019) Securing future water supply for Iran through 100% renewable energy powered desalination. *International Journal of Sustainable Energy Planning and Management*, 23, 39–54.

-
- Caldera, U. & Breyer, C. (2020) Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems. *Energy*, 200, 117507.
- Chalvatzis, K. J. & Ioannidis, A. (2017a) Energy supply security in southern Europe and Ireland. *Energy Procedia*, 105, 2916-2922.
- Chalvatzis, K. J. & Ioannidis, A. (2017b) Energy supply security in the EU: Benchmarking diversity and dependence of primary energy. *Applied Energy*, 207, 465-476.
- Chang, Y. & Lee, J. L. (2008) Electricity market deregulation and energy security: a study of the UK and Singapore electricity markets. *International Journal of Global Energy Issues*, 29(1-2), 109-132.
- Chang, Y. & Putra, N. A. (2012) The non-traditional security perspective on energy security policies in Singapore, *Rethinking Energy Security in Asia: A Non-Traditional View of Human Security*. New York, USA: Springer, 37-58.
- Checchi, A., Behrens, A. & Egenhofer, C. (2009) Long-term energy security risks for Europe: A sector-specific approach. Bruxelles, Belgium: Centre for European Policy Studies.
- Cherp, A. & Jewell, J. (2013) Energy security assessment framework and three case studies, *International Handbook of Energy Security*. Cheltenham, UK and Massachusetts, USA: Edward Elgar Publishing, 146-73.
- Chester, L. (2010) Conceptualising energy security and making explicit its polysemic nature. *Energy Policy*, 38(2), 887-895.
- Child, M., Koskinen, O., Linnanen, L. and Breyer, C., (2018) Sustainability guardrails for energy scenarios of the global energy transition. *Renewable and Sustainable Energy Reviews*, 91, pp.321-334.
- Chow, E. & Elkind, J. (2005) Hurricane Katrina and U.S. energy security. *Survival*, 47(4), 145-160.
- Chung, W.-S., Kim, S.-S., Moon, K.-H., Lim, C.-Y. & Yun, S.-W. (2017) A conceptual framework for energy security evaluation of power sources in South Korea. *Energy*, 137, 1066-1074.
- Ciută, F. (2010) Conceptual notes on energy security: Total or banal security? *Security Dialogue*, 41(2), 123-144.
- Cohen, G., Joutz, F. & Loungani, P. (2011) Measuring energy security: Trends in the diversification of oil and natural gas supplies. *Energy Policy*, 39(9), 4860-4869.

Colgan, J. D. (2014) Oil, domestic politics, and international conflict. *Energy Research & Social Science*, 1, 198-205.

Constantini, V. and Gracceva, F., (2004) Social Costs of Energy Disruptions. INDES Working Paper No. 6, 1 March 2004. Milan, Italy.

Cox, E. (2018) Assessing long-term energy security: The case of electricity in the United Kingdom. *Renewable and Sustainable Energy Reviews*, 82, 2287-2299.

Creti, A. & Fabra, N. (2007) Supply security and short-run capacity markets for electricity. *Energy Economics*, 29(2), 259-276.

De Joode, J., Kingma, D., Lijesen, M., Mulder, M. & Shestalova, V. (2004) *Energy policies and risks on energy markets: A cost-benefit analysis*. The Netherlands: CPB Netherlands Bureau of Economic Policy Analysis.

De Vos, R. & Baken, J. (2004) Security of supply: Energy security solutions hinder development of sustainable infrastructures. *Refocus*, 5(1), 58-59.

Deese, D. A. (1979) Energy: Economics, politics, and security. *International Security*, 4(3), 140-153.

Demski, C., Poortinga, W. & Pidgeon, N. (2014) Exploring public perceptions of energy security risks in the UK. *Energy Policy*, 66, 369-378.

DIVA-GIS (2011) Free Spatial Data. Available Online [<http://www.diva-gis.org/Data>], [Accessed 26. May 2020].

Dreyer, I. (2013) International energy security challenges for Europe in the coming years. *International Issues & Slovak Foreign Policy Affairs*, 22(3), 3.

Dunham, I. M. & Schlosser, K. (2016) Energy security discourses and environmental protection measures in U.S. federal energy legislation: An introductory exploration. *The Extractive Industries and Society*, 3(1), 86 - 94.

Dyer, H. & Trombetta, M. J. (2013) *International handbook of energy security*. Cheltenham, UK and Massachusetts, USA: Edward Elgar Publishing.

Eaves, J. & Eaves, S. (2007) Renewable corn-ethanol and energy security. *Energy Policy*, 35(11), 5958-5963.

El-Anis, I. (2012) The political economy of energy security and nuclear energy in Jordan. *The Central European Journal of International and Security Studies (CEJISS)*, 6(1), 13-35.

-
- Erdal, L., Pektaş, A. O., Ozkan, O. & Özkan, F. (2015) Security of energy supply in Japan: A key strategy and solutions. *International Journal of Global Warming*, 7(1), 128-159.
- Evans, A., Strezov, V. & Evans, T. J. (2012) Assessment of utility energy storage options for increased renewable energy penetration. *Renewable and Sustainable Energy Reviews*, 16(6), 4141-4147.
- Faeth, P. (2012) US Energy security and water: The challenges we face. *Environment: Science and Policy for Sustainable Development*, 54(1), 4-19.
- Farfan, J. & Breyer, C. (2017) Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *Journal of Cleaner Production*, 141(Supplement C), 370-384.
- Farinosi, F., Mysiak, J. & Carrera, L. (2013) Climate variability and energy security in Italy. Lecce, Italy: *CMCC Research Paper* (205).
- Farrell, A. E., Zerriffi, H. & Dowlatabadi, H. (2004) Energy infrastructure and security. *Annual Review of Environment and Resources*, 29(1), 421-469.
- Fida, E., Islami, B., Bruci, E. D., Baraj, B., Kamberi, M., Mucaj, L. & Ndini, M. B. (2009) Security Of The Energy Sector In Albania In The Face Of Climate Change, *Energy and Environmental Challenges to Security*. New York, USA: Springer, 331-370.
- Findlater, S. & Noël, P. (2010) Gas supply security in the Baltic States: A qualitative assessment. *International Journal of Energy Sector Management*, 4(2), 236-255.
- Foo, K. Y. (2015) A vision on the opportunities, policies and coping strategies for the energy security and green energy development in Malaysia. *Renewable and Sustainable Energy Reviews*, 51, 1477-1498.
- Franki, V. and Višković, A., (2015) Energy security, policy and technology in South East Europe: Presenting and applying an energy security index to Croatia. *Energy*, 90, pp.494-507.
- Gang, L. (2010) Evolution of energy security policies in Australia. *Resources and Industries*, 12(2), 21-25.
- García-Gusano, D. & Iribarren, D. (2018) Prospective energy security scenarios in Spain: The future role of renewable power generation technologies and climate change implications. *Renewable Energy*, 126, 202-209.
- Gawdat, B. (2005) Energy Security: The Caspian Sea. *Minerals & Energy - Raw Materials Report*, 20(2), 3-15.

- German, T. C. (2009) Pipeline politics: Georgia and energy security. *Small Wars & Insurgencies*, 20(2), 344-362.
- Gheorghe, A., Muresan, L., Celac, S., Caceu, S., Degeratu, C., Lenes, L., Kanovits, C., Bores, R., Prebensen, C. & Refvem, T. (2011) An energy security strategy for Romania: Promoting energy efficiency and renewable energy sources, *Energy Security*. New York, USA: Springer, 337-412.
- Ghorbani, N., Aghahosseini, A. & Breyer, C. (2017) Transition towards a 100% Renewable Energy System and the Role of Storage Technologies: A Case Study of Iran. *Energy Procedia*, 135, 23-36.
- Ghorbani, N., Aghahosseini, A. & Breyer, C. (2020) Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – Achieving zero greenhouse gas emissions and overcoming the water crisis. *Renewable Energy*, 146, 125-148.
- Gillessen, B., Heinrichs, H., Hake, J. F. & Allelein, H. J. (2019) Energy security in context of transforming energy systems: A case study for natural gas transport in Germany. *Energy Procedia*, 158, 3339-3345.
- Glavinov, A., Stanikevski, J. & Vejseli, U. (2017) Critical infrastructure protection and energy security—key factors for building sustainable energy strategy in the Republic of Macedonia. *International Scientific Journal*, 17(32), 49-59.
- Glynn, J., Chiodi, A., Gargiulo, M., Deane, J. P., Bazilian, M. & Gallachóir, B. Ó. (2014) Energy Security Analysis: The case of constrained oil supply for Ireland. *Energy Policy*, 66, 312-325.
- Gnansounou, E. (2008) Assessing the energy vulnerability: Case of industrialised countries. *Energy Policy*, 36(10), 3734-3744.
- Gnansounou, E. (2011) Measuring energy security vulnerability, in Sovacool, B. K. (ed), *The Routledge handbook of energy security*. Oxford, UK & New York, USA: Routledge.
- Gracceva, F. & Zeniewski, P. (2014) A systemic approach to assessing energy security in a low-carbon EU energy system. *Applied Energy*, 123, 335-348.
- Grubb, M., Butler, L. & Twomey, P. (2006) Diversity and security in UK electricity generation: The influence of low-carbon objectives. *Energy Policy*, 34(18), 4050-4062.
- Gupta, E. (2008) Oil vulnerability index of oil-importing countries. *Energy Policy*, 36(3), 1195-1211.

Guta, D. and Börner, J. (2017), "Energy security, uncertainty and energy resource use options in Ethiopia: A sector modelling approach", *International Journal of Energy Sector Management*, Vol. 11 No. 1, pp. 91-117.

Haegel, N. M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y.-M., De Wolf, S., Dimmler, B., Feldman, D., Glunz, S., Goldschmidt, J. C., Hochschild, D., Inzunza, R., Kaizuka, I., Kroposki, B., Kurtz, S., Leu, S., Margolis, R., Matsubara, K., Metz, A., Metzger, W. K., Morjaria, M., Niki, S., Nowak, S., Peters, I. M., Philipps, S., Reindl, T., Richter, A., Rose, D., Sakurai, K., Schlatmann, R., Shikano, M., Sinke, W., Sinton, R., Stanbery, B. J., Topic, M., Tumas, W., Ueda, Y., van de Lagemaat, J., Verlinden, P., Vetter, M., Warren, E., Werner, M., Yamaguchi, M. & Bett, A. W. (2019) Terawatt-scale photovoltaics: Transform global energy. *Science*, 364(6443), 836.

Haghighi, S. S. (2007) *Energy Security: The external legal relations of the European Union with major oil and gas supplying countries*. London, UK: Bloomsbury Publishing.

Halder, P. K., Paul, N., Joardder, M. U. H. & Sarker, M. (2015) Energy scarcity and potential of renewable energy in Bangladesh. *Renewable and Sustainable Energy Reviews*, 51, 1636-1649.

Hammad, A. & Al-Momani, H. (2013) Politics and Energy Security in Jordan, *The Global Conference on Renewables and Energy Efficiency for Desert Regions (GCREEDER 2013)*. Amman, Jordan:
Online https://www.researchgate.net/profile/Ahmad_Alshwawra/publication/338165817_Politics_and_Energy_Security_in_Jordan/links/5e03bf34a6fdcc28373ef9ba/Politics-and-Energy-Security-in-Jordan.pdf. [Accessed 05. June 2020]

Hedenus, F., Azar, C. & Johansson, D. J. A. (2010) Energy security policies in EU-25—The expected cost of oil supply disruptions. *Energy Policy*, 38(3), 1241-1250.

Helin, K., Jaäskelainen, J. and Syri, S., (2018) Energy security impacts of decreasing CHP capacity in Finland. *15th International Conference on the European Energy Market (EEM)* (pp. 1-5). IEEE.

Herington, M. J. & Malakar, Y. (2016) Who is energy poor? Revisiting energy (in) security in the case of Nepal. *Energy Research & Social Science*, 21, 49-53.

Holley, C. & Lecavalier, E. (2017) Energy governance, energy security and environmental sustainability: A case study from Hong Kong. *Energy Policy*, 108, 379-389.

Hoogeveen, F. & Perlot, W. (2007) The EU's policies of security of energy supply towards the Middle East and Caspian region: Major power politics? *Perspectives on Global Development and Technology*, 6(1), 485-507.

- Hossain, Y., Loring, P. A. & Marsik, T. (2016) Defining energy security in the rural North—Historical and contemporary perspectives from Alaska. *Energy Research & Social Science*, 16, 89-97.
- Hovhannisyán, K. (2003) Sustainable development and energy security in Armenia: a step towards dilemma. *Lund University*, 33.
- Hughes, L. (2009) The four ‘R’s of energy security. *Energy Policy*, 37(6), 2459-2461.
- IEA, International Energy Agency (2001) *Towards a sustainable energy future*. Paris, France: Organisation for Economic Co-operation and Development (OECD) Publishing.
- IEA, International Energy Agency (2007) *Energy security and climate policy-assessing interactions*. Paris, France: Organisation for Economic Co-operation and Development (OECD) Publishing.
- IEA, International Energy Agency (2016) *World Energy Balances 2016*. Paris, France: Organisation for Economic Co-operation and Development (OECD) Publishing.
- Isaacs, R. & Molnar, A. (2017) Island in the neoliberal stream: energy security and soft re-nationalisation in Hungary. *Journal of Contemporary European Studies*, 25(1), 107-126.
- Islam, A., Chan, E.-S., Taufiq-Yap, Y. H., Mondal, M. A. H., Moniruzzaman, M. & Mridha, M. (2014) Energy security in Bangladesh perspective — An assessment and implication. *Renewable and Sustainable Energy Reviews*, 32, 154-171.
- Islam, M. N. (2003) Energy Security and Sustainable Human Development: A Bangladesh Perspective. *Human Security in South Asia: Energy, Gender, Migration, and Globalisation*, p.95.
- Jaber, J. O., Elkarmi, F., Alasis, E. & Kostas, A. (2015) Employment of renewable energy in Jordan: Current status, SWOT and problem analysis. *Renewable and Sustainable Energy Reviews*, 49, 490-499.
- Jamasb, T. & Pollitt, M. (2008) Security of supply and regulation of energy networks. *Energy Policy*, 36(12), 4584-4589.
- Jan, K. & Goldwyn, D. L. (2005) *Energy and security: Toward a new foreign policy strategy*. Washington, DC, USA: Woodrow Wilson Centre Press.
- Janeliūnas, T. & Molis, A. (2006) Energy security of Lithuania: challenges and perspectives. *Lithuanian political science yearbook*, pp. 200-223.
- Jansen, J. C. (2009) *Energy services security: concepts and metrics*. Amsterdam, The Netherlands: Energy Research Centre of the Netherlands.

-
- Jansen, J. C. & Seebregts, A. J. (2010) Long-term energy services security: What is it and how can it be measured and valued? *Energy Policy*, 38(4), 1654-1664.
- Jewell, J., Cherp, A. & Riahi, K. (2014) Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. *Energy Policy*, 65, 743-760.
- Jewell, J., Cherp, A., Vinichenko, V., Bauer, N., Kober, T., McCollum, D., Van Vuuren, D. P. & Van Der Zwaan, B. (2013) Energy security of China, India, the EU and the USA under long-term scenarios: Results from six IAMs. *Climate Change Economics*, 04(04), 1340011.
- Johansson, T. B. & Nakićenović, N. (2012) *Global energy assessment: Toward a sustainable future*. Cambridge, UK: Cambridge University Press.
- Johnson, C. & Boersma, T. (2013) Energy (in) security in Poland the case of shale gas. *Energy policy*, 53, 389-399.
- Johnson, C. & Boersma, T. (2015) The politics of energy security: Contrasts between the United States and the European Union. *Wiley Interdisciplinary Reviews: Energy and Environment*, 4(2), 171-177.
- Jones, C. R., Kaklamanou, D. & Lazuras, L. (2017) Public perceptions of energy security in Greece and Turkey: Exploring the relevance of pro-environmental and pro-cultural orientations. *Energy Research & Social Science*, 28, 17-28.
- Jonsson, D. K., Johansson, B., Månsson, A., Nilsson, L. J., Nilsson, M. & Sonnsjö, H. (2015) Energy security matters in the EU Energy Roadmap. *Energy Strategy Reviews*, 6, 48-56.
- Jordan, M., Manley, D., Peters, R. S. & Stoltz, R. (2012) *Goals of energy policy: Professional perspectives on energy security, economics, and environment*. Albuquerque, NM, USA: Sandia National Laboratories/US Department of Energy..
- Joskow, P. L. (2007) Supply security in competitive electricity and natural gas markets, *Utility Regulation in Competitive Markets: Problems and Progress*. Cheltenham, UK: Edward Elgar Publishing.
- Jun, E., Kim, W. & Chang, S. H. (2009) The analysis of security cost for different energy sources. *Applied Energy*, 86(10), 1894-1901.
- Jääskeläinen, J., Lager, J. & Syri, S. (2019) Development of Energy Security in Finland and in the Baltic States since 1991, *2019 16th International Conference on the European Energy Market (EEM)*. Ljubljana, Lithuania, 18-20 Sept. 2019.

- Jääskeläinen, J., Veijalainen, N., Syri, S., Marttunen, M. & Zakeri, B. (2018) Energy security impacts of a severe drought on the future Finnish energy system. *Journal of Environmental Management*, 217, 542-554.
- Kaare, K. K., Koppel, O. & Leppiman, A. (2013) The Eastern Baltic LNG terminal as a prospect to improve security of regional gas supply, *Proceedings of the 2013 International Conference on Environment, Energy, Ecosystems and Development*. Venice, Italy , pp. 158-164.,.
- Kamsamrong, J. & Sorapipatana, C. (2014) An assessment of energy security in Thailand's power generation. *Sustainable Energy Technologies and Assessments*, 7, 45-54.
- Kanchana, K. & Unesaki, H. (2014) ASEAN energy security: An indicator-based assessment. *Energy Procedia*, 56, 163-171.
- Kanchana, K. & Unesaki, H. (2015a) Assessing energy security using indicator-based analysis: The case of ASEAN member countries. *Social Sciences*, 4(4), 1269-1315.
- Kanchana, K. & Unesaki, H. (2015b) Assessing energy security using indicator-based analysis: The case of ASEAN member countries. *Social Sciences*, 4(4).
- Karakasis, V. P. (2015) Energy Security and the Cyprus Question. *Politikon: The IAPSS Journal of Political Science*, 27, 5-35.
- Kasekamp, A. (2006) Energy Security of Estonia in the Context of the Energy Policy of the European Union. Tallinn, Estonia: Estonian Foreign Policy Institute.
- Kaygusuz, K., Toklu, E. & Avci, A. C. (2015) Energy security in a developing world: a case of Turkey. *Journal of Engineering Research and Applied Science*, 4(1), 265-277.
- Kazarian, U. (2018) Energy Security in Armenia and the South Caucasus. *Fletcher Sec. Rev.*, 5, 50.
- Keppler, J. H. (2007) *International relations and security of energy supply: Risks to continuity and geopolitical risks*. Brussels, Belgium: Directorate-general for external policies of the union, Policy Department.
- Kilickaplan, A., Bogdanov, D., Peker, O., Caldera, U., Aghahosseini, A. & Breyer, C. (2017) An energy transition pathway for Turkey to achieve 100% renewable energy powered electricity, desalination and non-energetic industrial gas demand sectors by 2050. *Solar Energy*, 158, 218-235.
- Kim, H., Shin, E.-s. & Chung, W.-j. (2011) Energy demand and supply, energy policies, and energy security in the Republic of Korea. *Energy Policy*, 39(11), 6882-6897.

- Kim, J. E. (2014) Energy security and climate change: How oil endowment influences alternative vehicle innovation. *Energy Policy*, 66, 400-410.
- Kirchner, E. & Berk, C. A. N. (2010) European energy security co-operation: Between amity and enmity. *JCMS: Journal of Common Market Studies*, 48(4), 859-880.
- Kochetkov, Y. & Yurkovskaya, T. (2015) Expert Estimation of the ways for creating energy security potential in Latvia. *Inziner. Ekonom.–Eng. Econ*, 26, 130-141.
- Kononov, Y. D. (2014) Evaluation of strategic threats in predictive studies of power industry. *Studies on Russian Economic Development*, 25(3), 246-250.
- Kosowska, K., Czarnota, R., Stopa, J., Kosowski, P. & Janiga, D. (2018) The energy security of Armenia. *International Multidisciplinary Scientific GeoConference: SGEM: Surveying Geology & mining Ecology Management*, 18, 875-882.
- Kovačovská, J. (2010) *Energy Security in European Conditions*. Master thesis Masaryk University, Faculty of social studies. Available online: http://is.muni.cz/th/170482/fss_m/Kovacovska-Diplomova-praca.pdf [Accessed 05. June 2020].
- Kozulj, R. (2010) The Quest for Energy Security in Argentina. *Series on Trade and Energy Security*.
- Kruyt, B., van Vuuren, D. P., de Vries, H. J. M. & Groenenberg, H. (2009) Indicators for energy security. *Energy Policy*, 37(6), 2166-2181.
- Kucharski, J. & Unesaki, H. (2015) A policy-oriented approach to energy security. *Procedia Environmental Sciences*, 28, 27-36.
- Kumar, S. (2016) Assessment of renewables for energy security and carbon mitigation in Southeast Asia: The case of Indonesia and Thailand. *Applied Energy*, 163, 63-70.
- Kumar, S., Goteti, N. S. & Savargaonkar, P. (2016) Co-benefit technologies, green jobs, and national innovation systems, in Lohani, B. N., Kawai, M. & Anbumozhi, V. (eds), *Managing the Transition to a Low-Carbon Economy: Perspectives, Policies, and Practices from Asia*. Tokyo, Japan: Asian Development Bank Institute.
- Kunz, A., (2012) Indian energy security. *Nuclear Energy Policy*. Seminar paper. Prague: Charles University in Prague.
- La Viña, A. G. M., Tan, J. M., Guanzon, T. I. M., Caleda, M. J. & Ang, L. (2018) Navigating a trilemma: energy security, equity, and sustainability in the Philippines' low-carbon transition. *Energy research & social science*, 35, 37-47.

- Lakić, N. (2013) Energy security of the republic of Serbia. *International Journal of Economics & Law*, 9(9), 77-86.
- Laldjebaev, M., Morreale, S. J., Sovacool, B. K. & Kassam, K.-A. S. (2018) Rethinking energy security and services in practice: National vulnerability and three energy pathways in Tajikistan. *Energy Policy*, 114, 39-50.
- Le Coq, C. & Paltseva, E. (2009) Measuring the security of external energy supply in the European Union. *Energy Policy*, 37(11), 4474-4481.
- Lefèvre, N. (2010) Measuring the energy security implications of fossil fuel resource concentration. *Energy Policy*, 38(4), 1635-1644.
- Leonavičius, V., Genys, D. & Krikštolaitis, R. (2015) Public perception of energy security in Lithuania. *Journal of security and sustainability issues*, 4, 312-322.
- Leonavičius, V., Genys, D. & Krikštolaitis, R. (2018) Public perception of energy security in Lithuania: between material interest and energy independence. *Journal of Baltic Studies*, 49(2), 157-175.
- Lesbirel, S. H. (2004) Diversification and energy security risks: The Japanese case. *Japanese Journal of Political Science*, 5(01), 1-22.
- Lovins, A. B. & Lovins, L. H. (1981) *Energy policies for resilience and national security*. USA: Earth, F. O. T.
- Lu, W., Su, M., Zhang, Y., Yang, Z., Chen, B. & Liu, G. (2014) Assessment of energy security in China based on ecological network analysis: A perspective from the security of crude oil supply. *Energy Policy*, 74, 406-413.
- Löschel, A., Moslener, U. & Rübhelke, D. T. G. (2010) Indicators of energy security in industrialised countries. *Energy Policy*, 38(4), 1665-1671.
- Magazzino, C. (2016) Is per capita energy use stationary? Time series evidence for the EMU countries. *Energy Exploration & Exploitation*, 35(1), 24-32.
- Mahmud, K. (2012) Power Grid Interconnection of South Asian Region to Retain Sustainable Energy Security and Figure Out The Energy Scarcity. *Global Journal of Researches in Engineering*, (https://globaljournals.org/GJRE_Volume12/3-Power-Grid-Interconnection-of-South.pdf), 12(10), 15-19.
- Martchamadol, J. & Kumar, S. (2012) Thailand's energy security indicators. *Renewable and Sustainable Energy Reviews*, 16(8), 6103-6122.
- Maslow, A. H. (1943) A theory of human motivation. *Psychological Review*, 50(4), 370-396.

-
- Matsumoto, K. i. (2015) Energy Structure and Energy Security under Climate Mitigation Scenarios in China. *PLOS ONE*, 10(12), e0144884.
- Matsumoto, K. i. (2017) Transition of energy security performances in Japan: historical and scenario analysis. *Euro - Asian Journal of sustainable energy development policy*, 5, 2, 1-12.
- Matsumoto, K. i. & Andriosopoulos, K. (2016) Energy security in East Asia under climate mitigation scenarios in the 21st century. *Omega*, 59, 60-71.
- Matsumoto, K. i., Doumpos, M. & Andriosopoulos, K. (2018) Historical energy security performance in EU countries. *Renewable and Sustainable Energy Reviews*, 82, 1737-1748.
- Matsumoto, K. i. & Shiraki, H. (2018) Energy security performance in Japan under different socioeconomic and energy conditions. *Renewable and Sustainable Energy Reviews*, 90, 391-401.
- Miller, L. B., Lieber, R. J., Maddox, J., Mancke, R., Vernon, R. & Willrich, M. (1977) Energy, security and foreign policy: A review essay. *International Security*, 1.4, 111-123.
- Mitchell, C., Watson, J. & Whiting, J. (2013) *New challenges in energy security: The UK in a multipolar world*. Basingstoke, United Kingdom: Palgrave Macmillan.
- Moore, S. (2017) Evaluating the energy security of electricity interdependence: Perspectives from Morocco. *Energy Research & Social Science*, 24, 21-29.
- Månsson, A., Sanches-Pereira, A. & Hermann, S. (2014) Biofuels for road transport: Analysing evolving supply chains in Sweden from an energy security perspective. *Applied Energy*, 123, 349-357.
- Müller-Kraenner, S. (2007) *Energy security, Re-measuring the world*. London, UK: Routledge.
- Narula, K. (2014) Is sustainable energy security of India increasing or decreasing? *International Journal of Sustainable Energy*, 33(6), 1054-1075.
- Narula, K. (2015) Comparative assessment of energy sources for attaining Sustainable Energy Security (SES): The case of India's residential sector. *International Journal of Sustainable Energy Planning and Management*, 5, 27-40.
- Narula, K. & Reddy, B. S. (2015) Three blind men and an elephant: The case of energy indices to measure energy security and energy sustainability. *Energy*, 80, 148-158.

- Narula, K. & Reddy, B. S. (2016) A SES (sustainable energy security) index for developing countries. *Energy*, 94, 326-343.
- Neff, T. L. (1997) *Improving energy security in Pacific Asia: Diversification and risk reduction for fossil and nuclear fuels*. Massachusetts, USA: Project Commissioned by the Pacific Asia Regional Energy Security (PARES) Massachusetts Institute of Technology, Centre for International Studies.
- Nkomo, J. C. (2009) Energy security and liquid fuels in South Africa. *Journal of Energy in Southern Africa*, 20(1), 20-24.
- Nomikos, J. M. (2016) Intelligence Requirements for Cyber Defence, Critical Infrastructure and Energy Security in Greece. *National security and the future*, 17(1-2), 43-48.
- Nyman, J. (2018) Rethinking energy, climate and security: a critical analysis of energy security in the US. *Journal of International Relations and Development*, 21(1), 118-145.
- Ojeaga, P. (2014) Rethinking regional energy policy: Towards averting another energy crisis. Do threats matter in the supply and generation process? *Journal of Energy Technologies and Policy*, 4(No.6).
- Okeke, R. C. & Nzekwe, F. I. (2014) Energy security and sustainable development in Nigeria. *Arabian Journal of Business and Management Review (OMAN Chapter)*, 4(3), 63.
- Okonta, I. (2013) Nigeria: Policy incoherence and the challenge of energy security. A. Goldthau, *The Handbook of global energy policy*. Sussex, UK: Wiley-Blackwell. p.501-520.
- Onamics, G. R. C. (2005) *Onamics energy security index - Central and Eastern Europe*. Washington, DC, USA: Onamics LLC.
- OSGeo, Open Source Geospatial (2016) *QGIS (Quantum Geographic Information System)*, 2016. Available online: <http://qgis.osgeo.org> [Accessed 05. June 2020].
- Pająk, K., Kvilinskyi, O., Fasiiecka, O. & Miśkiewicz, R. (2017) Energy security in regional policy in Wielkopolska region of Poland. *Ekonomia i Środowisko*. 2 (61), 123-138
- Pascual, C. & Elkind, J. (2010) *Energy security: Economics, politics, strategies, and implications*. Washington, DC, USA: Brookings Institution Press.
- Pavlović, B. S. & Ivezić, D. D. (2017) Availability as a dimension of energy security in the republic of Serbia. *Thermal science*, 21(1 Part A), 323-333.

-
- Phdungsilp, A. (2015) Assessing energy security performance in Thailand under different scenarios and policy implications. *Energy Procedia*, 79, 982-987.
- Prasetyono, E. (2008) Energy security: An Indonesian perspective, in Marquina, A. (ed), *Energy Security: Visions from Asia and Europe*. London, UK: Palgrave Macmillan UK, 214-217.
- Radovanović, M., Filipović, S. & Pavlović, D. (2017) Energy security measurement – A sustainable approach. *Renewable and Sustainable Energy Reviews*, 68, 1020-1032.
- Ralph, N. & Hancock, L. (2019) Energy security, transnational politics, and renewable electricity exports in Australia and Southeast Asia. *Energy Research & Social Science*, 49, 233-240.
- Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L., Fasihi, M., Khalili, S., Dahlheimer, B., Gruber, G., Traber, T., De Caluwe, F., H-J., F. & Breyer, C. (2019) *Global energy system based on 100% renewable energy—power, heat, transport and desalination sectors*. Lappeenranta, Finland and Berlin, Germany Available at: http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf. [Accessed 09. May 2019].
- Reddy, B. S. (2015) Sustainable energy security for India—An indicator-based approach, *Energy Security and Development*. New York, USA: Springer, 3-38.
- Ren, J. & Sovacool, B. K. (2014) Enhancing China's energy security: Determining influential factors and effective strategic measures. *Energy Conversion and Management*, 88, 589-597.
- Ren, J. & Sovacool, B. K. (2015) Prioritizing low-carbon energy sources to enhance China's energy security. *Energy Conversion and Management*, 92, 129 - 136.
- Rifkin, J. (2011) *The third industrial revolution: How lateral power is transforming energy, the economy, and the world*. Basingstoke, UK: Palgrave Macmillan.
- Rogers-Hayden, T., Hatton, F. & Lorenzoni, I. (2011) 'Energy security' and 'climate change': Constructing UK energy discursive realities. *Global Environmental Change*, 21(1), 134-142.
- Ryu, H., Dorjragchaa, S., Kim, Y. & Kim, K. (2014) Electricity-generation mix considering energy security and carbon emission mitigation: Case of Korea and Mongolia. *Energy*, 64, 1071-1079.
- Röhrkasten, S. & Westphal, K. (2012) Energy security and the transatlantic dimension: a view from Germany. *Journal of Transatlantic Studies*, 10(4), 328-342.

- Sachsenmaier, D. (2011) *Global perspectives on global history: theories and approaches in a connected world*. Cambridge, UK: Cambridge University Press.
- Sahir, M. H. & Qureshi, A. H. (2007) Specific concerns of Pakistan in the context of energy security issues and geopolitics of the region. *Energy policy*, 35(4), 2031-2037.
- Samrina, N. (2004) Energy security for Bangladesh: prospects and strategic implications of natural gas. Champaign, IL, USA: *ACDIS Occasional Paper*.
- Sankar, T.L., Raza, H.A., Barkat, A., Wijayatunga, P., Acharya, M. and Raina, D.N., (2005). Regional energy security for South Asia. *SARI/Energy Programme*, New Delhi, India.
- Sarukhanyan, S. (2011) Energy security of Armenia: main achievements and challenges. *21st Century* (2)(10).
- Scheepers, M., Seebregts, A., De Jong, J. & Maters, J. (2006) *EU standards for energy security of supply*. Petten, The Netherlands: Energy research Centre of the Netherlands.
- Seebregts, A. J. & Welle, A. J. (2018) Energy Security in Ireland: A Statistical Overview. *Policy Studies*, 2017, 2016.
- Seifeddine, R. & Abdeldjalil, P. B. (2017) Investment in Renewable Energies as a Tool to Achieve the Energy Security: a Comparative Study Between Algeria and Morocco. *Revue Académique des Études Sociales et Humaines* (18), 3.
- Selvakkumaran, S. & Limmeechokchai, B. (2012) Assessment of energy security and co-benefits of low-carbon society scenarios in Thailand. *Suranaree Journal of Science and Technology*, 61-78.
- Semenenko, I. (2016) Energy security of Ukraine in the context of its sustainable development. *Equilibrium. Quarterly Journal of Economics and Economic Policy*, 11(3), 537-555.
- Senderov, S.M., Yusifbeyli, N.A., Rabchuk, V.I., Huseynov, A.M., Nasibov, V.K., Guliyev, G.B., Vorobev, S.V. and Smirnova, E.M., (2018) Modern problems of energy security of the Caspian regions of Russia and Azerbaijan. In *E3S Web of Conferences* (Vol. 69, p. 01014). EDP Sciences.
- Sharifuddin, S. (2014) Methodology for quantitatively assessing the energy security of Malaysia and other southeast Asian countries. *Energy Policy*, 65, 574-582.
- Simpson, A. (2005) Energy security and earth rights in Thailand and Burma (Myanmar). *Energy Security and the Indian Ocean Region*. Oxford, UK & New York, USA: Routledge. 253-84.

-
- Smil, V. (2010) *Energy transitions: history, requirements, prospects*. Westport, CT, USA: Praegar.
- Song, Y. C., Gao, M., Meng, H. D., Zhang, Y. & Han, Y. (2013) Study on Energy Structure and Energy Security in Inner Mongolia 2013. Bäch, Switzerland: Trans Tech Publ.
- Sovacool, B. K. (2011a) Evaluating energy security in the Asia pacific: Towards a more comprehensive approach. *Energy Policy*, 39(11), 7472-7479.
- Sovacool, B. K. (2011b) *The Routledge handbook of energy security*. Oxford, UK & New York, USA: Routledge.
- Sovacool, B. K. (2012) Energy security: Challenges and needs. *Wiley Interdisciplinary Reviews: Energy and Environment*, 1(1), 51-59.
- Sovacool, B. K. (2013a) An international assessment of energy security performance. *Ecological Economics*, 88, 148-158.
- Sovacool, B. K. (2013b) Assessing energy security performance in the Asia Pacific, 1990–2010. *Renewable and Sustainable Energy Reviews*, 17, 228-247.
- Sovacool, B. K. (2013c) Energy policymaking in Denmark: Implications for global energy security and sustainability. *Energy Policy*, 61, 829-839.
- Sovacool, B. K. & Brown, M. A. (2010) Competing dimensions of energy security: An international perspective. *Annual Review of Environment and Resources*, 35, 77-108.
- Sovacool, B. K. & Bulan, L. C. (2012) Energy security and hydropower development in Malaysia: The drivers and challenges facing the Sarawak Corridor of Renewable Energy (SCORE). *Renewable Energy*, 40(1), 113-129.
- Sovacool, B. K. & Mukherjee, I. (2011) Conceptualizing and measuring energy security: A synthesized approach. *Energy*, 36(8), 5343-5355.
- Sovacool, B. K., Mukherjee, I., Drupady, I. M. & D'Agostino, A. L. (2011) Evaluating energy security performance from 1990 to 2010 for eighteen countries. *Energy*, 36(10), 5846-5853.
- Sovacool, B. K. & Tambo, T. (2016) Comparing consumer perceptions of energy security, policy, and low-carbon technology: Insights from Denmark. *Energy Research & Social Science*, 11, 79-91.
- Spring, Ú. O. (2020) Energy Security: Policies and Potentials in Mexico, *Earth at Risk in the 21st Century: Rethinking Peace, Environment, Gender, and Human, Water, Health, Food, Energy Security, and Migration*. New York, USA: Springer, 413-447.

- Stirling, A. (2014) From sustainability to transformation: Dynamics and diversity in reflexive governance of vulnerability, in Hommels, A., Mesman, J. & Bijker, W. E. (eds), *Vulnerability in Technological Cultures: new directions in research and governance*. Massachusetts, USA: MIT Press, 305.
- Strielkowski, W., Lisin, E. & Tvaronaviciene, M. (2016) Towards energy security: Sustainable development of electrical energy storage. *Journal of Security and Sustainability Issues*, 6, 235-244.
- Taliotis, C., Howells, M., Bazilian, M., Rogner, H. & Welsch, M. (2014) Energy security prospects in Cyprus and Israel: A focus on natural gas. *International Journal of Sustainable Energy Planning and Management*, 3, 5-20.
- Tatalović, S. (2008) Energy Security and Security Policies: The Republic of Croatia in Comparative Perspective. *Politička misao: časopis za politologiju*, 45(5), 115-134.
- Teräväinen, T., Lehtonen, M. & Martiskainen, M. (2011) Climate change, energy security, and risk — Debating nuclear new build in Finland, France and the UK. *Energy Policy*, 39(6), 3434-3442.
- Tidemann, C. (2019) Barriers to Energy Security in Australia: The Electricity Sector Governance and the Need for Change, *Energy Security*. New York, USA: Springer, 93-122.
- Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D. & Breyer, C. (2019) Long term load projection in high resolution for all countries globally. *International Journal of Electrical Power & Energy Systems*, 111, 160-181.
- Tongsopit, S., Kittner, N., Chang, Y., Aksornkij, A. & Wangjiraniran, W. (2016) Energy security in ASEAN: A quantitative approach for sustainable energy policy. *Energy Policy*, 90, 60-72.
- Turton, H. & Barreto, L. (2006) Long-term security of energy supply and climate change. *Energy Policy*, 34(15), 2232-2250.
- UN, United Nations (2015) *Sustainable development goals knowledge platform*. New York, USA. <https://sustainabledevelopment.un.org/sdgs> [Accessed 05. June 2020]
- UNDP, United Nations Development Program, UNDESA, United Nations Department of Economic and Social Affairs & WEC, World Energy Council (2004) *World energy assessment 2004: Overview*. New York, USA.
- UNDP, United Nations Development Programme (2000) *World energy assessment - Energy and challenges of sustainability*. New York, USA.

UNDP, United Nations Development Programme (2011) *Energy access for the poor: Energizing the millennium development goals*. New York, USA.

UNFCCC, United Nations Framework Convention on Climate Change (2015) *Adoption of the Paris Agreement - proposal by the president*. Paris, France. Available: <https://unfccc.int/resource/docs/2015/cop21/eng/109.pdf> [Accessed 05. June 2020].

USChC, U.S. Chamber of Commerce (2012) *International Index of Energy Security Risk*. Washington DC, USA. Available: <https://www.globalenergyinstitute.org/sites/default/files/InternationalIndex2012.pdf> [Accessed 05. June 2020].

Valentine, S. V. (2011) Emerging symbiosis: Renewable energy and energy security. *Renewable and Sustainable Energy Reviews*, 15(9), 4572-4578.

Vidakis, I. & Baltos, G. (2013) *The Energy Security and Greece*. Athens, Greece: DYROS Publishing.

Vidican-Auktor, G. (2017) Energy security, sustainability, and development in Morocco, *The Political and Economic Challenges of Energy in the Middle East and North Africa*. Oxford, UK & New York, USA: Routledge, 236-247.

Vivoda, V. (2010) Evaluating energy security in the Asia-Pacific region: A novel methodological approach. *Energy Policy*, 38(9), 5258-5263.

Vivoda, V. (2016) *Energy security in Japan: challenges after Fukushima*. Oxford, UK & New York, USA: Routledge.

Von Hippel, D. & Hayes, P. (2007) Energy Security for North Korea. *Science*, 316(5829), 1288-1289.

Von Hippel, D., Suzuki, T., Williams, J. & Hayes, P. (2011) Evaluating the energy security impacts of energy policies, in Sovacool, B. K. (ed), *The Routledge handbook of energy security*. Oxford, UK & New York, USA: Routledge.

Wahlin, W. E. (2006) *Powering up a nation: Energy security in Japan and Australia*. The Australian Review of Public Affairs, vol. November, The University of Sydney, Sydney, Australia, Available: <http://www.australianreview.net/digest/2006/11/wahlin.html> [Accessed 05. June 2020]

Wang, Q. & Zhou, K. (2017) A framework for evaluating global national energy security. *Applied Energy*, 188, 19-31.

Watcharejyothin, M. & Shrestha, R. M. (2009) Effects of cross-border power trade between Laos and Thailand: Energy security and environmental implications. *Energy Policy*, 37(5), 1782-1792.

- WEC, World Energy Council (2014) *World energy trilemma: Time to get real-the case for sustainable energy investment*. London, UK.
- WEC, World Energy Council (2019) *World energy Trilemma Index*. London, UK.
- Wieloński, A. & Machowski, J. (2008) The energy security of Poland. *Studies of the Industrial Geography Commission of the Polish Geographical Society*, 10, 86-92.
- Willrich, M. (1976) International energy issues and options. *Annual Review of Energy*, 1(1), 743-772.
- Winrow, G. M. (2009) Turkey: Energy security and central Asia: The politics and economics of the so-called Great Game, *Facing Global Environmental Change*. New York, USA: Springer, 437-444.
- Winzer, C. (2012) Conceptualizing energy security. *Energy Policy*, 46, 36-48.
- Wu, G., Liu, L.-C., Han, Z.-Y. & Wei, Y.-M. (2012) Climate protection and China's energy security: Win-win or tradeoff. *Applied Energy*, 97, 157-163.
- Wu, K. (2014) China's energy security: Oil and gas. *Energy Policy*, 73, 4-11.
- Yao, L. & Chang, Y. (2014) Energy security in China: A quantitative analysis and policy implications. *Energy Policy*, 67, 595-604.
- Yates, A. & Greet, N. (2014) Energy Security for Australia: Crafting a Comprehensive Energy Security Policy. Engineers Australia, 61. Available <https://search.informit.com.au/documentSummary;dn=801618872639226;res=IELENG> [Accessed 05. June 2020].
- Yergin, D. (1991) *The prize: The epic quest for oil, money and power*. New York, USA: Simon & Schuster.
- Yergin, D. (2006) Ensuring energy security. *Foreign Affairs -New York-*, 85(2), 69.
- Yergin, D. (2011) *The quest: Energy, security, and the remaking of the modern world* London, UK: Penguin.
- Zachmann, G. (2014) Energy Security of Georgia. Policy Paper Series [PP/01/2014] Berlin, Germany: *German Economic Team Georgia*.
- Zafirakis, D. & Chalvatzis, K. J. (2014) Wind energy and natural gas-based energy storage to promote energy security and lower emissions in island regions. *Fuel*, 115, 203-219.

Zhang, H.-Y., Ji, Q. & Fan, Y. (2013) An evaluation framework for oil import security based on the supply chain with a case study focused on China. *Energy Economics*, 38, 87-95.

Zhao, H., Wu, Q., Hu, S., Xu, H. & Rasmussen, C. N. (2015) Review of energy storage system for wind power integration support. *Applied Energy*, 137, 545-553.

Čukaj, I. (2015) Economic Security as Priority, Energy Security, Advantage of Western Balkans and Albania. *European Journal of Business, Economics and Accountancy*, 4(1), 31.

Østergaard, P. A., Lund, H. & Mathiesen, B. V. (2014) Energy system impacts of desalination in Jordan. *International Journal of Sustainable Energy Planning and Management*, 1, 29-40.

Ćiković, H. (2008) The Analysis of the Influence of Energy Security on Foreign and Security Policy of the Republic of Poland. *Croatian International Relations Review*, 14(52/53), 119-128.

Čehulić, L., Kuznetsov, A. V., Celikpala, M. & Gleason, G. (2013) Energy security in South East Europe, in Cross, S., Kentera, S., Nation, R. C. & Vukadinović, R. (eds), *Shaping South East Europe's Security Community for the Twenty-First Century: Trust, Partnership, Integration*. London, UK: Palgrave Macmillan, 114-133.

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Definitions and dimensions of energy security: a literature review

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Definitions and dimensions of energy security: a literature review

Abdelrahman Azzuni * and Christian Breyer

This paper sheds light on an integral aspect of the global energy system: energy security. Energy security is a universal topic that shapes policies and regulations in order to achieve higher levels of energy security and thus provides societies with a better life. Understanding the concept and its implications requires a holistic definition, but current research literature lacks a commonly accepted, precisely defined definition. Therefore, the research gap is the absence of a comprehensive definition that takes into account all energy security dimensions, and the absence of well-studied relationships between energy security and its dimensions. Taking that in mind, the gap is addressed by a systematic review of energy security definitions and by building a structural dimensionalization of energy security. Thus, this review aims to track changing definitions of energy security in modern times and formulate a concise and comprehensive definition. Furthermore, using a structural approach, 15 dimensions, and related parameters of energy security are determined and categorized to illustrate the range of issues covered by the term and to enable precise evaluation of the energy security of energy systems. The results of this review show clearly how energy security could be defined generically to account all dimensions, and show the relationships between these 15 dimensions and energy security. Understanding all dimensions of energy security provides insights for policymakers to formulate policies that account for all of these dimensions. © 2017 Wiley Periodicals, Inc.

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INTRODUCTION

Energy security, as a universal concern,¹ has received great attention and has been the subject of many studies^{2–4} within different fields of science,⁵ policymaking,^{6,7} national energy policies,⁸ politics,⁹ international relations,¹⁰ and as a national security issue.¹¹ The importance of the topic stands behind its ability to shape policies and countries behavior.¹² Policymakers need to address energy security issues when regulations are made because energy security has an urgent priority.¹³ As policymakers aim to

ensure consumers' daily needs of energy are covered,¹⁴ actions should be taken to ensure energy security, and thus the ultimate goal of making societies lives better is achieved. As the last end of the imposed policy in any country is to ensure people's well-being, the importance of energy security consideration is its impact on how to promote citizens' well-being.

Although the energy security concept is 'as old as fire,'¹⁵ analysis following scientific research principles only started around 1975.¹⁶ Ang et al.¹ state that publications on energy security were rare before 2001, but in the 21st century, the topic has emerged as one of a great importance.¹⁷ There are many reasons for this growing interest: increased energy prices,² the growing dependence of industrialized economies on energy¹⁸ as an engine for economic growth^{3,19} and a driver for civilization²⁰ and society,²¹ the global energy supply crisis,²² climate change,^{23,24} energy demand and competition,²

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political conflict,⁹ social development,¹⁶ major disruptions in oil markets⁵ related to military upheavals,²⁵ complex global markets,^{26,27} threats to the energy system,^{28,29} and the mindset that considers energy security as equivalent to national security.³⁰ In general, energy affects every aspect of life³¹ and energy is thus crucial to the survival of a functioning modern society.^{3,32}

In view of the importance of the topic, there is a need for a comprehensive understanding of the term 'energy security.'¹ Only few works have attempted to clarify the nature of energy security,² for example, Ang et al.,¹ but most studies have been regionally focused such as Hossain et al.³³ This review article attempts to address this gap by providing an overview of energy security definitions, presenting a chronological analysis of the definitions offered, and creating a dimensionalization of energy security.

The paper is constructed as follows: First section considers drivers behind the need for a universally accepted definition of the concept. Second section provides a broad overview of key aspects: energy security definitions resulting from different standpoints³⁴; evolution of definitions over time, where it is noted that in the literature there is neither good understanding²⁶ nor a trend analysis¹ but only a confirmation of change³⁵; reasons behind the various definitions; and a proposal for a common definition for energy security.

Third section details dimensions and parameters of energy security. Energy security is a multi-dimensional concept^{5,34} with many parameters,²⁶ some of which are interdependent and others are independent.⁶ This dimensionalized analysis compiles dimensions of energy security established by previous research to provide a comprehensive definition and to empower assessment of the impact of the different dimensions and their interactions.

Fourth section concludes the paper and presents recommendations for utilization of the dimensional view developed in the work. In addition to being of value to the research community, the discussion in this work provides governments and policymakers with insights for energy security.

These four sections attempt to identify the gaps in previous research, and address them with novel solutions. The gaps as mentioned before are the absence of a comprehensive term for energy security,¹ the locality of previous studies,³³ and the selective dimensionalization of energy security. The novel approach of this review paper is to follow the definitions of energy security in a chronological way, in order to identify the dimensions considered in

literature. Furthermore, the novel systematic construction of 15 dimensions and their parameters is not preceded before in literature. The arrangement of the dimensions and their parameters with deep understanding of the interrelationships between them and energy security is new. The novel solution provided in this review paper is the promotion of considering all of these dimensions and parameters in the decision-making and the policymaking.

Definition of Energy Security

A clear definition of energy security is critical, since energy security is a concept rather than a policy²⁶ or a strategy. Enhancement of energy security is a key goal of society^{2,8,36–40} and sustainable energy strategies⁴¹ because energy security is required to fulfill basic human needs.⁴² Personal and national energy security are paths to achieve freedom of choice, which allows progress to self-actualization in Maslow's hierarchy of needs.⁴²

However, targeting increasingly higher levels of energy security may result in overinvestment in energy security, resulting in nonoptimal use of resources that may be more valuably invested elsewhere. Consequently, the question arises: 'what is the needed level of energy security?' A wide range of diverse answers based on many different assessment tools and approaches^{30,43–46} have been proffered, depending on the definitions and dimensions used in the assessment. The need to address the issue of the optimal level of energy security provides further motivation for investigating definitions and dimensions of energy security.

Setting a goal of improved energy security requires a clear understanding of the concept of energy security itself. However, as concluded in many studies, the concept is not defined clearly,^{5,6} or is defined narrowly and disparately^{34,47,48} with no common consensus.^{49,50} The definitions are context dependent and polysemic in nature^{2,9,26,49} and the topic is approached with different assumptions³¹ and from different viewpoints. Consequently, researchers have described the term as abstract, elusive, vague, inherently difficult, and blurred.^{5,26,50–52}

Chronological Analysis of Energy Security Definitions

As mentioned earlier, the concept of energy security is as old as fire. Early humans had to secure a source of fire (e.g., wood) for heating, cooking, and protection,¹⁵ which met human needs at the time. As human civilization developed and new societal

structures, fuels and modes of transport were adopted, energy security became increasingly complex. Although the need for energy security has been ever-present, documented definitions of energy security are relatively new.¹⁶

Study of the evolution of a definition can provide insights into key aspects of the concept; therefore, a trend analysis of documented definitions of energy security is presented. This analysis considers only direct definitions of the concept; literature related to energy security but not explicitly defining the term is not considered. Moreover, definitions that neglect an essential part of the concept are also excluded. For example, the definition 'security of supply'^{49,53–58} is an obviously misleading definition because security of supply is only one part of the concept of energy security, as it excludes dimensions such as the environment, continuity of demand, and efficiency.⁵¹ The analysis traces the development of definitions of energy security from 1970 to 2000 in 10-year intervals and uses 5-year intervals for 21st century definitions. Some definitions are reused by later authors. The definitions and the literature where they are presented is summarized in Table S1 (Appendix S1, Supporting Information).

As stated earlier, the analysis in this work begins in the 1970s, where the first available record of a definition of energy security is by Willrich,⁵⁹ shortly after the energy crisis of 1973, and a part of the 'environmental awakening' witnessed in the 1970s and the 1980s. Drawing on research such as,^{60–62} Willrich⁵⁹ defined energy security as: 'Assurance of sufficient energy supplies to permit the national economy to function in a politically acceptable manner.' Although the focus of this definition is on the economy, politics and supply, many other dimensions were discussed in the article. The same definition was used by Miller et al.⁶³ but fewer dimensions were discussed in their work. Later, Deese⁶⁴ introduced the notion that energy security is a condition, a situation, or a status rather than a policy or an attitude. Deese emphasized the 'nation' as a whole rather than considering individuals and subgroups. Availability of resources is the focus in these two definitions, reflecting prevailing global conditions.

The 1980s saw few attempts to define energy security, an indication of greater international stability. Lovins and Lovins⁶⁵ introduced a definition that argued that energy security is to be reconsidered with more dimensions than merely the ability to keep the oil flowing (or energy availability).

In the 1990s, following the Gulf War, energy security was defined by Bohi and Toman⁴⁷ by defining its opposite, i.e., the loss of welfare because of process changes (e.g., oil price fluctuations due to

conflicts). In this decade, the notions of national security and regional security were emphasized by Neff.⁶⁶

At the beginning of the 21st century, research literature started to provide more precise definitions, and energy research started to see greater involvement of international organizations. The definition by the United Nations Development Program (UNDP)⁶⁷ introduced new notions of locality, supply, and import, in addition to availability. A similar approach was taken by the International Energy Agency (IEA) by defining the term using the notion of physical availability of supplies.⁶⁸ While the availability of local physical resources is clearly an important dimension of energy security, such availability can result in what has been termed as 'energy curse.'⁶⁹ In addition to price, supply reliability was later introduced into the definition.³

Two years later, the definition was developed by the inclusion of the state of being free of risks and disruptions,^{70,71} which was a notion that had previously been discussed by Neff.⁶⁶ The Iraq and Afghanistan wars affected energy perspectives, resulting in a necessity to include freedom from risks in the definition. The focus on possible risk spurred the UNDP⁷² to update their definition by adding a further dimension to energy security—the environment.

The trend of adding more dimensions to the definition of energy security continued in 2005 with the inclusion of infrastructure,⁷³ national power,⁷⁴ and sustainability.⁷⁵

The period 2006–2010 saw considerable development in study of energy security, and 21 different definitions can be found in the literature. The approach of adding more dimensions to the definition and attempting to define the term by the sum of its components continued. Hughes⁷⁶ refers to the role of governments and polices, Bruusgaard⁷⁷ emphasizes the notion of the state, and Yergin¹⁷ focuses on two dimensions (availability and cost) to define energy security. Inclusion of the timeframe dimension was seen in 2006.⁷⁸ Through the whole period, definitions introduced a variety of new and extended notions ranging from the availability dimension,⁷⁹ the environment dimension,⁸⁰ the cost dimension,⁸¹ the efficiency dimension,⁸² the sustainable considerations,¹⁰ and the military dimension⁸³ to the notion of risks and threats to the economy.³⁵ A new element was introduced to the definition when the new term 'sustainability' was added.⁸⁴

Many definitions tried to simplify the issue of energy security by including important parameters in the definition. However, some dimensions are still missing (e.g., culture, environment, and technology),

making the definitions deficient. A further change occurred with the inclusion of electricity in the definition,⁸⁵ whereas previously oil had been considered the main source of energy.

The years since 2010 have witnessed different approaches to formulating a definition of energy security. In the beginning of this period, researchers tried to add as many different dimensions as possible,^{33,86–92} which was a continuation of the previous trend. A feature of this approach is that the definition of energy security became longer and longer, as researchers found more dimensions worthy of consideration. An alternative approach to formulating the definition was seen in 2012, when researchers aimed to resolve the question of ‘What is included in energy security?’ by simplifying the definition so that it can be used for different sectors with different perspectives. The first innovation was by Johansson and Nakićenović,⁹³ who provided a definition that can be used with any energy system, whether oil, gas, or electricity, etc. The notion of risk and threat was partially presented. However, a weakness with their definition was that it was limited to the energy provision point of view (services) and failed to account for the producers.

From the research point of view, simplification of the definition seems attractive as long as the definition includes all sides. In 2013, Čehulić et al.⁹⁴ attempted to formulate a very simple definition by defining energy security as: ‘The freedom from disruption of energy supplies for whatever reason.’ This definition has the advantage that it can be used for any perspective in any dimension but the drawback that it focuses only on the supply side. Another innovative definition was provided by Jewell et al.^{95,96} Their definition: ‘Low vulnerability of vital energy systems,’ is conceived in very wide, general and vague terms, and thus needs further explanation. According to their approach, the meanings of vulnerabilities, vital and the systems in consideration need to be defined, i.e., the terms need reformulation to give better understanding. A further attempt in providing a simple definition was undertaken by Kucharski and Unesaki.⁴⁸ They defined energy security as ‘Assessing various types of risk in the energy system.’ The drawback of this definition is the notion of energy security as an action. While assessing the risks can be a part of having a higher level of energy security but it does not cover all aspects. Making new laws, for example, is a step subsequent to evaluation and is a part of the energy security concept. However, the use of the term ‘risks’ is important for the definition, as will be discussed later.

Noticeably, the number of researchers providing a definition for energy security increased vastly in this period. The 29 different definitions within 5 years show the disagreement in the scientific community regarding how to deal with the issue. As can be seen in Figure 1, the number of researchers providing definitions of energy security has increased over time. The second trend is the way in which researchers have approached the concept; at first, the definitions are simple and general but sufficient for their time. Then, researchers started to include more terms within the definition to show that different parameters are involved. The last change was simplification but with provision of more comprehensive terms so that subparameters were removed but references to them were included in the definition.

As mentioned earlier, other researchers have tried to discuss the concept but have confused it with other terms (e.g., security of supply is the focus of most researchers⁹⁷) or have not provided a clear definition. There is an obvious difference between energy security and security of supply,¹⁸ which fails to include important dimensions of energy security. For example, Hoogeveen and Perlot⁵⁴ state: ‘Security of supply is a general term to indicate the access to and availability of energy at all times.’ The same limitation can be found in other literature.^{5,49,53–58,98–104} Only recently, scholars such as Erdal et al.¹⁰⁵ have started to differentiate between energy security and security of energy supply, providing different definitions for each concept.

Adopted Definition

As Aristotle reputedly said, ‘he who controls the definition, controls the debate.’³² Thus, a suitably generic term to cover all aspects of the concept is needed to overcome the complexity of the term.¹⁰ The first step in formulation of such a definition is to include the three parts of the energy system, supply, demand, and transfer, as UNDP et al.⁷² suggest that energy security should not only be focused on security of supply. Furthermore, if energy security is to be defined comprehensively, the concept of sustainability has to be taken into consideration.¹⁰⁶ Also, the concept of threat, risk, and vulnerability, i.e., the degree to which the system is unable to cope with events,¹⁰⁷ should be included.

Energy security has two words ‘energy’ and ‘security.’ According to the Oxford dictionary, energy is the strength or the power that can result in work. From another perspective, energy can have different forms but never disappears nor is created from nothing; it changes from one form to another (first

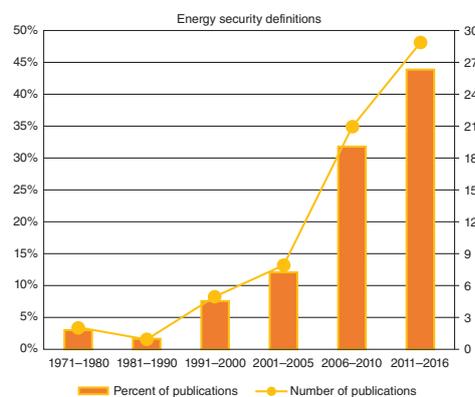


FIGURE 1 | Scientific documents defining energy security, occurrence percentage and numbers in time spans.

law of thermodynamics). Energy is thus: kinetic in moving objects, heat in small particle movement, electrical in electricity grid, chemical in molecular bonds (e.g., oil or gas), electromagnetic (e.g., solar irradiation), and so forth.

On the other side of the term, 'security' means: 'the state of being free from danger or threat,'¹⁰⁸ 'freedom from harmful threats'⁷¹ or in the words of Arnold Wolfers, 'the absence of threats to the adopted values.'¹⁰⁹

Therefore, in this work, energy security is defined as the *feature (measure, situation, or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats*. By this definition, all perspectives are taken into consideration, any dimension can be included, and all risks can be accounted for.

DIMENSIONS AND PARAMETERS OF ENERGY SECURITY

Following the definition of energy security in the previous section, the paper next considers dimensions and parameters of energy security and their relationships. Previous work has listed a large collection of dimensions and parameters that are important for energy security (Table S1, Appendix S1, Supporting Information), and the literature has diverse approaches to determine factors to be considered when dealing with energy security. Some researchers use dimensions³² and some use aspects.⁹³

The use of many parameters has been criticized, because the term should not be too specific and more

indicators do not guarantee a better assessment.³⁰ However, any dimension or parameter that has a relationship with energy security should be addressed because, as Yergin¹⁷ states, 'energy security discussion should be expanded to include more dimensions,' because energy security challenges are heterogeneous.³² The degree to which each parameter is linked to energy security and its significance differs. Thus, there is a lot of index analysis in literature⁵¹ in which researchers try to give a numerical value to energy security parameters in order to make a general evaluation⁵¹ of the security of a system against certain threats.

The methods to measure energy security differ a lot in literature. As summarized by Ang et al.,¹ there are many different ways to measure energy security based on the interest of the authors and the dimensions they include. First, authors attempt to study a specific location or period of time. Then, they choose their focus area of which dimensions are important to them. After that, indexes are formed to cover only the wanted dimensions from energy security. The methods to construct numerical indexes vary. First, each dimension or parameter is given a value. Then, these values are normalized to one another. Normalization can take place by a min-max, distance to a reference point or standardization. After the studied dimensions and parameters have the same meaning of their values, the impact of each value in the course of energy security evaluation is given a weight. Weighting can be done in several ways, for example, equal weights, principle component analysis (PCA), or analytic hierarchy process (AHP). The last step in these methods is to put all the values for dimensions and their weights in aggregation. Aggregation of all the informative data inherited in each dimension provides a numerical energy security index.

However, it is out of the scope of our article to give numerical values of how a parameter can be measured. Here, the aim is to address all possible factors, even though some of them might be interconnected, but as none of the parameters is identical, all parameters can provide information and insights. How to measure the exact parameter and how important it is differ based on the perspective, the interest, and the desired result.

To analyze energy security dimensions and parameters, our approach has three main parts: analyzing the different dimensions and parameters one by one, illuminating the relationship between the parameter and energy security, addressing the threats to each dimension, and discussing indexes that can be used to measure energy security parameters.

In most of the dimensions, the energy system is described by three parts: The energy source (production), the energy services (consumption), and the transfer from the production to consumption.⁴⁸ Furthermore, the first-order relationship and impacts between energy security and different parameters is to be taken into account.²⁵

Availability

This dimension is a critical dimension for energy security. Availability is always included in the discussion.⁵⁰ The importance of energy availability lies in its support of economic and welfare growth; when availability is weakened, it limits economic expansion and lead to changes in technological and consumption patterns.⁸⁹ In that sense, availability is discussed in relation to access to services,^{6,51} to sufficient supplies,³⁶ or to the availability of consumers.¹¹⁰ Therefore, availability has three parameters: *availability of energy resources*, e.g., oil or gas, *availability of means to transform resources into services*, e.g., energy infrastructure or pipelines, and the *availability of energy consumer*, e.g., public use of energy or industrial use.

The principle meaning of availability is existence. Therefore, the three main parameters of the availability dimension should exist. If energy resources do not exist, there is no notion of energy system, so the first parameter is that energy resources have to be available. Nowadays, the current energy system has no problem with energy resources. The global coal reserves are $1 \cdot 10^7$ TWh, the global oil reserves are $2.5 \cdot 10^6$ TWh, and the global natural gas reserves are $2 \cdot 10^6$ TWh.¹¹¹ The global energy assessment (GEA) has ranges for the reserves based on different literature and differentiating between conventional and nonconventional resources. The values are for global coal reserves $0.48 \cdot 10^7$ – $0.6 \cdot 10^7$ TWh, oil reserves $2.4 \cdot 10^6$ – $3.7 \cdot 10^6$ TWh, and gas reserves $0.7 \cdot 10^7$ – $2.1 \cdot 10^7$ TWh.⁹³ Another estimation for the current resources is made by Perez and Perez.¹¹² The global coal reserves are $7.9 \cdot 10^6$ TWh, the oil reserves are $2.1 \cdot 10^6$ TWh, and the gas reserves are $1.9 \cdot 10^6$ TWh.^{111,112} Based on current global energy consumption, oil reserves are enough for more than 55 years,¹¹¹ 52 years of current production,¹¹³ or for 23 years if global consumption grows by 5% annually.¹¹⁴ Also, the world's proven reserves of coal are estimated to last for 122 years of production at current rates,¹¹³ proven reserves of natural gas (conventional and unconventional) are estimated to sustain current production levels for 61 years.¹¹³ In addition to these resources, there

exists what is called ambient/renewable energy (e.g., wind power, solar energy, flow-of-the-river, and marine energy), which principally can be used to cover the demand.⁸² For example, the theoretical potential of solar energy alone is (89300 TW),¹¹⁵ that is approximately 7000 times the global energy consumption in 2013 (162 TWh).¹¹⁶ Therefore, energy exists plenty and sufficiently to cover all global demands as *per se* for the foreseeable future and hence many energy analysts, from the past as (1970s) and the more recent (2000s), agree that there is enough energy to meet global demand.^{84,117} Thus, there is no energy security issues in regards to availability of the energy sources on a global level.^{67,72} However, the resources (mainly fossil fuels) and the demand are not distributed evenly around globe.^{60,67,118} Therefore, existence of energy resources can be a constraint to achieve energy security if the perspective is narrowed down to a specific small populated area (e.g., Shanghai). On the other hand, if renewable energy (solar, wind, biomass, and hydropower) sources are taken into consideration, there is a more balance between the existence of resources and demand. The distribution of these resources is much more even than fossil fuels and thus the demand in different places is covered by nearby renewable resources.

The second parameter of the availability dimension is *the consumers (demand perspective)*. The demand parameter is as legitimate preoccupation as the resource parameter for countries where their revenues are from energy exports.^{90,119} Nowadays, the discussion about the demand side is taken place as part of energy security as what is known as 'security of demand'.⁷¹⁷ From energy producers' perspective, energy security denotes a quest for a market for their energy exports which correlates to increased (government) revenues.¹⁰ Today's population is around 7.35 billion and still expected to increase to 11.21 billion in 2100.^{120–122} Thus, people will continue to demand energy for various needs. Hence, as long as humans live, there will be available consumers for the available resources. Furthermore, the need for energy in different sectors of an industrialized society is high. Thus as long as the civilization continues, the energy demand will continue. However, the level of demand is a matter of disagreement, but for humans to live comfortably, individual consumption should reach at least about 40 MWh/cap.¹²³ These numbers seem incredible in contrast to the figure of 1.6 billion people (20% of global population) who do not have access to modern energy services.¹²⁴ Therefore, in order to live a sustainable future, all those people should be provided with energy (electricity) to reach

the individual consumption demand. That picture confirms the increase in demand predicted by many agencies.¹¹³ This means ‘security of demand’ is assured. The final question is how to utilize these resources for the growing demand in a sustainable way, the answer is renewable energy as Breyer et al.¹²³ conclude.

The last parameter of the availability dimension is *access to these energy resources* transferring them to energy services for consumers, which is usually the concern for researchers. Having access to the energy services was a concern through the history.¹²⁵ Individuals, societies, and countries paid a huge cost to obtain such access. Full access that results in the provision of needed energy services to consumer is considered to enhance energy security and hence drives the development path of a society.⁸⁹ On the other side, less access reduces energy security. The access importance is infrastructure-related. Secure infrastructure and transport routes are essential for energy security⁹⁰ because energy infrastructure is one of the most vulnerable elements of modern societies.⁸⁰ For such, breakthroughs in developing infrastructure are needed to enhance energy security.^{126,127} For example, developing new technology to harvest solar energy or new methods to generate electricity from water, both as sources of renewable energy.

Nevertheless, there are comprehensive risks and threats associated with the availability. Energy existence abundantly in one location with ultimate access can deteriorate energy security resulting of many problems such as the ‘Dutch Disease’¹²⁸ or ‘Resources Curse’.^{69,129} The Dutch disease occurs by the overvaluation of the currency of a country usually because of the export of natural resources.¹³⁰ This leads to the loss of competitiveness and thus deindustrialization of the economy. As was found by Cavalcanti et al.,¹³¹ abundant availability is not the driver for Dutch disease *per se* but rather its volatility. The other burden is the resources curse. Principally in most of the cases, energy availability tempts those who are in power to use it for their own benefits even if it is against the benefit of their people. The situation follows the political environment of when the resources were found; if a country is stable with determined roles for people in power and legitimate body to check on them, the newly found resources are less probable to be a curse. Otherwise, if there is no questioning to those in power, the resources are highly probable to be a curse.^{132,133} In other cases, other nations or governments decide to control the access to an energy resource by overthrowing current controllers or owners, starting a war against energy rich countries (resource war). Resource wars, defined

by Ciuta³¹ as hot conflicts triggered by a struggle to grab valuable resources. Furthermore, disrupted or limited access to the required energy like absence or ruin of infrastructure¹³⁴ will result of what is referred as energy poverty.¹²⁶ Energy poverty increases social difference and political tension and blocks the way to development.⁸⁰ In real life, destruction of production or processing infrastructure comes with the biggest risk.²¹ Another threat to the energy system is the depletion of energy sources,¹³⁵ which is sometimes exaggerated.¹²⁷ If it happens to utilize more of renewable energy rather than fossil fuel, it will happen not because of fossil fuel depletion. As Sheikh Yamani, the former Oil Minister of Saudi Arabia, said ‘the Stone Age did not come to an end because of a lack of stones,¹²⁷ but due to economic reasons.¹³⁶ Furthermore, poverty can be worsened or alleviated by the energy access level³²

The numerical indexes that can be used are different, for example, reserve to production ratios,^{49,82} reserve per capita,⁵¹ resource estimates,¹³⁷ or total energy resources per capita.³⁶ However, many of these indexes will be of no use in a future energy system that relies on renewables because they were designed for a fossil-based system. Therefore other indexes will make more sense to measure this dimension, for example, final energy consumption per capita.²⁹ Last, since energy exists excessively on the global level, the question is left for us (humans) to decide how we want to live on our planet; whether to collapse or to succeed.¹³⁸

Diversity

Diversity is also highly pointed out as an important dimension to enhance energy security.¹²⁶ Since the beginning of the 20th century, Winston Churchill the First Lord of the British Admiralty made his famous statement that energy security lies in variety and variety only.¹²⁵ The concept of diversity is portrayed by the expression: ‘Don’t put all your eggs in one basket.’⁵³ In principle, more diverse systems are more secure.^{127,139} In that sense, if one part of the energy system malfunctions, other alternatives can replace it.¹⁷ It is unlikely for all parts to fail at the same time.⁶⁷ Thus, the impact is spread among the other parts of the system.⁴⁸

As Stirling¹⁴⁰ presents, diversity’s main parameters are *diversity of fuels (energy carriers)*, *diversity of sources*, *diversity of means to make the energy available to end-users* (e.g., technologies and transportation) and *diversity of consumers* (e.g., markets and sectors).

Energy carriers can be in form of matter-based chemical materials (oil, gas, or coal), or in form of nonmatter-based electromagnetic fields (electricity). A system depending only on oil is less secure than a system depending on oil and gas. The same is to be considered for the source and its location. An energy system that relies on one power plant is less secure than a system with power plant and electricity import.

Diversity of sources is the second parameter. This parameter is related to the notion of dependency (to be discussed below). Simply, if the energy system has only one source, it is less secure than the case if there are different sources. For example, many European countries relied on Russia as their source of gas. This situation resulted in a 'crisis' in 2012.¹⁴¹ Germany and other European countries had less gas than needed to cover their gas demand. Should these countries have had a diverse set of sources and suppliers, the situation would have been easier, and energy security would have been preserved.

Diversity of technology is important because it allows for more options. Development of renewables promotes new energy sources utilization¹⁴² and hence enhances energy security.⁴⁰ For example, Germany witnessed an enhancement in energy security in January and February 2017, in contrast to France.¹⁴³ Because of security failures of French nuclear power plants several short-term shut downs led to power supply shortage in France and imports from neighboring countries had been required to keep the French power system stable during the winter, due to an ill-balanced diversity of technology in France. In contrast, Germany, with a much higher share of renewable energy (wind and solar) and substantial less nuclear energy than the highly nuclear energy-dependent France, balanced the energy system, in addition to utilizing coal and gas plants output.¹⁴³ In this sense, a more diverse system that comprises renewables is more secure and decreases the threat of electricity blackout. The same concept applies for transportation, what routes are used (land or water), how many routes are used, and what methods are used (pipelines, LNG terminals, grid, ships, etc.), all play a role in the diversity dimension. For example, diversification of transport routes diminishes motivation for terrorist attacks,¹²⁷ since it may not cause a significant level of harm.

The last parameter is *the consumers' profile*. Having one market (one country) is less secure in comparison to having more markets. Also, being able to provide energy services to more diverse users (industry, commercial, residential, military, etc.) is an advantage for the energy system.

However, this concept of diversity to enhance security can be applied only if all other dimensions are neutralized. Diversification alone is insufficient to enhance energy security if costs or compatibility are not to be taken into account.⁴⁸ For example, it is more diverse to use coal and oil rather than using oil alone, but the environmental and health impacts of this diverse system reduce energy security as it affects other dimensions. Furthermore, renewable energy takes the lead in building a more diverse and more secure energy system.¹⁴⁴ In addition, in many cases the enhancement does not have counter effects on the cost of the new system (renewables are cheaper), environment (renewables are cleaner), health, employment, etc.

To carry on, following the urge of nations to be independent, energy dependency is a term discussed a lot in literature.³¹ However, complete energy independence is merely a myth.²⁹ Total independence is not a guarantee of energy security at all,²¹ neither is dependency alone a concern to be triggered.¹⁴⁵ A dilemma has to be solved first, a total independence means less diversity and more threats by accidents, strikes, or newly discovered environmental effects.⁶⁶ Furthermore, many parts and devices of the energy system have to be imported.²⁹ Therefore, there should be an optimal choice between dependency and diversity. On the same tone, dependency on one country or region is usually discussed in literature. The example that is widely reported is the European reliance on Russian natural gas.^{146–148} Discussing this example can provide the cut point between diversity and dependency. If a country gets all of its energy from Russian natural gas (total dependency), energy security deteriorates. On the other hand, if a country relies on Russian natural gas among other sources of energy, their energy system is more secure (diverse). However, if this country decides to run all its energy system on nuclear energy built within its borders (total independent), the system will be less diverse and less secure, not to mention the intrinsic technical risk of nuclear. Furthermore, a country relying totally on nuclear energy within its borders has other negative consequences, such as becoming joint targets in wars¹⁴⁹ or targets to seize and control as an energy resource. It could be argued that for economic reasons, blackouts should be avoided at any cost and nuclear would be the best option for a base load power generation. However, an energy system can be run without base load power generation and new plants face very high cost¹⁵⁰ and the cluster risk of nuclear energy is also high; the cost of its failure on economy, environment, and society is much higher, as documented again in Fukushima.

Some of the indexes to measure diversity's impact on energy security are the diversity of energy sources in the total primary energy supply (TPES), electricity generation and the transport sector,⁹⁶ Herfindahl Hirschman index (HHI) for energy supply diversification corrected for political risk,⁵¹ energy trade per gross domestic product (GDP), energy import dependency,²⁹ Shannon-Wiener index (SWI),³⁰ and share of renewables in the energy system.⁸²

Cost

An interesting dimension that is often treated unfairly is the cost dimension. It is usually regarded as affordability of energy services (the price to be paid for energy). In our view, this is only one parameter for the cost dimension; there are other parameters to be addressed. Since there is a high correlation between energy and economy,¹⁵¹ this study will consider the different parameters of the cost dimension.

The first parameter is the *relation between energy price and energy security*. In terms of end-users and economy, a cheaper energy price is better because it can increase industrial production, enhance the economic growth, and encourage consumption.¹²⁶ This seems to enhance energy security but it is not as simple as that. Since energy security relies heavily on large-scale investment,⁷⁸ cheaper energy prices puts a burden on future planning. Also, scarce fund for investment has a structural impact on future prices¹⁵² and hence energy security. Cheap energy prices are a long-term problem because they lead to a false sense of instant security,¹⁵³ specially if there is no guarantee of such cheap prices for the future. When there is no guarantee for cheap prices in the future, societies and buyers become vulnerable to any price shocks.¹²⁶ On contrast, higher energy prices will reduce demand and encourage development of alternative energy resources,¹⁷ but at the same time limiting growth of energy-importing countries.¹⁵⁴ For example, an increase of \$10 in the price of a barrel of crude oil is likely to reduce economic growth in the industrialized countries by around 0.5 percentage points.^{25,68,72,79}

For producers, cheaper prices mean less revenue and may result in an economic loss. For a country, a nation or a society, such economic losses affect other services. So, does that mean a higher price achieves energy security for them? Up to a certain point, yes, because higher energy prices mean in the short-term higher profits,⁸⁴ growth in new supplies,¹⁷ and an increased capital investment¹²⁶ that can be used to establish a sustainable energy system¹⁵⁵ and to

achieve energy security.¹⁴⁶ However, on the other hand, higher revenue can cause the previously discussed 'Dutch disease.'

In regards to the first parameter (*energy price*), the last point is the nature of the pricing system. Stability of energy prices,¹⁴² price volatility,⁸² pricing system,¹⁵⁵ energy poverty,¹¹⁴ and peak oil¹³⁹ are the most discussed issues. Volatility of energy prices and their impact are the main challenges for energy security⁴ because a sudden change in energy prices may disrupt the whole economy.¹⁵⁶ As the World Energy Council states, volatility of energy prices has a critical uncertainty of the future economy.¹⁵⁵ For the pricing system, it follows the political discussion to come in a later sections, principally if energy to be subsidized by the government or not. International Monetary Fund estimates that there is 5 trillion USD of direct and indirect public means allocated to subsidize fossil fuels globally.^{155,157} Such subsidies affect the choices and the options for energy sources because real costs are not embedded in the price. The nature of the energy price might result in energy poverty, 'the absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe, and environmentally benign energy services to support economic and human development.'¹⁵⁸ This lack of choices can be the result of different causes but artificial taxes and subsidies can be a major reason. Another simpler definition for energy poverty is a situation where individuals spend more than 10% of their income on energy services.^{114,159} Such energy poverty means the consumer is unable to benefit from the available energy, making it useless and thus deteriorate energy security.¹³⁴ Last, it will be worth when talking about the nature of the pricing to notice the significance of the debate about peak oil.¹⁶⁰ The discussion is more about the increase of prices due to decrease in production, beyond the inflection point (supply is less than demand).¹³⁹ Such situations reduce energy security. As Zittel et al.¹⁶⁰ conclude, the combined peak of all fossil fuels may occur before 2020 and nuclear fuels' contribution is too low to have any significant influence. Thus, the future needs to be seen and planned accordingly. In that sense, renewable energy is the key for a cost-effective future energy system. The continuous reduction in solar energy cost is a pillar for the future if sustainability is to be achieved.¹⁶¹

The second parameter discussed in literature is the *cost of energy security in terms of supply disruption*.⁴ In other words, how much it costs if there is any disruption in a running system. The higher the cost of disruption and the more frequent it happens, the less secure the system is. Old estimates for the cost of oil

disruption in the American economy are 936 bUSD₂₀₁₆ (323 bUSD₁₉₈₀) for each 10 million barrels per day for 1 year.¹⁶² Where recent estimates show the expected cost of oil disruption in some scenarios to be between 29.5 and 31.6 b€/a for EU25.¹⁶³ Another study estimated Iraqi losses as 7 mUSD a day as a result of pipeline attacks in 2003.⁷⁷

The third parameter is *how much it costs to make an energy system more secure*. Energy security comes at a cost and it is not a question of achieving it at any cost.¹⁸ Since, this parameter is rarely addressed in literature, it is the most difficult to formalize its relationship with energy security. With its well connection to all other dimensions, it is a balance between what is paid and what the benefit is. An example of this parameter is the diversification cost; if an energy system runs only with nuclear energy and then it is proposed to be run on nuclear and solar energy, there should be a balance between the cost and the value of energy security to be attained. Many points are involved: the infrastructure cost for the whole system, the cost of environmental impact, the cost that will be paid for healthcare, the cost of military deployment to protect the sources, the cost of educating people about the action or the cost the society will pay in terms of welfare. Therefore, if the diversification step pays for all of these costs and others, it will increase energy security, otherwise, it will not. An obvious example is the estimate that the United States spends about 50 bUSD a year on security in the Middle East, without counting the costs of special operations like the war in Iraq, which costs more than 100 bUSD a year,¹⁶⁴ which in comparison to Department of Defense Homeland Security expenditures is very huge.¹⁶⁴ In addition, the estimated cost of U.S. force projection in the Persian Gulf for 1976–2007 is found by Stern¹⁶⁵ to be 6800 bUSD₂₀₀₈. The question that needs to be answered is: Is this spending justified to enhance energy security?

In that aspect, many researchers seek to find low-cost solutions that enhance energy security far from military deployment but by renewable energy.¹³⁶ As a cheap option in the long run, renewables can make the energy system more secure.¹⁶⁶ It starts with the structure of the cost and then the benefits. Mostly, renewables require capital expenditures with less operational expenditures. Thus, an energy system with only an upfront payment and almost zero running costs is considered more secure. In addition, renewables are environment friendly sources, thus reduce the carbon emission costs, making them a more cost-effective option.

From the different parameters, the threats on the cost dimension are diverse. Price volatility and

investment risks are threats to energy security³¹ because rapid changes in energy prices can disrupt the economy¹⁵⁶ and destabilize financial structures.⁶⁶ If prices change rapidly, the risk is the inability to calculate failure probabilities.⁶⁵ Another threat is the impact of energy poverty, such situations can rise internal political unrest,⁸² for example, Haiti and Cameron.¹⁶⁷

Last, the exact cost for energy security should be addressed with full consideration of all dimensions not only the price of energy disruption. As Jun et al.⁴ tried to provide an index to measure the cost of energy security, they had to limit themselves to a very narrow definition of energy security and they confessed that many other costs are not taken into their consideration. Other indexes measuring the cost are the fixed capital stock renewal factor or GDP per each percent of energy price change,⁹¹ the price's volatility,⁵¹ market costs of energy in €/MWh,⁸ economic costs of carbon price,⁸² or value of the energy not provided, such as value of lost load (VoLL).⁸⁵

Technology and Efficiency

Since technology is required for utilizing energy,¹⁴² energy security has a strong relationship to the *technology advancement*, directly and indirectly. In that sense, new technological solutions for production, transportation, conversion, storage, and distribution affect energy security.¹²⁶ Thus, new technologies provide new energy sources and hence increasing energy security. For example, introduction of new electrolysis technologies gave the energy system a new alternative energy carrier (hydrogen), apart from fossil fuel. New advancement in renewables results in more access to energy, though it is doubted by some researchers¹⁵⁶ but strongly emphasized by others¹⁶¹ to be a key for a 'more secure energy future'.¹⁶⁸ Apart from the direct impact of new technologies on energy security, indirect effects are huge. For example, advancement in surveillance technology provides early warnings of threats to the critical energy infrastructure, which diminishes the need for large troop deployment.⁷⁷

The second parameter for this dimension is to *enhance the efficiency of the energy system*.¹¹⁹ Energy efficiency plays a significant role toward achieving energy security.¹⁵⁵ The goal for R&D is to increase efficiency. It was known long time ago that increasing efficiency by technological development does not only make the energy system more secure^{40,61,114,169} but also provides a double-win for

the climate traits.¹⁵⁴ Efficiency is maximizing the output units per one unit of input¹¹⁹ by improving the performance of energy equipment or altering consumer behavior.¹¹⁴ Consumer efficiency is the ratio of energy service to the energy required to deliver that service.⁸⁵ When increasing this ratio, increased efficiency will increase availability of energy⁸⁵ for other uses. Although efficiency should be considered in energy security,¹⁷⁰ it should not be separated from other dimensions. Efficient systems will affect the cost dimension, because increasing efficiency requires investment that needs to be justified in regards to other costs.

However, the largest gain in energy efficiency is the shift to renewables and energy sector integration on basis of electricity; it was proposed very early by Lovins⁶² as a soft path instead of increasing reliance on dirty fossil fuel. In conventional thermal power plants, about two third of primary energy input is lost.¹¹³ This loss can be mitigated by using modern renewable electricity technologies, such as solar photovoltaic, wind energy, and hydropower. The transition from burning fuels for space heating toward (renewable) electricity powered heat pumps increases the energy efficiency by a factor of 3–4. The same gain in efficiency is achieved for the transition from low efficient internal combustion engine to battery electric vehicles. Furthermore, the huge loss of low efficient nuclear and coal power plants will be eradicated by high efficient solar and wind systems. This means gradual efficiency improvements of current appliances do not fix the fundamental problem of an energy system that is still based on burning fuels, which is the main reason for its poor performance in efficiency. Thus, a shift to high efficient solar and wind systems will eradicate the huge loss of low efficient nuclear and coal power plants and result in a dramatic increase in the efficiency of the energy system.

The third parameter is *energy intensity*. Energy intensity is the amount of energy required to produce one unit of GDP.⁶⁷ It represents how much energy is consumed to produce added value.⁸⁴ Energy intensity can be used to measure the efficiency of the system.¹⁷¹ Thus, to improve energy security, energy intensity should be reduced (reducing the dependence of the economy on energy).⁶⁷ However, the historical development has shown that developing countries first have to increase their energy intensity while building a modern infrastructure and on a more developed level less energy intensive investments are needed for further development.⁹³

The last parameter is *energy conservation*. Energy conservation is an inclusive term to describe

the actions that result in energy demand reduction¹³⁴ by users foregoing some of the services derived from energy use.⁸⁵ Energy conservation has a substantial impact on energy security but not automatically an enhancement,¹³⁴ because it provides a temporary demand reduction without a permanent behavior change.⁸⁵

However, technology advancement does not always lead to a more secure system. For example, cultural barriers to utilize new technologies can make them useless.¹⁷² In addition, nuclear energy and nuclear proliferation brought a huge risk to the system as its negative impacts on the society and on the environment concern many.¹²⁷ Also, the development of nuclear weapons with the mass destruction capabilities carries a huge threat to the energy security.⁷⁷ Furthermore, because of the rebound effect, enhancement of energy efficiency does not always improve energy security. The rebound effect is the loss in expected efficiency benefits due to behavioral tendency to use more energy services that are made cheaper (backfire).¹⁷³ It is generally expressed as a ratio of the loss compared to the expected benefit.¹⁷⁴ However, a recent review study by Gillingham et al.¹⁷⁵ concluded that a lot of support for the backfire hypothesis is not found due to the limited understanding of the macroeconomic rebound effect.

Although quantifying technological improvement and efficiency improvements is a difficult task,¹²⁶ some researchers tried to quantify this dimension with metric indexes, for example, expenditure on research and development,⁴⁴ share of equipment with expired service life⁹¹ or electricity distribution losses,⁴⁴ and more commonly energy intensity.^{105,171}

Location

This dimension deals with the spatial features of the energy system and its relation to energy security. Studies about energy security differ from local to global, from urban to rural, and from national to international, based on the different needs of each study.³³ Haghighi²¹ argues that energy security is not only about internal national but also about the regional security. Policymakers, on contrast, are concerned only with national energy security.⁹⁶ Therefore, many parameters are to be involved.

The first parameter is about the *energy system boundaries*. When analyzing any energy system, the location, the size, and the boundaries should be determined. Two main points are needed to be identified; first, control area, i.e., the jurisdiction within

which the energy system is to be studied, second, size and area of where the system has an impact.⁸²

The second parameter is the *location of energy source*. As discussed earlier, the existence of energy resources in a specific location can result in deterioration of energy security. In addition, the location of the resources affects its accessibility, e.g., difference between oil resources in Saudi Arabia and Venezuela, such different accessibilities cause more cost to get the energy from specific resources.

The third parameter is the *density factor*. The density factor can affect energy security positively or negatively. Although, dense systems have higher energy efficiency, better environmental performance, and better social effects,¹⁷⁶ energy resources in a small area, e.g., oil fields or oil countries are military targets, as seen in World War II (WWII).¹²⁵ Such situations reduce the energy security because it requires more protection for the transportation routes as was seen in the WW II when United States blocked oil from going to Japan.^{125,162} This example supports the view presented by Müller-Kraenner⁸⁰ in which he argues that in a decentralized system there are less pipelines and water paths to be guarded by military.

The two perspectives shape the debate between centralized–decentralized systems. Another advantage for a decentralized system is the impact the threats cause on the whole system. Centralized systems are enemy targets and thus reduce energy security.¹⁶² They are much vulnerable than decentralized systems,⁶⁵ especially if technical failure probabilities and social acceptance are taken into consideration. For example, in a centralized system, bombing of a single substation enabled a military coup in Chile.¹²⁵ On contrast, in a decentralized electricity generating system, an earthquake in one region will not affect the whole system as much as centralized facility affected by an earthquake.¹⁶² For this, Franki and Višković⁸ argue that decentralized systems that use renewable energy enhance energy security, because it combines the advantages of a centralized system (higher energy efficiency, better environmental performance, and better social effects¹⁷⁶) with the security advantages of the decentralized system. Therefore, developing decentralized renewable energy systems is the future to enhance energy security.

The *land use* is the next parameter. The concept of deforestation is usually discussed in literature. Forest that is cut to generate energy with all the negative impacts of carbon dioxide (CO₂) emissions, reduction of natural habitat, and causing visual pollution shows obvious negative impacts of energy use.⁶⁰ Furthermore, usually the landscape is altered¹³⁵ and the

land is left in an unromantic moon landscape as in lignite coal mines.⁸⁰ The food–energy nexus is a clear example of how the conflicts between the land use for energy and for food production can take place. Moreover, another point is the energy waste, such as nuclear waste.^{177,178} Currently, the waste is just stored somewhere. The storage location (which is usually designed for an extremely long term) can cause a lot of conflicts especially if it is close to human activities, because of its health, environmental, and social impacts. Furthermore, as will be seen in the culture dimension, awareness about energy technologies increased, thus a new concept evolved ‘Not In My Back Yard’ reducing the available lands for energy production. Many people refuse to have the energy generation or processing close to them, but do not show such concern for locations far from them. The concept ‘NIMBY’ (Not In My Back Yard) differs between people depending on what informative streams they are encountered with, but also whether they receive direct or indirect benefits. Thus, many people resist having nuclear or coal-fired power plants near them because of the harmful impact, but others resist renewable because of the false information that they were given about certain technologies or because of ill-balanced benefit sharing.

Another parameter is *globalization*. Since the future of energy system is seen with mutual benefiting and fair competition in a globalized world,⁷⁰ regional and international interconnection will enhance energy security.¹⁵⁵ The dilemma with such a globalized system is the definition of control area (defined by national borders with a state). The states are challenged by global processes from above, and by the forces of regionalism and localism from below.⁹⁷ However, a recent research indicates that a decentralized renewable energy system is possible without global trading of energy thus reducing risks.^{136,179}

Furthermore, the *human settlement and population distribution* play a role in shaping the energy security. As humans are the end-users of the energy, historically, they used to settle close to energy sources. However, nowadays the situation is the opposite. The energy producers should have access to more consumers to assure continuous demand. More population in one region means more market and more demand. Energy resources found in Alaska are transported to where the demand is rather than people moving to Alaska. However, such global interconnection with long distances between the energy source and end-users increases risks of energy security.⁶⁵

On the same tone, the *location’s geography* affects the energy security. For example, geography

of Strait of Hormuz has more importance for the oil pathways out from the gulf region (20% of the global crude oil trade)⁹⁰ or strait of Malacca where 80% of Japan and Korean oil passes¹⁷ and 30% of shipped oil around the world.⁹⁰ The threat of disruption is higher in smaller areas. Thus, high traffic density and less diverse rout options with more military deployment reduce energy security. On the other side, during WW II, America managed to find plenty of different routes to supply Europe with energy through the wideness of the Atlantic Ocean. Further and apart from the military consideration, dense energy industry is a threat to energy security, 97% of mankind industrial production come from fossil fuel.⁶⁰ Larger power stations tend to have complex failure modes, more difficult repairs and higher unit costs of spare parts.⁶⁵

The last parameter is *industrial intensity*. Energy intensive industries are vulnerable to energy disruption. Therefore, redistributing energy intensive industries within a country or to other countries reduce the risk to the economy and increase energy security.⁶⁶

Many indexes can be used to evaluate the location's effect on the energy security such as nuclear waste per m², environmental footprint of energy facilities or the distance for energy delivery from suppliers to consumers.¹⁰²

Timeframe

This dimension is related to how the energy security is seen. Does energy security need to be considered on a long run (+500 years) or a short term (one year or less) to provide relevant information?⁸² Moreover, what is the optimal time span for energy security to be studied? Short-term considerations attract attention of private stakeholders⁸² and policymakers.⁹⁶ For long term, key concerns are for policy analysts and informed policymakers.⁸²

On contrast, energy-related decisions made today have long-term implications for how energy is produced, stored, and used.¹²⁶ Because, the future energy system is likely to differ than today's energy system,¹⁵¹ in the long run, energy security depends on the risk management of the present.¹⁸⁰ The relationship between the timeframe and the energy has three parameters as summarized by Sovacool³²: *to look forward or backward, time an event takes to cause an impact and how long an impact lasts*.

The first parameter is to determine where to see the current energy system in *relation to the timeline*. It has the two notions of forward and backward. To look to the past and analyze how the current system

was achieved. On the other side, to look to the future and predict how the future energy system will look like to be secure.

The second parameter, *length of the event*, is related to events that occur in the system, how long an event needs to last in order to build up and be able to cause harm on the system.⁹⁷ Stress or sudden events affect the energy system differently. Long-term rising prices for energy import affect the economy differently than a sudden price hike.²⁵

The last parameter is the *length of a struggle* in the energy system due to a specific event. For example, the formation of IEA was due to the 1973 Arab oil embargo (event), but (the impact) is still seen as the continuous operating of IEA.

Wrong analysis of the system due to wrong timeframe use is the biggest threat. The enormity and longevity of the energy investments require consumers to participate actively¹²⁶ to avoid deterioration of energy security. Dealing with the threats has short-term component and a long-term component. For the short term, emergency measures such as coordination of energy stocks are needed. For the long run, policies to diversify the energy system, to enhance flexibility, and to increase energy efficiency are needed.⁶⁸

An index to determine the optimal time span would be life expectancy index,^{181,182} technology cycle,¹⁷⁰ or timely bilateral agreements.

Resilience

Resilience had a lot of discussion in recent years.^{15,183} Resilience means the ability to withstand diverse disruptions⁹³ without experiencing a change in the energy security baseline,³³ an adaptive capacity,^{36,48} or the capacity to tolerate disturbance and continue delivering services¹⁸⁴ with the same function, structure, identity, and feedbacks.⁸⁹ Yergin¹⁷ refers to resilience as security margin because in general a more resilient energy system results in enhancing energy security^{21,96} as long as other dimensions are not worsened, e.g., significant unjustified cost.⁶⁸ Thus, the whole point of resilience dimension in these definitions is the ability to function after disturbance. For this, Johansson and Nakićenović⁹³ link resilience with diversity dimension, that, if one part fails, the system switches to other alternatives. A resilient system can switch between different energy suppliers, different energy transition pathways and energy carriers, and different consumers.¹⁰²

For the energy supply, there should be emergency stockpiles.⁴⁸ These stocks, e.g., stored energy in batteries or hydro reservoirs or oil tanks, are

stored until they are needed. Creating such spare capacity enhances energy security.^{84,126} For the energy transfer facilities, the system needs to absorb the disturbance and still functions, for example, the ability to switch immediately to another fuel, other equipment, or infrastructure.⁶⁸ For the consumers' side, energy producers should be able to sell their energy to other customers if a disturbance takes place. Also, they need to have spare capacity in order to increase production when energy is more demanded.¹²⁷

The risks resilience lies in two parts, being rigid and being static. Both follow the concept of passive resilience and active resilience.⁶⁵ Passive resilient systems can bounce without breaking, trying to get back to their stable situation till the disturbance is gone. Active resilient system can learn, adapt, and profit from the change or the stress by using the events of failure.⁶⁵

Several indexes can be used to evaluate resilience, for example, emergency stockpiles or capacity margins,³⁶ spare production backup supplies and storage capacity and national emergency plans,¹⁷ resilience capacity index (RCI),¹⁸³ or ratio of total primary energy supply to GDP.¹⁸⁵

Environment

Environment is what surrounds us. When energy systems are to be considered, the environment is regarded as an important dimension. Therefore, an environmental view of energy security needs to be considered internationally.¹⁴² For that, there are many parameters to be included.

The first parameter consists of *energy resources, rate of exploitation, and location shape after exploitation*. The issue of earth resources is an important determination of the environment.²⁹ Resources should not be depleted faster than the natural ability of regeneration¹³⁵; else, energy security is reduced. In history, humans plundered the plant resources without considering the negative consequences.¹³⁵ Even nowadays, humans use 140% of the resource and absorption capacity of planet earth with a tendency to increase.^{186–188} This massive impact of human activities on planetary systems initiated even a new age, called Anthropocene.^{189–191} Rebalance of human activities to the limits of planet Earth had been already identified by Meadows et al.⁶⁰ but it took long time to find first indications that it could be done without shrinking population or economic activities, but on basis of 100% sustainable and renewable energy systems.¹²³ Such fast exploitation of the resources makes the land useless for food

production with projection to be severely compromised by climate change.¹⁵⁴ Last, energy resources in many cases are hazardous material³² with negative impacts on the environment and the people using it.

The second parameter is the *extraction methods*. The extraction methods themselves should not cause harm to the environment. In addition, the methods for the energy transfer should be secure environmentally. An obvious example is the oil spills in different oceans, killing the sea environment (flora and fauna). Energy security is deteriorated by such events. The method of extraction for wind energy depends mostly on wind turbines that can affect avian mortality.³² In addition, CSP (concentrated solar power) has the threat of high temperature spots that might cause death to flying animals. However, the death of birds per generated energy unit is substantially higher for coal-fired power plants due to the very harmful heavy metal emissions.¹⁹² Furthermore, extraction of nuclear energy generates a lot of radioactive waste. The disposal of such waste is an unavoidable dilemma when it comes to energy security.¹⁹³ And recently, the fracking technology of shale stones to extract shale gas is very dangerous for the environment because of the used chemicals and the need to destroy the earth layers all the way down to the shale.¹⁹⁴

The third parameter is the *outcome of the energy usage*. It is the most noticeable impacts of humans using energy systems. The CO₂ and greenhouse gas emissions, global warming,⁶⁰ climate change,^{106,195} heavy-metal emissions, water contamination,⁸⁷ acidic rain,¹⁰⁶ air pollution,¹⁹⁶ and indoor suffocation¹⁹⁷ are among the environmental challenges resulting from energy systems. One example of energy use impacts on the environment is nitrous oxide production. Nitrous oxide diffuses up to the stratosphere, where its photochemical products attack the ozone layer allowing harmful ultra violet (UV) irradiation to penetrate to the earth.⁶⁵ For these considerations, the energy system is more secure with less harmful environmental impacts. The developed concept of ecological footprint measures the impact of humans' consumption including energy and food.^{186,198,199} It is simply, the amount of nature that humans occupy in order to live with modern consumption of energy.²⁰⁰

The fourth parameter is the *effect from climate conditions and climate change on the energy security*. Some natural events happen regardless the energy system, such as earthquakes and volcanoes whereas some disasters occur because of humans activities as a result of climate change.¹⁹⁵ These events affect energy systems profoundly.¹²⁶ The effect can be positive and can be negative. For example, the environmental conditions of climate change can enhance energy

security by reducing heating demand, providing new trade sea-routes, revealing new energy exploration locations for oil and gas, generating the possibility for more biomass converted from increased CO₂ levels and utilizing more of wind energy.¹²⁴ As Johansson and Nakićenović⁹³ describe, energy security can be enhanced by the new opened marine transportation routes as a result of a retreat of Arctic Ocean. However, on the other side, the negative impacts are seen to overthrow the positive ones by orders of magnitude, that is, environmental conditions can deteriorate to a point on which societies cannot function anymore and nations reach the point of collapse,¹¹⁴ even humans cannot live outside anymore.²⁰¹ Such situation impinges energy security and many examples can be drawn up. If the entire inland ice of Greenland melts due to climate change, the worldwide sea level will increase by 7 m.⁸⁰ Taking in mind that most of the worldwide assets are located on shorelines, the severity of such event is clear. Even if such an event will not have an impact on the society and the assets, rising sea levels will require redesigning and reconstruction of the energy systems,¹²⁶ which will cause incredible high cost. The example of societies becoming close to the collapse point is what was seen in Hurricanes Katrina and Rita (August and September 2005) which affected the electricity and gas energy systems.^{17,202} Therefore, tougher and unstable climate conditions reduce energy security. Thus, weather patterns are a major energy security concern for the global community.¹⁵⁵ The German Advisory Council on Global Change reported the impacts of the climate change on: freshwater resources, food production, storm and flood disasters, and climate migration.²⁰³ All these four have direct and indirect effects on energy security of the energy system. Scarcity of freshwater will lead to conflicts and water wars destroying energy systems. Deterioration of food production will result in conflicts that are initially limited to local levels then worsened to destabilize neighbor countries through refugee flows, arms trafficking, collapse of social systems, and violent conflicts. Storms and floods resulting from climate change destroy energy routes and transfer infrastructure, generation, and extraction facilities; thus, the energy security of the system is deteriorated by climate change. The climate migration is predicted to be a huge issue, because climate change induced refugees fleeing tough conditions will head toward safer places, which will result in more demand and pressure on energy resources.

The fifth parameter is the *energy-water nexus* (interdependence between water and energy).^{204,205} An important part of the environmental dimension for energy security is water. An increase in energy demand will lead to an increase in water demand and vice

versa.¹¹¹ Water is required for energy generation, heating, and extraction of natural resources. Also, water needs energy for its extraction and treatment. Therefore, there should be a balance between the consumed energy to produce drinkable water and the water needed for energy generation.²⁰⁶ A secure energy system is the one that achieves that balance. Thus, many researchers try to find that balance. For example, Caldera et al.²⁰⁷ propose renewable electricity based sea-water desalination to achieve the balance.

The threats to this dimension are diverse including, but not limited to, the impacts of climate change such as storm surges.¹²⁶ The impact of climate change and the failure of good adaptation policies are considered in 2016 as the most threatening risks for years to come.²⁰⁸ Another threat is the ignorance of the relationship between the environment and the energy system; some researchers argue that there should not be an environment dimension for energy security.⁹⁶ In that view, climate and energy security are district concerns and should be addressed by different communities of policymakers because of the lack of proof that climate change would necessarily reduce energy security.¹²⁴ Our stance is different, environmental concerns should be a dimension in energy security, because there are risks and threats related to the environment involved in the energy system. One obvious argument to support our point is the radioactive nuclear waste. Many researchers found that there are a well-connected relationship and sever impacts from nuclear materials (as part of the energy system) on the environment.^{209–211} Also, radioactive waste must be managed properly so as not to cause harm to people or permanent damage to the environment.²¹² But, until the moment, there is no any satisfactory solution to nuclear waste problem.^{32,213} The energy system strongly affects the environment and thus the environmental dimension is to be included in the energy security discussion. As Jun et al.⁴ put it nicely ‘No form of energy production or use is without environmental impact.’

Last, many indexes are used to evaluate the environmental dimension. For example, generation of energy related radioactive waste, lifecycle carbon emissions, or water withdrawals per kWh,³⁶ water stress,¹¹¹ CO₂ emissions per capita,³⁰ and carbon intensity, i.e., CO₂ production per kWh consumed^{171,214} are all possible indicators. One indicator that was addressed before is the ecological footprint.^{215–217}

Health

From the surrounding (environment) to the main concern (humans), energy security affects and is

affected by the health of people; healthy life is a universal human desire.⁶⁰ In this sense, there are two main parameters for the health dimension with many points within each parameter.

The first parameter is the *impact of healthy individuals and society on the energy system*. Starting from people who are involved in energy production, they must be in a good health to do their tasks. Healthier workers have a higher productivity,^{218,219} and thus the energy system will function more efficiently and hence enhance energy security. The second point is the health of people involved in the transfer section. All energy sector employees are to be concerned. Less sick absence means less expenditure on healthcare. In addition, productivity of energy sector workers increases with healthier workers. The last point in this parameter is the impact of healthier consumers. Healthier consumers use energy more effectively and thus enhance energy security. A healthier society reduces the healthcare expenditure and hence enhances the national economy, which in return, will make the energy system more secure. They can spend more on sustainable options and thus more efficient systems. Alternatively, they spend the money on developing new technologies that enhance energy security.

The second parameter is the *impact of the energy system on the health of individuals and societies*. If the energy system affects national and international health negatively, its security is deteriorated, and vice versa. In this parameter, there are three categories of people affected by the energy system. People involved in the energy industry in any of its stages. End-users and consumers of energy services. Last, the national and international society that is affected by the energy system even if they do not use it.

In general, effects on workers in energy industries are the second biggest health impact globally.⁹³ If the energy exploitation affects workers' health, it reduces energy security. Many examples are there, for instance, though negative effect of nuclear energy is aimed to be avoided,¹⁸⁴ many workers suffer long-term diseases. Furthermore, German Federal Constitutional Court decision about the accelerated nuclear power phase out in Germany is quite important for future nuclear investments. The court emphasized in its decision that phasing out of nuclear plants could be even accelerated for the common welfare, to protect life and health of the population, to protect the environment and future generations.²²⁰ Workers in the coal extraction mines suffer from different diseases. Coal exploitation releases tons of toxic materials that contaminate water and impair health.²²¹ In addition, 70% of rail traffic in the United States is

due to coal transportation, and rail transport is associated with accidents and deaths.²²¹ Also, most of the energy carriers are hazardous materials,⁶⁵ threatening energy sector workers.

The second group is the consumers. Many use fossil fuel and dirty energy for their daily life uses. The word dirty energy is derived from the outcome of the energy use that is usually ashes and emission (in addition to heat and light). Emissions result in cases of suffocation and long-term cancer.²²² Such direct impacts on the consumers deteriorate energy security.

The last group is the national and international society. More than 5% of all health issues around the world are due to the current energy system, in addition to 5 million deaths per year.⁹³ Even if these individuals are not involved in the energy system, they are affected. Many obvious examples exist; nuclear waste reduces societies' health.⁶⁶ Chernobyl accident in Ukraine or Fukushima accident in Japan affected millions of people. Heavy metal emissions from a coal-based energy systems result in cancer and other diseases.²²² Since energy systems affect everyone in the society: doctors, teachers, soldiers, and so on, the whole society loses its functionality if these people are not able to carry on their duties due to negative impacts from the energy system.

The threat to this dimension is the lack of recognition and less awareness of the connection between health and energy security and thus no actions are taken to solve the problems. The reasons for this lack of awareness is subsidies as summarized by Coady et al.¹⁵⁷ For example, additional 30–170 million people will suffer from malnutrition or undernutrition by 2080²⁰³ if the problem of climate change is not solved. On the other hand, if the problem is solved, annual benefits (less expenditure on healthcare systems) range from 5.7 to 210 mUSD.²²³ The solution is promoted by many researchers to be renewable energy.¹²³

Examples for indicators in this dimension are: health spending per capita with the United Nations Human Development Index,¹⁸² the infant mortality rate (IMR),²²⁴ or emission per capita.^{221,223}

Culture

Culture is an important aspect of energy security.¹⁵⁴ In general, cultures affect how people shape, react, or deal with specific issues. In some literature, it is referred to as social acceptability²²⁵ or public participation.¹⁵⁴ On the other side, events and conditions can change some parts of the culture.²²⁶ In that,

energy systems and energy security are not an exceptions.

Since energy system instability has a cultural and social nature,⁹⁴ the first parameter is thus *how cultures affect energy security*. Humans' effect is seen in the three stages of energy systems (production, transfer, and consumption). In the production stage, energy poverty will encourage societies to produce energy anyhow to cover their demand even if such energy resources cause a lot of harm on the environment or the health (reducing energy security).¹² Another example of how can culture affect the production stage of the energy system is the Bolshevik revolution in 1917. The revolutionary spirit and culture made the workers to stop the oil production from Baku's oil fields.¹²⁵ Nationalization of energy production facilities has affected and will affect the energy system and its security.¹²⁵

The way how energy flows is affected by public and private suppliers. If the culture is more materialistic, suppliers tend to concentrate on meeting the energy demand from industrial consumers at the cost of the poor with low demand,²²⁷ this attitude will hinder energy security of the other part of the society, the poorest.

When it comes to the consumption side, liberal individuals are more likely to engage in a responsible consumption behavior to achieve energy security.²²⁸ Social justice promotes secure energy systems that benefit the masses rather than the few elite.⁸⁸ Furthermore, from demographic point of view, age and gender play a role in the consumption attitude in regards to energy security.²²⁸ For example, the youngest groups show that energy security is in their top priority in comparison to elderlies.²²⁸ These findings have put more pressure to find solutions for the demographic transition into older societies.²²⁹ Having more young citizens will alter the energy consumption into a sustainable scheme. The solution that many countries opt to is to stabilize child/woman ratios at around 2.1, which leads automatically to a stabilized population.^{122,230,231}

In the three stages, *cultural acceptance* of new laws that enhance energy security (e.g., CO₂ tax) is a necessity.¹⁸⁴ For example, NIMBY movements in some areas¹⁰⁶ threatened wind power advocates³² and reduced the ability to make new regulations regarding wind energy, solar energy, or nuclear energy, reducing the diversity of the system and thus deteriorating energy security.

The second parameter is *how energy conditions can shape or change cultural behavior*. From the history, it is seen how the discovery of resources

changed civilizations and cultures.¹³⁵ Disruption of energy production that leaves societies without needed energy cause serious social conflicts,⁷⁹ with immediate negative results.²⁵ Simply having to wait in line to buy gasoline has led some Americans to shoot each other.⁶⁵ Wealthy and powerful societies achieve energy security easier than poor ones.⁷³ Such financial consideration alter energy consumers' purchasing behavior.¹¹⁴ Furthermore, energy excess will change habits related to energy consumption⁸⁷ and affect the social atmosphere in which identity is developed.²²⁸

The threat to this dimension is the psychological effect.⁶⁶ Societies and individuals are manipulated by media, which presents a distorted reality, misleading conclusions, or even wrong facts. Last, one common index to describe the culture dimension is the human development index (HDI).¹⁰⁵

Literacy

Knowledge and access to information is an important dimension for energy security.²³² As humans are concerned with the energy security of the system, they should know about it. The literacy of energy security has three levels: information should be available (provided or taught), information should be adorned so people will have the desire to learn, and then people use this information in order to achieve energy security. In order to achieve energy security, the literacy should be on different measures: features of the energy system, how the system works, how it affects the society, how it can be improved, and more importantly how to use it securely. Energy literacy gives homeowners more control over their own energy security.³³

The first parameter is the *availability of information*. Information should be available (provided or taught) in order to promote energy security.²⁹ Also, the quality of the information matters, high quality information supports energy market to well function,¹⁷ which enhances energy security. Furthermore, it is not enough to have market information alone; public awareness should be priority in order to enhance energy security. Moreover, awareness alone is not the goal, there should be structured educational programs about energy and energy security to supplement the understanding of the system and how to utilize it effectively.²¹² For example, the information for end-consumers about which devices are more efficient and which are not.

The second parameter is related to *how the information is presented and how the knowledge is*

spread. Information should be adorned so people will have the desire to learn. In that way, governmental support for the development of the energy system is needed.⁴⁷ Adequate funding of research and development in the field of energy is the way to achieve energy security.¹²⁷ Such governmental support and financial support is incentive for people to learn about energy and energy security. For example, introduction of ecolabeling schemes and regulation by the government encourages customers to consider the environmental dimension of energy security in their decisions.⁸⁵ Also, disseminating market information enhances energy security¹²⁶ by allowing customers to react effectively. The Japanese Top-runner program is one example of presenting the information about energy application and efficient regulations to customers.^{233–235}

The last parameter for literacy is the *use of energy information in order to achieve energy security*. In general, individuals with higher levels of education are more likely to have responsible attitudes in regards to energy security.²²⁸ Awareness, knowledge, and education result in trained workers for the energy system to be run securely.²³⁶

Most of the threats to the energy system in the dimension of literacy are the workforce constraint.³⁵ That lack of qualified employees might cause many disruptions in the system.⁶⁷ Such scarcity of talents affects energy infrastructure development negatively and thus deteriorates energy security.¹⁵⁵ Apart from the workforce constraint, lack of enough market information that allows for competitive consumer decisions can result in energy market failure,²³⁷ with all of the negative impacts on energy security. Lord Nicholas Stern clearly pointed out that ‘The existence of climate change is the largest and widest ranging market failure ever seen.’²³⁸ This market failure is a result of poor policy and regulations because of lobbyism and corruption. However, a major part is the lack of needed knowledge delivered to end-customers.

Some researchers suggest public resistance to new power generating units or annual cost of car accidents³⁶ as indexes for literacy. Others suggest innovation research investment.¹⁴² However, an equally informative index would be the number of courses about energy systems at schools.

Employment

The relationship between energy security and employment is a two-way relationship. Higher unemployment rates can be a result of a less secure energy system. When energy prices skyrocket over the energy poverty threshold (energy security

deteriorates), a lot of pressure is put on nominal wages.²⁵ Thus, a higher unemployment rate may happen.²³⁹ However, different countries might experience the situation differently, so that steadily but moderately increasing energy prices may lead to more innovations in energy efficiency, even increasing the employment and the energy security. When energy security is deteriorated by disruption, many jobs can be lost. For example, in November 1976 in the United States, over a million people were laid out of work in 20 states.²⁴⁰ The cost of this situation was 435 mUSD₂₀₁₆ (100 mUSD₁₉₇₆) in unemployment benefits. Therefore, a more secure energy system may lead to higher employment rates.

On the other hand, the employment rate can affect the energy security. A higher employment rate means revenue generation opportunities for individuals,¹⁷⁰ stronger purchasing power, and more financial resources directed to the energy system.

Furthermore, the employment rate and conditions in each stage of the energy system (people who work in production field or energy transfer) affect energy security. For example, in 2010, there were 9.1 million jobs globally related to the provision of electrical energy alone.^{151,241} Having the experts to run the system efficiently is considered to enhance its security. Bad conditions for workers reduce energy security because of more exposure to risks. Finally, employment in the energy sector is a good example for an index for this dimension.^{232,242}

Policy

There is a strong relation between policy and energy security,⁷⁰ thus, energy security cannot be separated from political interests.¹⁵³ Because achieving energy security is an important goal,⁵¹ its concerns affect the way how the decisions are made.²⁹ Therefore, energy politics will determine our survival as we know it on our planet.²²⁹

The first parameter is the *relationship between energy security and the political system, its stability and its internal and external relations*. First of all, a solid political structure is needed to achieve energy security.⁷³ The political system can be located in between two extreme ends; total democracy in which individuals and societies decide for themselves (the decision is made following the citizens’ will), to a total dictatorship in which all the decisions are taken by one person, a group, or a party without bearing in consideration the citizens’ will.

Theoretically, in democratic systems, majority makes the decisions; with representatives from the different sectors in the society hence ensuring citizens’ will.

In such systems, energy security is clearly seen as the responsibility of the state⁹⁷ that represents individuals. However, such a system has a threat of being overdominated by one view of energy security resulting in underestimating the other dimensions. For example, if left-wing parties are in power, the social dimensions of energy security will have more importance than the cost dimension. Even within the democratic approach, there are the presidential model and the parliamentary model where the decision power is in different hands resulting in different estimation of different dimensions of energy security. On the other hand, in a dictatorship regime, the decision power is with a person or a group, without any representation of citizens' will. Therefore, energy security dimensions that are related directly to the society are typically not considered, resulting in a high probability of losing security grounds for the energy system.

The type of political system affects how the country manages its foreign relationship.¹⁷ The foreign relations range from mutual dependence and cooperation⁸⁰ to a total dependence on a certain ally.²⁴³ In many cases, democratic systems seek to benefit their societies when they make their relations, but on contrast, dictators tend to make the relations based on their own interests relying more on similar dictator systems and comforting other nations.²⁴⁴ In that sense, converging national interests is needed to attain energy security.⁹² Such orientation of the political system can result in political interventions from other countries and organizations, either positively or negatively. Embargoes and sanctions reduce energy security,⁸³ whereas energy treaties and agreements enhance energy security⁶⁷ by fostering political strength and stability.

Down the way, after the political system is defined, the second parameter is *regulations* that affect energy security. In general, regulations swing between free markets in which practicalities are determined by market mechanisms (e.g., supply-demand balance) or controlled markets where the procedures are determined by one authority.¹¹⁴ There are supporters for both sides, for example, Barton⁷⁰ argues that, stricter law and more regulations and control enhance energy security, because free markets usually look for short-term profits⁶⁷ and produce harmful emissions that lead to the death of citizens. However, on the other side, Chester²⁶ and Lakić¹⁵³ consider liberalization of the energy market to increase energy security, because a regulated market with a lot of subsidies for certain energy services promote irrational use of energy, let alone societal lack of responsibility to use energy efficiently. Nevertheless, less regulated markets promote irrational use of natural resources that leads to harmful emissions and high societal costs.

Supporters of more regulated markets use different arguments, e.g., obligations to hold reserves²⁴³ will create incentives to drive changes in consumption patterns.²²⁹ Such standards can be translated as promotion of certain energy services or technologies⁸⁵ to enhance the energy security. On contrast, energy subsidies are considered to be unsustainable energy security policies¹⁵⁵ because they channel investment,³² specially for fossil fuels. An example of panic resulted from subsidies and its unsustainability is what was seen in 2015 in Mexico and United Arab Emirates in which low oil prices forced subsidy reforms.²⁴⁵ However, if subsidies are meant to bring the system back into balance like subsidizing clean renewable energy (e.g., solar energy), they can be considered a sustainable option (reforms in Mexico), in particular, all energy technologies had been heavily subsidized during their introduction phase. Although they channel the consumers' choices but that is needed because big oil companies that control the oil industry care about profit more than a sustainable society. For example, there is a 4700 bUSD post-tax subsidies and 333 bUSD (around 5000 bUSD total) of public means annually allocated to subsidize fossil fuels globally (coal is the biggest source of post-tax subsidies then petroleum).¹⁵⁷ This amount of subsidy is used directly and indirectly to channel consumers toward fossil fuel, whereas they could be used in other investments³² such as new clean technology, improving health and education or improving public infrastructure.

The subsidy is the most important part of the regulated market. As reported by Coady et al.,¹⁵⁷ the subsidy of coal, oil, and gas is not sustainable and reforms should take place. Furthermore, they calculated the benefits in terms of reforms that cut subsidies from fossil fuel. The results show that the world can produce more than 3000 bUSD in benefits for fiscal balances, environment, human health, and economy.

Based on this discussion, our view is that each piece of regulation has to be analyzed separately in order to determine how it affects energy security regardless what market model is to be used. There should be a combination between the two models, a combination that has a mere purpose of enhancing energy security, using such a combination promotes energy security.¹¹⁴ For example, a free market model does not mean enhancing energy security if it allows the use of coal as a cheap option with all the threats coal holds for environment and health. However, a more liberal market where the cheapest energy option is clean, renewable energy will promote energy security. On the other hand, imposing

governmental tariff on energy imports will reduce diversity and hence reduce energy security. However, a ban on building coal-powered electricity generation plants will accelerate the transition for alternative cheaper and cleaner options, which is seen nowadays

The third parameter is the *governance of the system*, how the regulations and the decisions are applied. The implementation of the regulations is meant to enhance energy security.²⁹ The typical situation to be expected is that the governance follows the regulations determinately. However, sometimes the situation diverges from that situation in two paths: if the regulations are made without the citizens' will, people might pay no heed to the regulations and act in inconsistency with the regulations. For example, people might find climate standards and measures too expensive; especially if they are made by a government that does not represent citizens' will (autocratic systems). The other option is to repeal against elected persons who made the regulations¹²⁶ and choose others (democratic systems). Another example is the construction of nuclear power plants in regions where citizens' will is against nuclear energy but supporting renewables. This might lead to less cooperation between the society and such power plants; for example, society might boycott buying electricity from nuclear power plants causing its bankruptcy or force the government to phase out nuclear energy, which happened recently in Germany. The second path is applying the regulations selectively by responsible persons to attain their own benefits.⁷⁷ An example of such a corruption that deteriorates energy security is the nuclear waste buried in some African countries. Regulations prevent nuclear waste to be buried in the country but because of the corruptions, some people in high positions manipulated the regulations for a huge payment to allow this waste.

The importance of policy dimension makes its threats and risks a key concern for energy investors.¹⁵⁵ Political uncertainty causes a threat to energy security.¹⁴⁶ Corruption and transparency affect the energy system. Whatever the political system and the regulations are, corruption and intransparency deteriorate energy security.⁷³ Although, Elkind¹²⁶ argues that policymakers and state's officials must be required to take a Hippocratic Oath, hardly, any system is lacking so much transparency as the energy system.⁸⁰ In a dictatorship system, energy revenues facilitate corruption, establish privileged links of power, and reduce motivation for good governance resulting in negative impacts on energy security.²²⁹ In a democratic system, the situation is slightly better because the public monitor officials, but even though, many researchers are skeptical about it. Müller-

Kraenner⁸⁰ claims that 'like oil and water, oil and democracy do not mix well.' They do not coexist.²⁴⁶ The interests of the energy elite are in many cases against the interests of the population and can lead to policies for their own benefit¹⁵³ even in democratic systems. In such cases, the citizens' will is not followed. That is not only a threat for the energy system, but also a threat for the whole social and political system. In Organisation for Economic Co-operation and Development (OECD) countries and in particular in some European countries, there is no clear political executing, regardless the overwhelming citizens' will and strong support to shift into renewable energies as reported by Knebel et al.²⁴⁷ The reasons are not obvious but may have to do with lobbyism, vested interests, and lack of democratic values.

Leading and driving of the interests of societies is the second major threat for the policy dimension. The use of energy security to promote certain policies is seen as a 'carte blanche' to achieve political goals that fit the elite by whatever means, even military.⁷⁷ Leading public opinion to think about an issue affecting energy security in a certain way in order to legitimize the use of military force to attain goals, that could otherwise not be attained, is the concept of securitization.⁷⁷ This will be also discussed in the next section. Securitization is a huge threat to energy systems because it makes policy and actions to underestimate other factors, all to satisfy the elite.¹⁰⁶

Last, some numerical indexes for this dimension are subsidies and standards regulations,⁸² transparency indexes, political stability, World Bank's Worldwide Governance Indicator,⁴⁰ and energy efficiency standards.²²⁴

Military

Military is usually used to exercise power in order to achieve certain goals. Energy is crucial in military⁸⁴ and their relationship has many parameters to be addressed.

The first parameter is the use of *energy resources for military purposes*. Using jet fuel in air-jet fighters (in average two barrels of crude oil are needed to make one barrel of military jet fuel²⁴⁰), electromagnetic lasers in location determination or nuclear energy in nuclear weapons are among the needs of modern military forces. Therefore, having a functional military to protect the energy system and increase the energy security needs a lot of energy. To give an overview of how much energy is needed for military, Smil²⁴⁸ states that about 5% of all United States and Soviet Union energy consumption between 1950 and 1990 went to weapons' development.

However, the use of energy in the military can reduce the energy security of the system especially if the casualties of that use are big. For example, the use of nuclear weapon in a military operation affects the environment negatively, thus, reducing energy security. Furthermore, as many think war is not the best way to solve humanity's problems, the cost for using energy in conflicts is not justified.

The second parameter is the 'Militarization' concepts of energy security. Principally, militarization is more involvement of military forces to affect the energy system as an object to have the wanted effect. Klare²⁵⁰ argues that a huge competition will take place in 21st century where wars will be fought over resources not over ideology. The case has been that nearly all cross-border wars and civil wars in 21st century that have taken place during the past two generations are due to energy resources.²⁴⁸ In that way, energy resources are a significant factor causing military conflicts.¹²⁷ Therefore, in this parameter, military is used as a mean to serve higher ends⁶⁵ by protecting, capturing, or destroying energy system composition (resources, transportation routes, or infrastructure). Although, Deutch et al.²⁰² argue that energy infrastructure cannot be defended by military means, however, many countries have devoted large resources for securing critical energy infrastructure.⁷⁷ In our view, infrastructure still needs to be protected by military forces because it constitutes an attractive target for terrorist acts,⁷⁷ as will be discussed later. For example, in 1990, Iraq attacked Kuwait in order to control oil fields¹²⁵ and in WW II the Germans attacked the oil shipment lines in the Atlantic Ocean. Another example is the installation of ice breakers to the Canadian navy in order to support its claims about natural energy resources in the Arctic.⁸⁰ In that sense, the energy system was the goal of the military operation in order to reduce the security of the opponent or increase the energy security of the attacker.

The third parameter is the *use of energy as a mean in a military conflict to achieve political objectives*.¹²⁹ One example is what was seen in the WW II, when the United States deliberately restricted energy exports to Japan to force them withdrawing their military forces from East Asia.¹²⁵ This concept became to be known as 'Energy Weapon.' Although there is a debate how effective the use of energy weapon is, under certain circumstances, it will achieve its goals.¹⁴⁸ However, nowadays, there is a greater confidence that successful use of energy as a political weapon is relatively limited.⁹⁰ Also, sanctions to stop buying energy from specific energy producer can be considered as energy weapon.⁹⁰

The fourth parameter is the *destabilization factor*.¹²⁹ Energy systems can destabilize societies resulting in conflicts and military operations taking place. Many points can be seen within the destabilization parameter. The resources curse which was mentioned in the availability dimension can result in military involvement, such as civil wars, unrest, military coups, and governments being forced out, which were seen specially in 1950s in the Middle East because of oil resources.¹²⁵ Another point of the destabilization factor is the military involvement as a result of environmental deterioration. A good example is Easter Island where deforestation caused military involvement and violence.²⁵¹ Furthermore, terrorism funding¹²⁶ using energy revenues for fueling military conflicts 'Economies of violence'⁸⁰ is another point of the destabilization factor, e.g., Iran funding Hezbollah.³⁶

When threats and risks on the energy security are to be discussed the first threat to mention is 'Securitization.' Securitization is a theoretical term that is used for energy security nowadays. Securitization is presenting a public issue to be as an existential threat that requires extreme actions out of the political normal procedure.²⁵² Securitization leads to legitimize the use of military force in order to attain goals that could otherwise not be attained.⁷⁷ An example is the issue of oil supply, as the United States saw the continuity of oil supply as a national priority thus deploying its military in the Gulf.

The second threat is terrorism and piracy that impose a huge threat on the energy system.²⁵³ For example, Al-Qaeda threatened to attack global energy critical infrastructure.¹⁷ Terrorist attacks usually have temporary effects and their damage is rapid, but their effect on the economy is vast.¹⁴⁵

The third threat to the energy security within the military dimension is the impact of postmilitary operations. The remaining of wars is a threat to flora and fauna (deteriorating energy security).⁸⁰ Such military operations destroy energy infrastructure, deteriorate health, and damage environment.³² For example, Soviet and German gas grenades were left after the WW II in the field reducing security of that region.

The last threat within military dimension is its relations to other dimensions. Use of military is always tremendous, expensive, and cause a lot of visible and invisible casualties on the economy, the environment, and the society.⁶⁷ Therefore, the exact effect on energy security cannot be always positive. There should be a balance with other dimensions. For example, in the United States, total funding for Iraq reached about 600 bUSD after 6 years of the Iraq war; in comparison to Department of defense homeland security efforts of

50 bUSD.¹⁶⁴ In addition, the estimated cost of American force projection in the Persian Gulf for 1976–2007 is found by Stern¹⁶⁵ to be 6800 bUSD₂₀₀₈. Such imbalance between the dimension is debatable whether it pays off the expenses or not.

Energy consumption for military purposes²⁴⁸ or military expenditures¹⁶⁵ can be numerical indexes for this dimension.

Cyber Security

As nowadays all energy infrastructures depend on the digital support¹⁸⁴ with future prediction of more digital devices,²⁵⁴ the digital dimension is important for energy security. Although, the paradigm is of another nature than the physical one, cyber security affects the physical energy system severely. The importance of this dimension, though rarely discussed in literature, is uncountable. Computers and digital programs control the whole energy system (production, connections, and consumption).²⁵⁴ Destruction in the cyber dimension can cause tremendous economic loss.²⁰² Even anticipation for disruption such as the common Y2K computer bug of January 1, 2000, can do the same.¹⁷ Therefore, any failure in the cyber dimension will cause a certain impact on the system.

The first parameter of cyber dimension is *connectivity*. Because energy systems are controlled by automated digital programs⁹³ and are connected to the internet.²⁵⁴ In addition to self-failure, cyberattacks on energy systems are growing²⁵⁵ and thus cyber security is becoming a pacing issue.⁹³ Such cyberattacks are easier and safer than causing the same harm by physical attacks.²⁵⁶ Digital programs of the energy infrastructure are an attractive target for terrorists because they are 'soft,' easily destroyed, or incapacitated by a cyberattack.²⁰²

The second parameter is the *software being used*. Supervisory control and data acquisition (SCADA) and industrial control systems (ICS) have real-time control and monitoring of energy facilities and equipment but they are vulnerable to threats.^{155,202} In many cases, failures of the digital system are self-failures as what happened for Soviet natural gas pipeline in Siberia.⁸⁷ The huge blast and detonation of the pipeline was thought a nuclear explosion. However, after the investigation, it turned out, there was a malfunction in the computer control system. On contrast, in many cases, the system failure is caused by virus attacks. For example, in January 2003, the Davis-Besse nuclear power plant in Ohio was offline for 5 hours because of a virus attack on its SCADA system.³² Another example is

what was reported by Shalal²⁵⁷ that some power plants in South Korea and in Germany have been targets for disruptive cyberattack.

For this, the last parameter is the *information technology (IT) skills, how to keep a system functioning against the cyber threats and attacks?* The more secure the digital system is, the more secure the whole energy system is. But how to achieve that? Escribano Francés et al.²⁵⁶ refer to a main point: the IT skills. Thus, if the skills are exploited in designing the system, energy systems will enable real-time monitoring, decision optimization, and remote control.²⁵⁸ On the other hand, if the skills are available for the attackers, the energy systems will be vulnerable, for their control computers being disabled, for their instruments being rested or for the calibrations being biased as pointed out very early by Lovins and Lovins.²⁴⁰ Examples of skilled attackers targeting the energy system are many: Lithuania faced a cyber assault by pro-Russian hackers in 2008 because of its unilateral veto on an EU energy partnership deal with Russia,²⁵⁹ the 2014 cyberattack on the nuclear power plants in South Korea,²⁶⁰ the Shamoon cyberattack in 2012 on Saudi Aramco, the largest oil producer in the world,²⁵⁵ and attacking Iranian nuclear facilities with 'Stuxnet'.²⁶¹

When it comes to threats and risks of this dimension, there is a lot of improvement needed in the system. Many parts of the transmission and distribution grid system were 'developed' without concern for cyber security.²⁶² For example, smart meters were developed to cope with the development of smart energy systems e.g., smart grid; however, many consumers and service providers have shown concerns about their information security. In the smart grid systems, the most vulnerable part is the transmission part,²⁶³ in which meters are easily vulnerable to hackers' attacks.²⁶⁴ Also, there seems to be a low level of awareness of the resulting impact of the cyber threats.¹⁵⁵ And the system vulnerabilities of SCADA systems are highly underestimated, rarely disclosed, and the incidents affecting them are hardly reported.³² Finally, an example for indexes that can be used to evaluate the cyber security of a system is the rate of cyberattacks on a certain system or the economic losses resulting from a specific attack.

CONCLUSION

After this exploratory dive into energy security, this paper tracked the definition of energy security along

TABLE 1 | Summary of Energy Security Dimensions and Parameters

Dimensions	Parameters
Availability	Existence of resources Existence of consumers Existence of means of transport (access)
Diversity	Diversity of sources Diversity of fuel (energy carriers) Diversity of means (technologies, transportation) Diversity of consumers
Cost	Energy price (consumers, producers, pricing system/subsidies, energy poverty, peak oil, and stability/volatility) Cost of disruption Cost of securing the system
Technology and efficiency	New technology advancement Energy system efficiency Energy intensity Energy conservation
Location	Energy systems boundaries Location of energy source Density factor (centralized/decentralized) Land use Globalization Population settlement and distribution Geography Industrial intensity
Timeframe	Timeline Length of the event Length of the effect (struggle or impact)
Resilience	Adaptive capacity
Environment	Exploration rate and resources' location Extraction and transportation methods Outcomes from energy use Impact resulting from environmental change Relationship to water
Health	Impact of people's health on the energy system Impact of the energy system on health of (energy sector workers, consumers, and international society)
Culture	Cultural effect on the energy system [production, connection, consumption, cultural acceptance (NIMBY, Not In My Back Yard)] Energy conditions shaping cultural aspects
Literacy	Information availability (quality, market information, public awareness, and structured educational program) Information presentation and provision Usage of energy information
Employment	Effect of energy security on unemployment rate Effect of employment rate on energy security
Policy	Political system, democracy/dictatorship (nature, stability, citizen's will, and internal and external relationship) Regulations (liberalized and controlled market, rules, and subsidies)

(continued overleaf)

TABLE 1 | Continued

Dimensions	Parameters
	Governance (flowing the rules (transparency), following the rules selectively, not following the rules, corruption)
Military	Energy use for military purposes Militarization Energy as a mean in a military conflict (energy weapon)
	Destabilization factor (resources curse, environmental deterioration, and economies of violence)
Cyber security	Connectivity (Cyberattacks) Software use (Supervisory control and data acquisition, SCADA, program failures) IT skills

the history through scientific literature review as summarized in Table S1 of the Appendix S1. In total, there were 66 different definitions, found in 104 literature sources (peer-reviewed papers, scientific journals, and books). In tracking the definition of energy security, it was obvious that the repetition of some definitions in many places, implying a wider acceptance for some definitions than the others. However, the conclusion out of the literature was that there is no consensus about how to define energy security or what to be included in the discussion. Therefore, the efforts were not constrained on the literature review of the definitions but rather continued to formulate a definition that is generic enough to be applied in the present with the lessons from the past that leads to be accepted by other researchers for the future. The adopted definition for energy security is 'the feature (measure, situation, or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats.'

Based on this definition, in order to have a sustainable energy system that functions optimally, its dimensions and threats should be identified. It is the second part of this paper. Energy security dimensions were identified and designed to cover all the different aspects in energy security. In total, this article concludes the need to include 15 different dimensions (Availability, Diversity, Cost, Technology and Efficiency, Location, Timeframe, Resilience, Environment, Health, Culture, Literacy, Employment, Policy, Military, and Cyber Security) if energy security is to be addressed perfectly. These dimensions were tracked in the same literature that energy security definitions were studied and summarized in Table S1 of the Appendix S1. Figure 2 represents the occurrence, frequency of each dimension in these literature sources as summarized in Table S2 of the Appendix

S1. It is obvious that, availability, cost, and policy were the main three dimensions that were present in most of the literature. On the other hand, cyber security was the least to be discussed when it comes to energy security, though it is one of the most important dimensions nowadays. This leads us to the conclusion that cyber security did not have its sufficient discussion within the energy security discussion. It can be concluded that although the energy system is nothing without people, social-oriented dimensions (health, culture, literacy, and employment) experienced less coverage by the discussion about energy security. Another important point to stress on is the absence of any literature that identified all the 15 dimensions, proving the novelty of this identification this paper has. The conclusion is that each one of them discussed energy security partially without addressing all the dimensions, as they needed to be addressed.

As discussed throughout the course of this paper, each dimension has different parameters that attribute to that specific dimension. The summary of each dimension and its parameters is presented in Table 1. Furthermore, the discussion of each dimension went on to determine the threats on energy security that are related to each dimension. Last, some numerical indexes were represented for each dimension.

This overview of energy security with all of the discussed topics provides recommendations for policymakers, governments, and researchers. In order to come up with inclusive and comprehensive agenda for energy security, all the 15 dimensions and their parameters should be taken into account. The exclusion of any of these dimensions will result in an imbalanced outcome and decisions in regards to energy security because all the dimensions are interdependent and can affect each other.

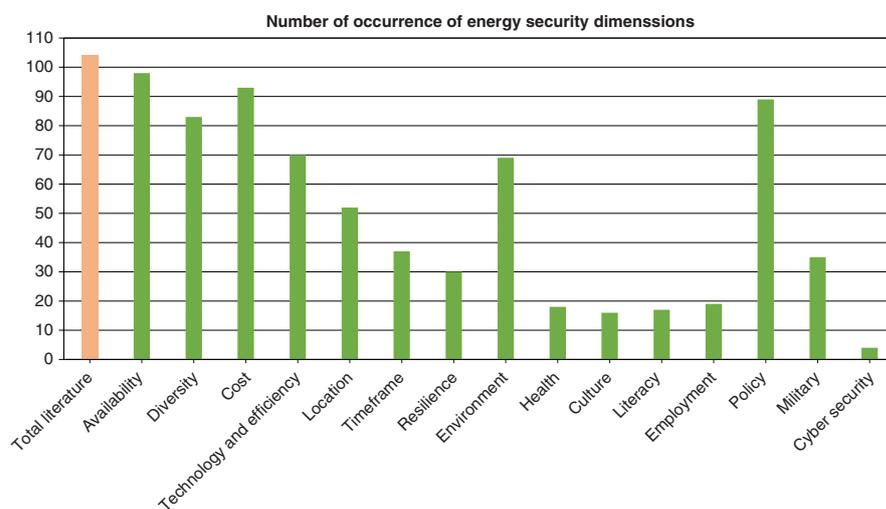


FIGURE 2 | The frequency of different dimensions mentioned/discussed in literature.

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REFERENCES

- Ang BW, Choong WL, Ng TS. Energy security: definitions, dimensions and indexes. *Renew Sustain Energy Rev* 2015, 42:1077–1093.
- Vivoda V. Evaluating energy security in the Asia-Pacific region: a novel methodological approach. *Energy Policy* 2010, 38:5258–5263.
- Bielecki J. Energy security: is the wolf at the door? *Q Rev Econ Finance* 2002, 42:235–250.
- Jun E, Kim W, Chang SH. The analysis of security cost for different energy sources. *Appl Energy* 2009, 86:1894–1901.
- Löschel A, Moslener U, Rübhelke DTG. Indicators of energy security in industrialised countries. *Energy Policy* 2010, 38:1665–1671.
- Winzer C. Conceptualizing energy security. *Energy Policy* 2012, 46:36–48.
- Turton H, Barreto L. Long-term security of energy supply and climate change. *Energy Policy* 2006, 34:2232–2250.
- Franki V, Višković A. Energy security, policy and technology in South East Europe: presenting and applying an energy security index to Croatia. *Energy* 2015, 90(Part 1):494–507.
- Jonsson DK, Johansson B, Månsson A, Nilsson LJ, Nilsson M, Sonnsjö H. Energy security matters in the EU Energy Roadmap. *Energy Strat Rev* 2015, 6:48–56.
- Kirchner E, Berk CAN. European energy security cooperation: between amity and enmity. *J Common Mark Stud* 2010, 48:859–880.
- Dyer H, Trombetta MJ. *International Handbook of Energy Security*. Cheltenham; Northampton, MA: Edward Elgar Publishing; 2013.
- Kovačová J. *Energy Security in European Conditions*. Masaryk University, Faculty of Social Studies: Brno; 2010.
- Sovacool BK. Energy security: challenges and needs. *Wiley Interdiscip Rev Energy Environ* 2012, 1:51–59.

14. Johnson C, Boersma T. The politics of energy security: contrasts between the United States and the European Union. *Wiley Interdiscip Rev Energy Environ* 2015, 4:171–177.
15. Valentine SV. Emerging symbiosis: renewable energy and energy security. *Renew Sustain Energy Rev* 2011, 15:4572–4578.
16. Augutis J, Krikštolaitis R, Pečiulytė S, Konstantinavičiūtė I. Sustainable development and energy security level after Ignalina NPP shutdown. *Technol Econ Dev Econ* 2011, 17:5–21.
17. Yergin D. Ensuring energy security. *Foreign Aff* 2006, 85:69.
18. Kaare KK, Koppel O, Leppiman A. *The Eastern Baltic LNG Terminal as a Prospect to Improve Security of Regional Gas Supply*. Rhodes; Tallinn: Department of Logistics and Transport; Tallinn University of Technology; 2013, 28–30.
19. Kunz A. *Indian Energy Security. Nuclear Energy Policy*. Charles University in Prague; Prague; 2012.
20. Asif M, Muneer T. Energy supply, its demand and security issues for developed and emerging economies. *Renew Sustain Energy Rev* 2007, 11:1388–1413.
21. Haghghi SS. *Energy Security: The External Legal Relations of the European Union with Major Oil and Gas Supplying Countries*. London: Bloomsbury Publishing; 2007.
22. Aparicio G, Pinilla V, Serrano R. *Europe and the International Agriculture and Food Trade, 1870–2000*. IEHC Helsinki session: Helsinki; 2006.
23. Kim JE. Energy security and climate change: how oil endowment influences alternative vehicle innovation. *Energy Policy* 2014, 66:400–410.
24. Bang G. Energy security and climate change concerns: triggers for energy policy change in the United States? *Energy Policy* 2010, 38:1645–1653.
25. Constantini V, Gracceva F. *Social Costs of Energy Disruptions*. The Fondazione Eni Enrico Mattei: Milan; 2004.
26. Chester L. Conceptualising energy security and making explicit its polysemic nature. *Energy Policy* 2010, 38:887–895.
27. De Vos R, Baken J. Security of supply: energy security solutions hinder development of sustainable infrastructures. *Refocus* 2004, 5:58–59.
28. Teräsväinen T, Lehtonen M, Martiskainen M. Climate change, energy security, and risk—Debating nuclear new build in Finland, France and the UK. *Energy Policy* 2011, 39:3434–3442.
29. Kanchana K, Unesaki H. Assessing energy security using indicator-based analysis: the case of ASEAN member countries. *Soc Sci* 2015;4(4):1269–1315.
30. Phdungsilp A. Assessing energy security performance in Thailand under different scenarios and policy implications. *Energy Procedia* 2015, 79:982–987.
31. Ciută F. Conceptual notes on energy security: total or banal security? *Secur Dialog* 2010, 41:123–144.
32. Sovacool BK. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011.
33. Hossain Y, Loring PA, Marsik T. Defining energy security in the rural North—historical and contemporary perspectives from Alaska. *Energy Res Social Sci* 2016, 16:89–97.
34. Narula K, Reddy BS. Three blind men and an elephant: the case of energy indices to measure energy security and energy sustainability. *Energy* 2015, 80:148–158.
35. APERC, Asia Pacific Energy Research Centre. *A Quest for Energy Security in the 21st Century*. Tokyo: Asia Pacific Energy Research Centre; 2007.
36. Sovacool BK. Evaluating energy security in the Asia Pacific: towards a more comprehensive approach. *Energy Policy* 2011, 39:7472–7479.
37. Dunham IM, Schlosser K. Energy security discourses and environmental protection measures in U.S. federal energy legislation: an introductory exploration. *Extractive Indust Soc* 2016, 3:86–94.
38. Eaves J, Eaves S. Renewable corn-ethanol and energy security. *Energy Policy* 2007, 35:5958–5963.
39. Jordan M, Manley D, Peters RS, Stoltz R. *Goals of Energy Policy: Professional Perspectives on Energy Security, Economics, and Environment*. Our Energy Policy and Sandia National Laboratory: Washington, DC; 2012.
40. IEA, International Energy Agency. Energy security and climate policy-assessing interactions. Report no. 1281720488, Paris: Organisation for Economic Co-operation and Development (OECD) Publishing, 2007.
41. Andrews J, Shabani B. The role of hydrogen in a global sustainable energy strategy. *Wiley Interdiscip Rev Energy Environ* 2014, 3:474–489.
42. Maslow AH. A theory of human motivation. *Psychol Rev* 1943, 50:370–396.
43. Kumar S. Assessment of renewables for energy security and carbon mitigation in Southeast Asia: the case of Indonesia and Thailand. *Appl Energy* 2016, 163:63–70.
44. Sovacool BK. An international assessment of energy security performance. *Ecol Econ* 2013, 88:148–158.
45. Kanchana K, Unesaki H. ASEAN energy security: an indicator-based assessment. *Energy Procedia* 2014, 56:163–171.
46. Lu W, Su M, Zhang Y, Yang Z, Chen B, Liu G. Assessment of energy security in China based on ecological network analysis: a perspective from the security of crude oil supply. *Energy Policy* 2014, 74:406–413.
47. Bohi DR, Toman MA. Energy security: externalities and policies. *Energy Policy* 1993, 21:1093–1109.

48. Kucharski J, Unesaki H. A policy-oriented approach to energy security. *Procedia Environ Sci* 2015, 28:27–36.
49. Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. Indicators for energy security. *Energy Policy* 2009, 37:2166–2181.
50. Checchi A, Behrens A, Egenhofer C. *Long-Term Energy Security Risks for Europe: A Sector-Specific Approach*, vol. 309. Center for European Policy Studies: Bruxelles; 2009.
51. Narula K, Reddy BS. A SES (sustainable energy security) index for developing countries. *Energy* 2016, 94:326–343.
52. Sovacool BK, Mukherjee I, Drupady IM, D'Agostino AL. Evaluating energy security performance from 1990 to 2010 for eighteen countries. *Energy* 2011, 36:5846–5853.
53. Grubb M, Butler L, Twomey P. Diversity and security in UK electricity generation: the influence of low-carbon objectives. *Energy Policy* 2006, 34:4050–4062.
54. Hoogeveen F, Perlot W. The EU's policies of security of energy supply towards the Middle East and Caspian region: major power politics? *Perspect Glob Dev Technol* 2007, 6:485–507.
55. Jansen JC, Seebregts AJ. Long-term energy services security: what is it and how can it be measured and valued? *Energy Policy* 2010, 38:1654–1664.
56. Bazilian M, O'Leary F, O Gallachoir B, Howley M. *Security of Supply in Ireland 2006*. Cork: Energy Policy Statistical Support Unit; 2006.
57. Creti A, Fabra N. Supply security and short-run capacity markets for electricity. *Energy Econ* 2007, 29:259–276.
58. Findlater S, Noël P. Gas supply security in the Baltic States: a qualitative assessment. *Int J Energy Sector Manage* 2010, 4:236–255.
59. Willrich M. International energy issues and options. *Ann Rev Energy* 1976, 1:743–772.
60. Meadows DH, Randers J, Meadows DL, Behrens WW. *The Limits to Growth*. Club of Rome: New York; 1972.
61. Lovins AB. Energy strategy: the road not taken? *Foreign Aff* 1976, 55:65–96.
62. Lovins AB. *Soft Energy Paths: Toward a Durable Peace*. New York: Harper & Row; 1979.
63. Miller LB, Lieber RJ, Maddox J, Mancke R, Vernon R, Willrich M. Energy, security and foreign policy: a review essay. *Int Secur* 1977, 1:111–123.
64. Deese DA. Energy: economics, politics, and security. *Int Secur* 1979, 4:140–153.
65. Lovins AB, Lovins LH. *Energy Policies for Resilience and National Security*. Council on Environmental Quality, Executive Office of the President: Washington, DC, USA; 1981.
66. Neff TL. *Improving Energy Security in Pacific Asia: Diversification and Risk Reduction for Fossil and Nuclear Fuels*. Center for International Studies, Massachusetts Institute of Technology: Cambridge, MA; 1997.
67. UNDP, United Nations Development Programme. *World Energy Assessment—Energy and Challenges of Sustainability*. New York: United Nations Development Programme; 2000.
68. IEA, International Energy Agency. *Towards a Sustainable Energy Future*. Paris: Organisation for Economic Co-operation and Development (OECD) Publishing; 2001.
69. Closson S. *The Energy Curse: Dependency in Soviet and Russian policy*. Woodrow Wilson Institute and Patterson School of Diplomacy and International Commerce: Lexington, KY; Washington, DC; 2010.
70. Barton B, Redgwell C, Ronne A, Zillman DN. *Energy Security: Managing Risk in a Dynamic Legal and Regulatory Environment*. Oxford: Oxford University Press; 2004.
71. Lesbirel SH. Diversification and energy security risks: the Japanese case. *Jpn J Polit Sci* 2004, 5:1–22.
72. UNDP, United Nations Development Program, UNDESA, United Nations Department of Economic and Social Affairs, WEC, World Energy Council. *World Energy Assessment 2004: Overview*. New York: United Nations; 2004.
73. Onamics GRC. *Onamics Energy Security Index—Central and Eastern Europe*. Onamics LLC: Washington, DC; 2005.
74. Jan K, Goldwyn DL. *Energy and Security: Toward a New Foreign Policy Strategy*. Washington, DC: Woodrow Wilson Center Press; 2005.
75. Gawdat B. Energy security: The Caspian Sea. *Miner Energy—Raw Mater Rep* 2005, 20:3–15.
76. Hughes L. Preparing for the peak: energy security and Atlantic Canada. In: *Second International Green Energy Conference (IGEC)*, University of Ontario Institute of Technology, Canada; Department of Electrical and Computer Engineering, Dalhousie University, Halifax, Canada, 2006.
77. Bruusgaard KV. Protecting the energy weapon—new tasks for the Russian armed forces? Report no. ISBN 978-82-464-1115-6, Norway: Norwegian Defence Research Establishment (FFI); 2006.
78. Konoplyanik A, Walde T. Energy charter treaty and its role in international energy. *J Energy Nat Res Law* 2006, 24:523.
79. Costantini V, Gracceva F, Markandya A, Vicini G. Security of energy supply: comparing scenarios from a European perspective. *Energy Policy* 2007, 35:210–226.
80. Müller-Kraenner S. *Energy Security, Re-Measuring the World*. London: Routledge; 2007.

81. Florini A. *Global Governance and Energy. Energy Security: Economics, Politics, Strategies, and Implications*. Washington, DC: Brookings Press; 2009.
82. Jansen JC. *Energy Services Security: Concepts and Metrics*. Amsterdam: Energy research Center of the Netherlands (ECN); 2009.
83. Pascual C, Elkind J. *Energy Security: Economics, Politics, Strategies, and Implications*. Washington, DC: Brookings Institution Press; 2010.
84. Bahgat G. Europe's Energy Security: Challenges and Opportunities. *Int Aff* 2006, 82:961–975.
85. Rutherford JP, Scharpf EW, Carrington CG. Linking consumer energy efficiency with security of supply. *Energy Policy* 2007, 35:3025–3035.
86. Nurdianto DA, Resosudarmo BP. Prospects and challenges for an ASEAN energy integration policy. *Environ Econ Policy Stud* 2011, 13:103–127.
87. Sovacool BK, Bulan LC. Meeting targets, missing people: the energy security implications of the Sarawak Corridor of Renewable Energy (SCORE). *Contemp Southeast Asia: J Int and Strat Aff* 2011, 33:56–82.
88. Diesendorf M. Can energy security and effective climate change policies be compatible? In: Anceschi L, Symons J, eds. *Energy Security in the Era of Climate Change: The Asia-Pacific Experience*. London: Palgrave Macmillan; 2012, 72–87.
89. Blum H, Legey LFL. The challenging economics of energy security: ensuring energy benefits in support to sustainable development. *Energy Econ* 2012, 34:1982–1989.
90. O'Sullivan ML. The entanglement of energy, grand strategy, and international security. In: Goldthau A, ed. *The Handbook of Global Energy Policy*. West Sussex: Wiley-Blackwell; 2013, 30–47.
91. Kononov YD. Evaluation of strategic threats in predictive studies of power industry. *Stud Russ Econ Dev* 2014, 25:246–250.
92. Georgescu C. Energy terrorism security of energy in Romania and European union NATO's role in security of energy endogenous and exogenous influencing factors knowledge horizons. *Economics* 2015, 7:172.
93. Johansson TB, Nakićenović N. *Global Energy Assessment: Toward a Sustainable Future*. Cambridge: Cambridge University Press; 2012.
94. Čehulić L, Kuznetsov AV, Celikpala M, Gleason G. Energy security in South East Europe. In: Cross S, Kentera S, Nation RC, Vukadinović R, eds. *Shaping South East Europe's Security Community for the Twenty-First Century: Trust, Partnership, Integration*. London: Palgrave Macmillan; 2013, 114–133.
95. Jewell J, Cherp A, Vinichenko V, Bauer N, Kober T, McCollum D, Van Vuuren DP, Van Der Zwaan B. Energy security of China, India, the EU and the USA under long-term scenarios: results from six IAMs. *Clim Change Econ* 2013, 04:1340011.
96. Jewell J, Cherp A, Riahi K. Energy security under decarbonization scenarios: an assessment framework and evaluation under different technology and policy choices. *Energy Policy* 2014, 65:743–760.
97. Barrett M, Bradshaw M, Froggatt A, Mitchell C, Parag Y, Stirling A, Watson J, Winzer C. Energy security in a multi-polar world. University of Exeter; 2010. Available at: https://www.exeter.ac.uk/energysecurity/documents/Energy_Security_in_a_Multipolar_World_Discussion_Paper.pdf (accessed August 25, 2017).
98. Jamasb T, Pollitt M. Security of supply and regulation of energy networks. *Energy Policy* 2008, 36:4584–4589.
99. De Jooede J, Kingma D, Lijesen M, Mulder M, Shestalova V. *Energy Policies and Risks on Energy Markets: A Cost-Benefit Analysis*. CPB Netherlands Bureau of Economic Policy Analysis: The Hague; 2004.
100. Joskow PL. *Supply Security in Competitive Electricity and Natural Gas Markets. Utility Regulation in Competitive Markets: Problems and Progress*. Cheltenham: Edward Elgar Publishing; 2007.
101. Keppler JH. *International Relations and Security of Energy Supply: Risks to Continuity and Geopolitical Risks*. Brussels: Directorate-General for External Policies of the European Union, Policy Department; 2007.
102. Le Coq C, Paltseva E. Measuring the security of external energy supply in the European Union. *Energy Policy* 2009, 37:4474–4481.
103. Cabalu H. Indicators of security of natural gas supply in Asia. *Energy Policy* 2010, 38:218–225.
104. Cohen G, Joutz F, Loungani P. Measuring energy security: trends in the diversification of oil and natural gas supplies. *Energy Policy* 2011, 39:4860–4869.
105. Erdal L, Pektaş AO, Ozkan O, Özkan F. Security of energy supply in Japan: a key strategy and solutions. *Int J Glob Warm* 2015, 7:128–159.
106. Von Hippel D, Suzuki T, Williams J, Hayes P. Evaluating the energy security impacts of energy policies. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011.
107. Gnansounou E. Measuring energy security vulnerability. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011.
108. Narula K. Is sustainable energy security of India increasing or decreasing? *Int J Sustain Energy* 2014, 33:1054–1075.
109. Wolfers A. National security as an ambiguous symbol. *Polit Sci Q* 1952, 67:481–502.

110. Komkov NI, Krotova MV, Titov BY. Deregulating the domestic natural gas market: conditions and mechanisms. *Stud Russ Econ Dev* 2009, 20:13–22.
111. WEC, World Energy Council. *World Energy Resources 2013 Survey*. London: World Energy Council; 2013.
112. Perez R, Perez M. A fundamental look at energy reserves for the planet. In: *The IEA SHC Solar Update*, 2009, Vol. 50(2).
113. IEA, International Energy Agency. *World Energy Outlook 2015*. Paris: Organisation for Economic Co-operation and Development (OECD) Publishing; 2015.
114. Brown MA, Wang Y, Sovacool BK, D'Agostino AL. Forty years of energy security trends: a comparative assessment of 22 industrialized countries. *Energy Res Soc Sci* 2014, 4:64–77.
115. Tsao J, Lewis N, Crabtree G. Solar FAQs. In: *Energy Udo*, editor. Washington, DC: US Department of Energy, 2006.
116. IEA, International Energy Agency. *Key world Energy Statistics*. Paris: Organisation for Economic Co-operation and Development (OECD) Publishing; 2015.
117. Weingart JM. The Helios strategy: an heretical view of the potential role of solar energy in the future of a small planet. *Technol Forecast Soc Change* 1978, 12:273–315.
118. WEC, World Energy Council. *Europe's Vulnerability to Energy Crises*. London: World Energy Council; 2008.
119. Sovacool BK, Brown MA. Competing dimensions of energy security: an international perspective. *Annu Rev Env Resour* 2010, 35:77–108.
120. UN, United Nations. *World Population Prospects: The 2015 Revision*. New York: United Nations; 2015.
121. World Bank. Population 2014 : World development indicators database. 2015, 1–4. Available at: <http://databank.worldbank.org/data/download/POP.pdf>. (Accessed August 25, 2017).
122. UN, United Nations, DESA, Department of Economic and Social Affairs, PD, Population Division. *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. New York: United Nations (UN); 2015.
123. Breyer C, Heinonen S, Ruotsalainen J. New consciousness: a societal and energetic vision for rebalancing humankind within the limits of planet Earth. *Technol Forecast Soc Change* 2017, 114:7–15.
124. Luft G, Korin A, Gupta E. Energy security and climate change. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011, 43.
125. Yergin D. *The Prize: The Epic Quest for Oil, Money and Power*. New York: Simon & Schuster; 1991, 912 p.
126. Elkind J. Energy security: call for a broader agenda. In: Pascual C, Elkind J, eds. *Energy Security: Economics, Politics, Strategies, and Implications*. Washington, DC: Brookings Institution Press; 2010, 119–148.
127. Tagarinski M, Avizius A. Energy security for the Euro-Atlantic region. In: *Energy and Environmental Challenges to Security*. Stec S and Baraj B (eds.), Berlin: Springer; 2009, 1–32.
128. Baldwin R. The Dutch disease. *Economist* 1977, 26:82–83.
129. Månsson A. Energy, conflict and war: towards a conceptual framework. *Energy Res Soc Sci* 2014, 4:106–116.
130. Ueno PH. *Can Dutch Disease Harm the Export Performance of Brazilian Industry?* London: DRUID; 2010.
131. Cavalcanti DV, Tiago V, Mohaddes K, Raissi M. Commodity price volatility and the sources of growth. *J Appl Economet* 2015, 30:857–873.
132. Mehlum H, Moene K, Torvik R. Cursed by resources or institutions? *World Econ* 2006, 29:1117–1131.
133. Bhattacharyya S, Hodler R. Natural resources, democracy and corruption. *Eur Econ Rev* 2010, 54:608–621.
134. Hughes L. The four 'R's of energy security. *Energy Policy* 2009, 37:2459–2461.
135. Bardi U. *Extracted: How the Quest for Mineral Wealth Is Plundering the Planet*. Hartford, VT: Chelsea Green Publishing; 2014.
136. Breyer C, Bogdanov D, Gulagi A, Aghahosseini A, Barbosa L, Koskinen O, Baraza M, Caldera U, Afanasyeva S, Child M. On the role of solar photovoltaics in global energy transition scenarios. *Prog photovolt Res Appl* 2017, 25:27–745.
137. Martchamadol J, Kumar S. Thailand's energy security indicators. *Renew Sustain Energy Rev* 2012, 16:6103–6122.
138. Diamond J. *Collapse: How Societies Choose to Fail or Succeed*. London: Penguin Books; 2005.
139. Abdo H, Kouhy R. Readings in the UK energy security. *Energy Sour B: Econ Plan Policy* 2016, 11:18–25.
140. Stirling A. From sustainability to transformation: dynamics and diversity in reflexive governance of vulnerability. In: Hommels A, Mesman J, Bijker WE, eds. *Vulnerability in Technological Cultures: New Directions in Research and Governance*. Cambridge, MA: MIT Press; 2014, 305.
141. Henderson J, Heather P. *Lessons from the February 2012 European Gas "Crisis"*. Oxford Institute for Energy Studies: Oxford; 2012.

142. Yao L, Chang Y. Energy security in China: a quantitative analysis and policy implications. *Energy Policy* 2014, 67:595–604.
143. Franke A. German Feb coal, gas plant output down sharply from 5-year high in Jan. London: S&P Global Patts; 2017. Available at: <https://www.platts.com/latest-news/coal/london/german-feb-coal-gas-plant-output-down-sharply-26677375>. (Accessed August 26, 2016).
144. Ren J, Sovacool BK. Prioritizing low-carbon energy sources to enhance China's energy security. *Energy Conver Manage* 2015, 92:129–136.
145. Fattouh B. *How Secure Are Middle East Oil Supplies?* Oxford Institute for Energy Studies: Oxford; 2007.
146. Kovačová L. European Union's energy (in) - security-dependency on Russia. *Obrana a strategie* 2007, 2:5–21.
147. Lilliestam J, Ellenbeck S. Energy security and renewable electricity trade—will Desertec make Europe vulnerable to the “energy weapon”? *Energy Policy* 2011, 39:3380–3391.
148. Stegen KS. Deconstructing the “energy weapon”: Russia's threat to Europe as case study. *Energy Policy* 2011, 39:6505–6513.
149. Ustohalova V, Englert M. *Nukleare sicherheit in krisengebieten abschlussdokumentation*. Oko-Institut e.V. Institute for Applied Ecology: Berlin; 2017.
150. Child M, Breyer C. Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050. *Renew Sustain Energy Rev* 2016, 66:517–536.
151. Valentine SV. The fuzzy nature of energy security. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011, 56–73.
152. Bahgat G. Central Asia and energy security. *Asian Aff* 2006, 37:1–16.
153. Lakić N. Energy security of the republic of Serbia. *Int J Econ Law* 2013, 9:77–86.
154. Refaat A. The imperative need for an integrated energy and climate policy for Africa. *Int J Energy Environ* 2009, 3:29–43.
155. WEC, World Energy Council. *2015 World Energy Issues Monitor, Energy Price Volatility: The New Normal*. London: World Energy Council; 2015.
156. Edenhofer O, Hirth L, Knopf B, Pahle M, Schlömer S, Schmid E, Ueckerdt F. On the economics of renewable energy sources. *Energy Econ* 2013, 40 (Supplement 1):S12–S23.
157. Coady DP, Parry I, Sears L, Shang B. *How Large Are Global Energy Subsidies?* Washington, DC: International Monetary Fund (IMF); 2015.
158. Masud J, Sharan D, Lohani BN. *Energy for All: Addressing the Energy, Environment, and Poverty Nexus in Asia*. Mandaluyong: Asian Development Bank; 2007.
159. Rademaekers K, Yearwood J, Ferreira A, Pye S, Ian Hamilton P, Agnolucci DG, Karásek J, Anisimova N. *Selecting Indicators to Measure Energy Poverty*. Rotterdam: European Commission, DG Energy; 2016. 130 p.
160. Zittel W, Zerhausen J, Zerta M. *Fossil and Nuclear Fuels—The Supply Outlook*. Energy Watch Group/Ludwig-Beolkow-Foundation/Reiner-Lemoine-Foundation: Berlin; 2013.
161. Schellnhuber HJ, Rahmstorf S, Winkelmann R. Why the right climate target was agreed in Paris. *Nat Clim Change* 2016, 6:649–653.
162. EDP, Energy Defense Project. *Dispersed, Decentralized and Renewable Energy Sources: Alternative to National Vulnerability and War*. Washington, DC: Federal Emergency Management Agency; 1980.
163. Hedenus F, Azar C, Johansson DJA. Energy security policies in EU-25—the expected cost of oil supply disruptions. *Energy Policy* 2010, 38:1241–1250.
164. O'Hanlon M. *How Much Does the United States Spend Protecting Persian Gulf Oil? Energy Security: Economics, Politics, Strategies and Implications*. Washington, DC: Brookings Institution Press; 2010, 59–72.
165. Stern RJ. United States cost of military force projection in the Persian Gulf, 1976–2007. *Energy Policy* 2010, 38:2816–2825.
166. Balat M. Security of energy supply in Turkey: challenges and solutions. *Energy Conver Manage* 2010, 51:1998–2011.
167. Ngepah N. Exploring the impact of energy sources on production, inequality and poverty in simultaneous equations models for South Africa. *Afr Dev Rev* 2011, 23:335–351.
168. Ren J, Sovacool BK. Enhancing China's energy security: determining influential factors and effective strategic measures. *Energy Conver Manage* 2014, 88:589–597.
169. Augutis J, Martišauskas L, Krikštolaitis R. Energy mix optimization from an energy security perspective. *Energy Conver Manage* 2015, 90:300–314.
170. Kumar S, Goteti NS, Savargaonkar P. Co-benefit technologies, green jobs, and national innovation systems. In: *Managing the Transition to a Low-Carbon Economy: Perspectives, Policies, and Practices from Asia*. Lohani BN, Kawai M, Anbumozhi V, (eds.), Tokyo: Asian Development Bank Institute; 2016, 149–173.
171. Badea AC, Tarantola S, Bolado R. Composite indicators for security of energy supply using ordered weighted averaging. *Reliab Eng Syst Saf* 2011, 96:651–662.

172. Sovacool BK. The cultural barriers to renewable energy and energy efficiency in the United States. *Technol Soc* 2009, 31:365–373.
173. Berkhout PHG, Muskens JC, Velthuisen JW. Defining the rebound effect. *Energy Policy* 2000, 28:425–432.
174. Grubb MJ. Communication energy efficiency and economic fallacies. *Energy Policy* 1990, 18:783–785.
175. Gillingham K, Rapson D, Wagner G. The rebound effect and energy efficiency policy. *Rev Environ Econ Policy* 2016, 10:68–88.
176. He G, Bluemling B, Mol APJ, Zhang L, Lu Y. Comparing centralized and decentralized bio-energy systems in rural China. *Energy Policy* 2013, 63:34–43.
177. Ewing RC, Whittleston RA, Yardley BWD. Geological disposal of nuclear waste: a primer. *Elements* 2016, 12:233–237.
178. Tracy CL, Dustin MK, Ewing RC. Policy: reassess New Mexico's nuclear-waste repository. *Nature* 2016, 529:149–151.
179. Bogdanov D, Koskinen O, Aghahosseini A, Breyer C. Integrated Renewable Energy Based Power System for Europe, Eurasia and MENA Regions. In: *Proceedings of 5th International Energy and Sustainability Conference 2016*, Cologne, Germany, June 30 – July 1, 2016.
180. Ugaz P. Prospects for a transit regime on energy in the WTO. *Agenda Int* 2012, 18:247–298.
181. Ürge-Vorsatz D, Eyre N, Graham P, Harvey D, Hertwich E, Jiang Y, Kornevall C, Majumdar M, McMahon JE, Mirasgedis S. Energy end-use: building. In: Johansson TB, Nakićenović N, eds. *Global Energy Assessment-Toward a Sustainable Future*. Cambridge: Cambridge University Press; 2012, 649–760.
182. WEC, World Energy Council. *Assessment of Energy Policy and Practices*. London: World Energy Council; 2008.
183. Bakkensen LA, Fox-Lent C, Read LK, Linkov I. Validating resilience and vulnerability indices in the context of natural disasters. *Risk Anal* 2016, 1:1.
184. Gheorghe AV, Muresan L. *Energy Security: International and Local Issues, Theoretical Perspectives, and Critical Energy Infrastructures*. Berlin: Springer; 2011.
185. Guivarch C, Monjon S. Identifying the main uncertainty drivers of energy security in a low-carbon world: the case of Europe. *Energy Econ* 2017, 64:530–541.
186. WWF, World Wildlife Fund. *Living Planet Report 2016. Risk and Resilience in a New Era*. Gland: WWF International; 2016.
187. Wackernagel M, Rees W. *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island, BC: New Society Publishers; 1998.
188. Wackernagel M, Monfreda C, Schulz NB, Erb K-H, Haberl H, Krausmann F. Calculating national and global ecological footprint time series: resolving conceptual challenges. *Land Use Policy* 2004, 21:271–278.
189. Crutzen PJ. Geology of mankind. *Nature* 2002, 415:23.
190. Ruddiman WF. The Anthropocene. *Annu Rev Earth Planet Sci* 2013, 41:45–68.
191. Waters CN, Zalasiewicz J, Summerhayes C, Barnosky AD, Poirier C, Galuszka A, Cearreta A, Edgeworth M, Ellis EC, Ellis M, et al. The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* 2016, 351:2622.
192. Sovacool BK. Contextualizing avian mortality: a preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy* 2009, 37:2241–2248.
193. Wood S. Energy security and liberal democracy: ideals, imperatives and balancing acts. In: Dyer H, Trombetta MJ, eds. *International Handbook of Energy Security*. Cheltenham; Northampton, MA: Edward Elgar Publishing; 2013, 19.
194. Jackson RB, Vengosh A, Carey JW, Davies RJ, Darrah TH, O'Sullivan F, Pétron G. The environmental costs and benefits of fracking. *Annu Rev Env Resour* 2014, 39:327–362.
195. Munich Re, Munich Reinsurance Company. *Topics Geo: Natural Catastrophes 2013: Analyses, Assessments, Positions*. Munich: Munich Reinsurance Company; 2014.
196. Brown MA, Dworkin M. The environmental dimension of energy security. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011.
197. Islam A, Chan E-S, Taufiq-Yap YH, Mondal MAH, Moniruzzaman M, Mridha M. Energy security in Bangladesh perspective—an assessment and implication. *Renew Sustain Energy Rev* 2014, 32:154–171.
198. Wackernagel M. *Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability*. Vancouver: University of British Columbia; 1994.
199. López-Ruiz V-R, Alfaro-Navarro J-L, Nevado-Peña D. Knowledge-city index construction: an intellectual capital perspective. *Expert Syst Appl* 2014, 41:5560–5572.
200. Wackernagel M, Onisto L, Bello P, Linares AC, Falfán ISL, García JM, Guerrero AIS, Guerrero MGS. National natural capital accounting with the ecological footprint concept. *Ecol Econ* 1999, 29:375–390.
201. Pal JS, Eltahir EAB. Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nat Clim Change* 2016, 6:197–200.

202. Deutch JM, Lauvergeon A, Prawiraatmadja W. *Energy Security and Climate Change*. Washington, DC; Paris; Tokyo: Trilateral Commission; 2007. Report nr 0930503902.
203. WBGU. *German Advisory Council on Global Change. Climate change as a security risk*. Earthscan: London; 2008.
204. Sanders KT, Webber ME. The energy-water nexus: Managing water in an energy constrained world. *Earth Magazine*. Volume July, Virginia, P. Patrick Leahy; 2013. Available at: <http://www.earthmagazine.org/article/energy-water-nexus-managing-water-energy-constrained-world>. (Accessed August 25, 2017).
205. WEF, World Economic Forum. Introduction. In: *Water Security: The Water-Food-Energy-Climate Nexus*. The World Economic Forum, Water Initiative (ed.), Washington, DC: Island Press/Center for Resource Economics; 2011, 1–16.
206. IRENA, International Renewable Energy Agency. *Renewable Energy in the Water Energy and Food Nexus*. Abu Dhabi: International Renewable Energy Agency (IRENA); 2015.
207. Caldera U, Bogdanov D, Breyer C. Local cost of sea-water RO desalination based on solar PV and wind energy: A global estimate. *Desalination* 2016, 385:207–216.
208. WEF, World Economic Forum. *The Global Risks Report 2016 11th Edition*. Geneva: World Economic Forum (WEF); 2016.
209. Mietelski JW, Kierepko R, Brudecki K, Janowski P, Kleszcz K, Tomankiewicz E. Long-range transport of gaseous ¹³¹I and other radionuclides from Fukushima accident to Southern Poland. *Atmos Environ* 2014, 91:137–145.
210. Povinec PP, Gera M, Holý K, Hirose K, Lujanienė G, Nakano M, Plastino W, Sýkora I, Bartok J, Gažák M. Dispersion of Fukushima radionuclides in the global atmosphere and the ocean. *Appl Radiat Isot* 2013, 81:383–392.
211. Møller AP, Mousseau TA. Conservation consequences of Chernobyl and other nuclear accidents. *Biol Conserv* 2011, 144:2787–2798.
212. Kowal HJ. Nuclear energy in Australia. *Aust Defense Force J* 2011, 185:74–86.
213. Hohmeyer OH, Bohm S. Trends toward 100% renewable electricity supply in Germany and Europe: a paradigm shift in energy policies. *Wiley Interdiscip Rev Energy Environ* 2015, 4:74–97.
214. Grigoroudis E, Kouikoglou VS, Phillis YA. Energy sustainability of countries. In: Thomas KD, ed. *Handbook of Research on Sustainable Development and Economics*. Hershey, PA: IGI Global; 2015, 96.
215. McLellan R, Iyengar L, Jeffries B, Oerlemans N. *Living Planet Report 2014: Species and Spaces, People and Places*. Gland: World Wide Fund (WWF) International; 2014.
216. Wackernagel M, Schulz NB, Deumling D, Linares AC, Jenkins M, Kapos V, Monfreda C, Loh J, Myers N, Norgaard R. Tracking the ecological overshoot of the human economy. *Proc Natl Acad Sci* 2002, 99:9266–9271.
217. Wackernagel M, Beyers B. *Der Ecological Footprint: Die Welt neu vermessen*. Deutsche: Europäische Verlagsanstalt; 2010.
218. Baicker K, Cutler D, Song Z. Workplace wellness programs can generate savings. *Health Aff* 2010, 29:304–311.
219. Pritchett L, Summers LH. Wealthier is healthier. *J Hum Resour* 1996, 31:841–868.
220. BVerfG, Bundesverfassungsgericht. Judgement from First Senate of 6 December 2016, 1 BvR 2821/11, 1 BvR 321/12, 1 BvR 1456/12 In: *Germany FCCoFR*, (ed.), Karlsruhe: Germany. Federal Constitutional Court of the Federal Republic of Germany; 2016
221. Epstein PR, Buonocore JJ, Eckerle K, Hendryx M, Stout Iii BM, Heinberg R, Clapp RW, May B, Reinhart NL, Ahern MM. Full cost accounting for the life cycle of coal. *Ann N Y Acad Sci* 2011, 1219:73–98.
222. Pacesila M, Burcea SG, Colesca SE. Analysis of renewable energies in European Union. *Renew Sustain Energy Rev* 2016, 56:156–170.
223. Buonocore JJ, Luckow P, Norris G, Spengler JD, Biewald B, Fisher J, Levy JI. Health and climate benefits of different energy-efficiency and renewable energy choices. *Nat Clim Change* 2016, 6:100–105.
224. Reddy BS. *Sustainable Energy Security for India—An Indicator-Based Approach*. Energy Security and Development. Berlin: Springer; 2015, 3–38.
225. Tongsopit S, Kittner N, Chang Y, Aksornkij A, Wangjiraniran W. Energy security in ASEAN: a quantitative approach for sustainable energy policy. *Energy Policy* 2016, 90:60–72.
226. Moscovici S, Sherrard C, Heinz G. *Social Influence and Social Change*. London: Academic press; 1976.
227. Pachauri S. The energy poverty dimension of energy security. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011, 191–204.
228. Knox-Hayes J, Brown MA, Sovacool BK, Wang Y. Understanding attitudes toward energy security: results of a cross-national survey. *Glob Environ Change* 2013, 23:609–622.
229. Pascual C, Zambetakis E. The geopolitics of energy. In: Pascual C, Elkind J, eds. *Energy Security: Economics, Politics, Strategies, and Implications*. Washington, DC: Brookings Institution Press; 2010.

230. Ortiz I, Cummins M. *A Recovery for All: Rethinking Socio-Economic Policies for Children and Poor Households*. New York: United Nations Children's Fund (UNICEF), Division of Policy and Practice; 2012.
231. Nelson RR, Schultz TP, Slighton RL. *Structural change in a developing economy: Colombia's problems and prospects*. Princeton, NJ: Princeton University Press; 1971.
232. Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: a synthesized approach. *Energy* 2011, 36:5343–5355.
233. Kimura O. The Role of Standards: The Japanese Top Runner Programme for End-Use Efficiency. In: *Energy Technology Innovation: Learning from Historical Successes and Failures*. Grubler A, Wilson C, (eds.), Cambridge: Cambridge University Press; 2013.
234. Nordqvist J. *Evaluation of Japan's Top Runner Programme*. Belgium Energy Intelligence for Europe program: Brussels; 2006.
235. Nagata T. *Japan's Policy on Energy Conservation*. Tokyo: International Affairs Office, Energy Conservation and Renewable Energy Department, Agency for Natural Resources and Energy; 2014.
236. Balmer M. Enhancing decision-making capacity to support the implementation of emerging energy technologies. In: *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) SA*, editor, Cape Town: International Association for Management of Technology, 2015.
237. Goldthau A. The public policy dimension of energy security. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. Oxford; New York: Routledge; 2011, 129–145.
238. Stern NH, Peters S, Bakhshi V, Bowen A, Cameron C, Catovsky S, Crane D, Cruickshank S, Dietz S, Edmonson N. Stern review: the economics of climate change. In: *University LSoEL*, editor. Vol. 30. Cambridge: Cambridge University Press, 2006.
239. Snider LW. Arms exports for oil imports? The test of a nonlinear model. *J Conflict Resolut* 1984, 28:665–700.
240. Lovins AB, Lovins LH. *Brittle Power: Energy Strategy for National Security*. Baltimore, MD: Brick House Publishing; 1982.
241. REN21. *Renewables 2010 Global Status Report*. Paris: Renewable Energy Policy Network for the 21st Century; 2010.
242. Rutovitz J, Atherton A. *Energy Sector Jobs to 2030: A Global Analysis*. Sydney, Australia: Institute for Sustainable Futures, University of Technology Sydney for Greenpeace International; 2009.
243. Dreyer I. International energy security challenges for Europe in the coming years. *Int Issues Slovak Foreign Policy Aff* 2013, 22:3.
244. Kim TH. South Korea's strategic relationships with Sub-Saharan Africa. *J Int Polit* 2010, 50:111–135.
245. WEF, World Economic Forum. *Global Energy Architecture Performance Index Report*. Geneva: World Economic Forum (WEF); 2016, 2016.
246. Friedman T. The first law of petropolitics. *Foreign Policy* 2009, 154:28–36.
247. Knebel A, Hartman J, Kajimura R. Opinions on renewables—a look at polls in industrialised countries. *RENEWS KOMPAKT*, 2016.
248. Smil V. War and energy. *Encyclopedia Energy* 2004, 2:363–371.
249. Moran D, Russell JA. *Energy Security and Global Politics: The Militarization of Resource Management*. London: Routledge; 2008.
250. Klare M. *Resource Wars: The New Landscape of Global Conflict*. Henry Holt and Company—Macmillan: New York; 2001.
251. Mieth A, Bork H-R. Humans, climate or introduced rats—which is to blame for the woodland destruction on prehistoric Rapa Nui (Easter Island)? *J Archaeol Sci* 2010, 37:417–426.
252. Buzan B, Wæver O, De Wilde J. *Security: A New Framework for Analysis*. Boulder, CO: Lynne Rienner Publishers; 1998.
253. Liss C. The maritime dimension of energy security. In: Sovacool BK, ed. *The Routledge Handbook of Energy Security*. London; New York: Routledge Taylor & Francis; 2011.
254. WEC, World Energy Council. *World Energy Focus—December 2015*. London: World Energy Council; 2015.
255. Onyeji I, Bazilian M, Bronk C. Cyber security and critical energy infrastructure. *Electricity J* 2014, 27:52–60.
256. Escribano Francés G, Marín-Quemada JM, San Martín González E. RES and risk: renewable energy's contribution to energy security: a portfolio-based approach. *Renew Sustain Energy Rev* 2013, 26:549–559.
257. Shalal A. IAEA chief: nuclear power plant was disrupted by cyber attack. *Reuters*, 2016.
258. Frei C, Whitney R, Schiffer H-W, Rose K, Rieser DA, Al-Qahtani A, Thomas P, Turton H, Densing M, Panos E. *World Energy Scenarios: Composing Energy Futures to 2050*. Paris: Conseil Francais de l'énergie; 2013.
259. Pearson ILG. Smart grid cyber security for Europe. *Energy Policy* 2011, 39:5211–5218.
260. Cho HS, Woo TH. Cyber security in nuclear industry—analytic study from the terror incident in nuclear power plants (NPPs). *Ann Nucl Energy* 2017, 99:47–53.
261. Shakarian P, Shakarian J, Ruef A. Chapter 13—Attacking Iranian nuclear facilities: Stuxnet. In:

- Introduction to Cyber-Warfare*. Boston, MA: Syngress; 2013, 223–239.
262. Nunez KJ. Gridlock on the road to renewable energy development: a discussion about the opportunities and risks presented by the modernization requirements of the electricity transmission network. *J Bus Entrepren Law* 2012, 1:7.
263. Xie J, Stefanov A, Liu C-C. Physical and cyber security in a smart grid environment. *Wiley Interdiscip Rev Energy Environ* 2016, 5:519–542.
264. Shuaib K, Trabelsi Z, Abed-Hafez M, Gaouda A, Alahmad M. Resiliency of smart power meters to common security attacks. *Procedia Comput Sci* 2015, 52:145–152.

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Energy security and energy storage technologies

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Abstract

As the transition to a 100% renewable energy (RE) system is meant to enhance sustainability, energy security should be taken into consideration. Energy security is an important situation in which the system can function optimally and sustainably, free from risks and threat. Part of the energy security consideration is the discussion about different energy system elements. And one of the most important elements of the RE system is storage. The aim of this work is to analyse energy storage technologies from an energy security perspective. Different storage technologies are studied. The portfolio of the technologies include: Pump Hydro Storage (PHS), Thermal Energy Storage (TES), batteries, Adiabatic Compressed Air Energy Storage (A-CAES), and bulk storage for gas and liquid (biogas, H₂, CH₄, CO₂, O₂, liquefied gases, biodiesel, synthetic fuels, etc.) relevant for the energy transition. The results show clearly that not all storage technologies obtain the same level of energy security; TES is considered to have the highest level of security, and then the other storage technologies come in order from the highest to the lowest: batteries, gas/liquid storage, PHS, and the least secure energy storage technology is A-CAES. The conclusion is that all storage technologies show a positive relationship with energy security and all increase energy security, albeit at different levels. Therefore, it is recommended that manufacturers, energy system planners and policy makers adopt and improve storage technologies based on the need and the security of the system.

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1. Introduction

Energy is regarded as a key factor for economic growth [1, 2], the main driver for society [3] and civilization [4], and an important enabler of social development [5]. Energy is needed for several purposes such as industry, transportation, residential means and services [6]. For that, humans have been trying to utilize different sorts of energy from fossil to renewable fuels to fulfil basic human needs [7].

Nomenclature

A-CAES	Adiabatic Compressed Air Energy Storage
CAES	Compressed Air Energy Storage
CSP	Concentrated Solar Thermal Power
DMC	Dimethyl carbonate
DoD	Depth-of-Discharge
kWh	kilo-Watt-hour
LAES	Liquid Air Energy Storage
MW	Mega-Watt
PCMs	Phase Change Materials
PHS	Pump Hydro Storage
PNNL	Pacific Northwest National Laboratory
RE	Renewable Energy
TES	Thermal Energy Storage
Wh	Watt-hour

The first section of this paper provides the concept of energy security and its dimensions, as was conceptualized by Azzuni and Breyer [8]. Then, in the second section, different energy storage technologies are considered from as many energy security dimensions as possible. The technologies that are discussed are batteries, Pumped Hydro Storage (PHS), Thermal Energy Storage (TES), batteries, Adiabatic Compressed Air Energy Storage (A-CAES), and standard bulk storage for liquid and gas (biogas, H₂, CH₄, CO₂, liquefied gases, biodiesel, synthetic fuels, etc.).

2. Energy Security Dimensions

Energy security is a feature (measure, situation or status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats [8]. A comprehensive description of energy security includes 15 dimensions and many parameters for each dimension. A summary of the 15 dimensions and their parameters is presented in Table 1 with a schematic representation in Fig. 1.

Table 1. Summary of energy security dimensions and parameters.

Dimensions	Parameters
Availability	Existence of resources
	Existence of consumers
	Existence of means of transport (access)
Diversity	Diversity of sources
	Diversity of fuel (energy carriers)
	Diversity of means (technologies, transportation)
	Diversity of consumers

Cost	Energy price (consumers, producers, pricing system/subsidies, energy poverty, peak oil and stability/volatility) Cost of disruption Cost of securing the system
Technology & Efficiency	New technology advancement Energy system efficiency Energy intensity Energy conservation
Location	Energy systems boundaries Location of energy source Density factor (centralized/decentralized) Land use Globalization Population settlement and distribution Geography Industrial intensity
Timeframe	Timeline Length of the event Length of the effect (struggle or impact)
Resilience	Adaptive capacity
Environment	Exploration rate and resources' location Extraction and transportation methods Outcomes from energy use Impact resulting from environmental change Relationship to water
Health	Impact of people's health on the energy system Impact of the energy system on health of (energy sector workers, consumers, and international society)
Culture	Cultural effect on the energy system (production, connection, consumption, cultural acceptance (NIMBY)) Energy conditions shaping cultural aspects
Literacy	Information availability (quality, market information, public awareness and structured educational program) Information presentation and provision Usage of energy information
Employment	Effect of energy security on unemployment rate Effect of employment rate on energy security
Policy	Political system, democracy/dictatorship (nature, stability, citizen's will and internal and external relationship) Regulations (liberalised and controlled market, rules, subsidies) Governance (following the rules (transparency), following the rules selectively, not following the rules, corruption)
Military	Energy use for military purposes Militarization Energy as a mean in a military conflict (energy weapon)

	Destabilization factor (resources curse, environmental deterioration, economies of violence)
Cyber security	Connectivity (Cyber-attacks)
	Software use (SCADA, programme failures)
	IT skills

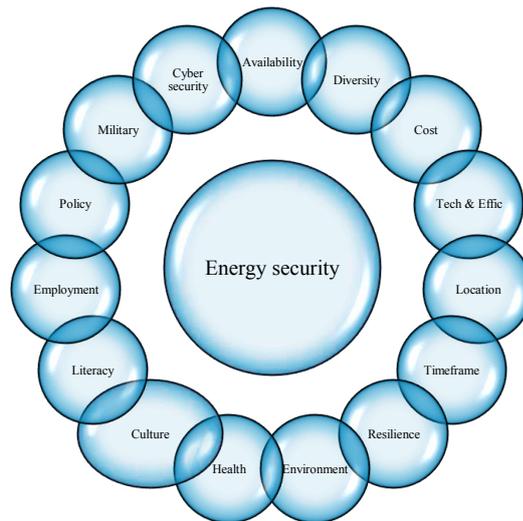


Fig. 1. Energy security dimensions

3. Storage Technologies

Energy storage is used usually to time-shift energy delivery [9]. There are many different energy storage systems and technologies. Although their utilization and commercial availability are different, each has a uniqueness. A summary of current situation of energy storage technologies is in Fig. 2 and Fig. 3.

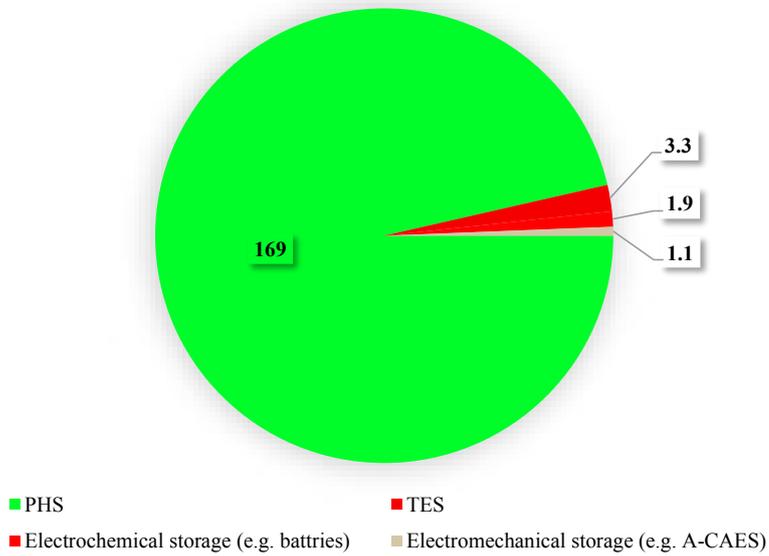


Fig. 2. Total installed capacity of storage technology. Adopted from mid-2017 data presented in [10]

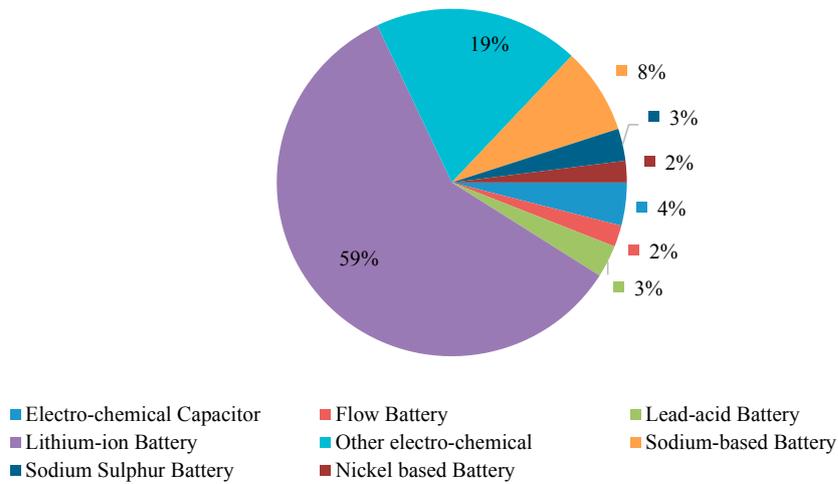


Fig. 3. Total global capacity of electrochemical storage. Adopted from mid-2017 data presented in [10]

4. Pumped Hydro Storage (PHS)

4.1. State of the art

PHS has a long history, large energy capacity and high technical maturity [11]. In 2012, PHS had a 99% share of worldwide storage capacity [12, 13]. Fig. 4 shows a typical PHS plant, which uses two water reservoirs. When there is electricity excess, water is pumped into the higher reservoir. Conversely, when electricity is needed, water can be released back into the lower reservoir. While moving down, water powers turbine units to generate electricity. The amount of energy stored depends on the height difference between the two reservoirs and the total volume of water [11]. Various PHS plants exist with power ratings from 1 MW to 3003 MW, with approximately 70–85% cycle efficiency and substantially more than 40 years lifetime [12, 14]. Even more than 70 years for some countries is reported by [15]. The applications of PHS systems involve energy management, frequency control, and supply reserve. However, with the restriction of site selection, PHS plants suffer from long construction time and high capital investment [11].

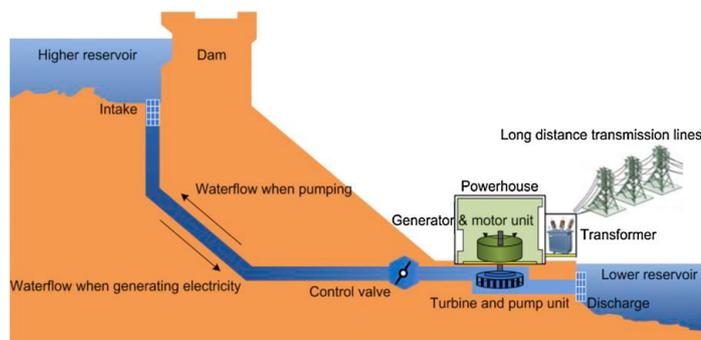


Fig. 4. Schematic description of a PHS plant [11]

4.2. Energy security analysis

PHS ranks high in **availability**. The technology is mature and available, and natural geographic formations are available for different reservoirs. On the other hand, concerns can be raised regarding the closeness of consumers to PHS plants. Most of the time, long distance transition lines are needed. First, they bring the excess electricity to the PHS location. Then, they are needed when plants are in discharge mode.

The second aspect of PHS security is the **diversity** dimension. Although in theory different fluids can be used to generate potential energy from excess electricity, water is the most dominant. That leaves PHS with low achievement for the diversity of carriers. However, since the concept depends on elevation, diverse naturally occurring geographical formations can be utilized. This gives more freedom of choice of where to build PHS plants.

The next dimension is the **cost** dimension. As PHS is a widespread and used technology, one can conclude that investment in such projects pays off. However, one of the major problems PHS plants face is substantial capital expenditures [16]. The cost threat for such large storage systems is the cost of disruption and cost of securing the installation. If a natural disaster occurs, it only takes a crack in the reservoir for all the water to be displaced. Such a situation could result in high repair cost. The high cost of disruption is inherently a result of the nature of PHS as a high energy density storage system. Moreover, the upper reservoir stores energy based on the elevation of the water in high quantities relative to the volume. For the **technology and efficiency** dimension, PHS systems are at a high level for energy security: the technology is mature and advancement is ongoing [11]. Further, as PHS is typically a large-scale installation, the efficiency is at a high level for energy security.

Theoretically, the **location** of PHS plants can be anywhere in the world, but other factors play a role in the location dimension. The first factor is the used fluid (water). The location of a PHS has to be close to a natural source of water or close to a renewable stream of water, either natural or artificial. Furthermore, climate and temperature should be taken into account, as water can evaporate or freeze if the operating temperature is not suitable. Also, if the reservoirs are large enough for marine life (fish) to exist, that results in higher achievement in the location dimension of energy security. Due to the fact that there is more than one purpose of the land, the land use is doubled.

Then, comes the dimension of the **timeframe**. With 40-70 years of lifetime for PHS, this storage technology can have a long timeline when energy can be stored. However, this long life span comes with the risk that the PHS structure is more vulnerable to climate change and conditions change. This might result in a longer situation with severe negative results, for example, longer periods of drought.

The **resilience** of PHS seems to be on the low side as a system but on the high side as a storage technology. If a problem happens within the system, e.g., a leakage in the reservoir, the system needs much effort to adapt to and retain the original situation. However, the adaptive capacity of such big reservoirs in PHS systems allows them to be a very good option for energy storage as they can accommodate excess electricity and they can be altered very quickly from charging to discharging of accumulated energy.

PHS proves to be a clean **environmental** option that can be used in the future for a global 100% renewable energy system [17]. Furthermore, as PHS systems rely on water, the negative impact on the health dimension is very low, so that it comes with low probability of health disturbance. For example, a failure could cause highly pressurized water to injure workers, or a water body could become a place for humans to dump their waste, thus harmful bacteria could breed. On the other side, PHS can have positive impact on **health**, as a source of recreational activities. These recreational activities can also be linked to the next dimension, culture. If water reservoirs are open to the environment and nearby human settlements, they may attract people to change some of their habits and shape their cultural values.

Moving forward, the **literacy** dimension has less to do with PHS on the technical level but has more to do on the social level. If people are educated enough about how their excess electricity is stored, a PHS system will gain more acceptance and the installations will be seen as an important part of people's energy system. Further, the technical staff needed to run or control PHS facilities can help reduce unemployment on the long-term.

The **policy** dimension has a lot to do with PHS. The first is the citizens' will. If the citizens in one locality prefer using PHS after being informed of their advantages and disadvantages, a policy has to be made to facilitate the installation of PHS, and vice versa. Further, regulations for how to deal with electricity excess and energy retained from PHS has to be clear. The priority should be given to the people benefiting from these PHS storage systems. Also, for governance, a weekly or monthly report of all associated costs, energy flows in and out, and negative and positive achievements should be transparent and made public.

For the last two dimensions, **military** and **cyber security**, PHS has some relationships that need to be addressed. If big reservoirs are used for PHS, they can be targets for military attacks. Such attacks can result in flooding of large areas and destroying human settlements. Therefore, the design of PHS systems has to be taken into consideration so that if a military operation is taking place, there is a minimum negative impact on society. Further, a cyber-attack on control centres for PHS systems can result of draining all the energy capacity at the wrong time.

5. Thermal Energy Storage (TES)

5.1. State of the art

TES stores thermal energy using different approaches in insulated reservoirs [11]. A typical TES system consists of a storage medium in a reservoir/tank, a packaged chiller or built-up refrigeration system (not all types of TES have this part), piping, pumps and controls. Based on the operating temperature, TES can be classified into two groups: low-temperature TES (e.g., aquiferous low-temperature TES and cryogenic energy storage) and high-temperature TES (e.g., latent heat TES, sensible heat TES and concrete thermal storage) [18-20].

Cooled or iced water is usually used in aquiferous low-temperature TES, that is more suitable for peak shaving and industrial cooling loads [4]. A cryogen (e.g., liquid nitrogen or liquid air) is used in cryogenic energy storage to get the electrical/thermal energy conversion. For instance, Liquid Air Energy Storage (LAES) [21] is attracting attention

due to the high expansion ratio from liquid to gas. Latent heat TES depends on Phase Change Materials (PCMs) as the storage media and uses the energy absorption or emission in liquid-solid transition of these PCMs at constant temperature [22]. Concrete thermal storage uses concrete to store heat energy carried in synthetic oil.

The above TES technologies have different features with various applications. More attention is paid to TES [23] because of the high storage density which can be used in buildings. In addition, cryogenic energy storage is expected to be used for future grid power management [11].

TES systems can store large amount of energy with a daily self-discharge of (0.05–1%), energy density of (80–500 Wh/l), specific energy of (80–250 Wh/kg) and capital expenditures of approximately (3–60 €/kWh) [18]. However, the cycle efficiency of TES systems used for electricity systems is low, at (30–60%) [18]. In Fig. 5, a TES system is presented. Electrical energy from wind is used to heat a bulk storage material. Heat is then recovered to produce steam vapour. The vapour steam drives a turbine to generate electricity [11]. Further, the system presented in Fig. 5 was enhanced by replacing the resistors with heat pumps, forming what is called a “Carnot Battery” [24], in order to achieve several advantages, e.g., low cost without degradation. In addition, another efficiency improvement is seen in the use of TES in Concentrated Solar Thermal Power (CSP) plants. Instead of the need to convert renewable energy from electricity to heat, solar heat energy is used to heat up the medium material in the TES systems [25, 26].

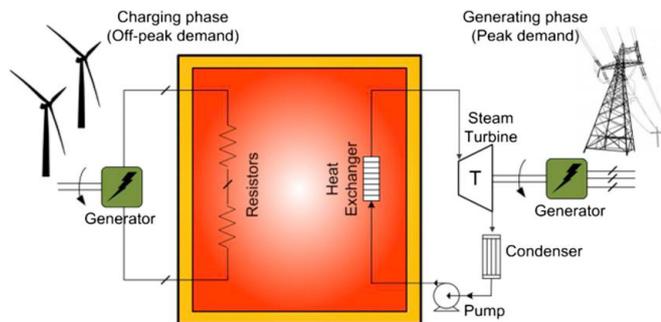


Fig. 5. TES system for excess wind generation [13]

In addition to the use of TES systems as electrical energy storage, where electricity is converted to heat and vice versa, TES systems can be used as heat storage. In this case, the efficiency should never be lower than 90%. Moreover, the intermediate steps of conversion are not needed. Fig. 6 shows an example of the use of TES for space heating. Heat from a heat source is used to heat up a liquid, e.g., water. Then, the hot water is used to heat up the medium material in the heat storage. Underground heat storage is used in a salt-water aquifer. The use of a salt-water aquifer plays a significant role as insulation of the heat storage. After that, when heat is needed, water carries out the heat from the heat storage into the users' buildings.

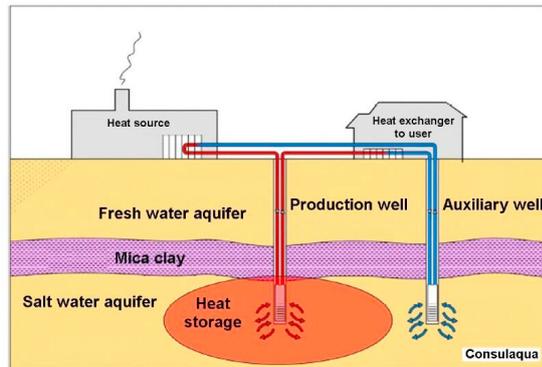


Fig. 6. An illustration of TES system used for space heating [27]

5.2. Energy security analysis

As TES has different technologies and approaches, the energy security analysis will be focused on TES for electrical systems. However, if need arises to comment on TES for heating systems separated from the main discussion, a suitable distinction will be made.

The **availability** looks to be on a high level. TES can use air, water, nitrogen, synthetic oil and other compounds. The availability of these substances is among the highest. Further, TES does not need a specific geographic location or a certain temperature of operation. That means the availability to consumers is rather guaranteed. TES can be deployed in both small-scale distributed systems and large-scale centralised systems. Both can be far from consumers or near them with available means of transport. Further, the needed equipment is available on a commercial scale. Therefore, TES availability is on a high level. The same is for TES systems for heating purposes.

TES has a very high **diversity** level, with many different materials that can be used, whether for the low temperature or the high temperature options. Low temperature storage at -18 to $+12$ °C is run usually with chilled water, but it can be run also with liquid air or liquid nitrogen. This enables more diverse options on the material side. Further, for the high temperature of $25 - 175$ °C, the options are greater and TES can be run with many different Phase Changing Materials [22]. Also, synthetic oil can be used in TES, with its diverse options. Furthermore, for the diversity of means, TES proves its capability to provide different technologies. No dependence on one technology or transportation method is noticed. In addition, many different types of heat exchangers can be used. All these considerations put TES at a high level for the diversity dimension.

For the **cost** dimension, TES systems are economically viable with relatively low capital expenditures of approximately (3–60 €/kWh) [16]. The material costs for some of the options like water and air put TES at a high level of energy security. However, the running cost for TES used for electrical systems is a bit high, due to its low cycle efficiency of 30–60% [11, 18]. In contrast, the efficiency of TES systems used for direct thermal heating is high and results in a low running cost. Further, the cost of disruption varies based on which technology is used for TES. If the material used for energy storage is compressed under high pressure, the cost of interruption is high and energy security is reduced. Such disruption with pressurized material can cause a lot of harm, especially if the TES system is distributed between buildings. However, the cost of securing these TES systems is low in comparison to other energy storage technologies. TES can be used with low temperature and/or with distributed vessels for different buildings. This means the cost of securing such a system is minimized. On the other hand, if the system is centralized with high energy density, the cost for securing the location and the whole TES installation is high. This results in TES having lower energy security than all other centralized storage technologies.

The **technology and efficiency** dimension has multiple considerations. For technology advancement, TES shows potential to improve the technology. The used technology for heat exchangers is mature. However, the development

and use of new and different materials are being researched and developed [18, 23]. Conversely, the energy efficiency of TES systems for electrical systems is not very high, unlike TES systems for heat systems, where the heat cycle efficiency can reach up to 90% [18]. Typically, TES has a small daily self-discharge loss of (0.05–1%) [16]. But the main issue with the technology is noticed when heat is not the needed form of energy. That heat is used to produce steam that generates electricity. The turbine (steam converted to mechanical energy) is typically the step that reduces the overall efficiency.

TES scores high when it comes to the **location** dimension. TES does not need a specific geographic location. Therefore, land can be used in several ways. In addition, TES can be installed close to human settlements, which means a higher score for energy security. The issue with TES arises when the density factor is considered. For higher efficiency, TES has been developed as a central energy storage with high energy density. This high density comes always with a failure risk and a malfunctioning threat. For that reason, it is preferable to have distributed TES systems to reduce the risk.

TES systems usually have long lifetimes, giving them a high score in the **timeframe** dimension. Further, for the distributed model of TES systems, the impact of any event is small since the TES size itself is small. A negative aspect of a TES system is its self-discharge. If the event that a generation failure lasts for a longer time, stored heat can be lost. Thus, the length of the impact has a severe result on the system.

Based on used technology and the intermediate medium, TES can have a high adaptive capacity or a low one, which is of high relevance for the **resilience** dimension. If a sudden change happens for a high-density centralized system, then the TES can adapt to the situation faster than for decentralized separated units. The advantage of TES resilience is based on the heat capacity of the used materials. Usually, materials that can store larger amounts of heat for longer times are used. This gives TES systems high resistance against the change. On the other hand, many TES systems for electrical systems are used typically for load shifting owing to their capacities. Thus, TES can adapt to varying load demands and adapt easily.

The **environment** dimension has a high score when it comes to TES. TES systems can store large quantities of energy without any major hazards [16]. The materials that are mostly used are not toxic, e.g., water, nitrogen or air. These substances exist in the environment naturally. Furthermore, the use of TES is based on a closed cycle so that the heat within the system is not released to the environment, but kept inside insulated walls. This means the system from the heat point of view has a negligible impact on the environment. However, in extreme weather environments, insulation has to be more efficient. On the other side of the system, if pumps, compressors or any of the machines use fossil fuels, the negative impacts from fossil fuels on the environment are counted against TES systems.

The **health** dimension is similarly approached to the environment. The materials that are used in the TES system typically have no hazardous characteristics. This means a high score in the health dimension. The only consideration for TES in the health dimension is the impact of high temperature and high pressure on the health of people, especially the workforce on the site or people living around the facility. If a failure takes place, personal health is at risk. Further, for distributed TES systems near human settlements, in addition to the health risk, there is a cultural impact.

This drives the discussion towards the next dimension, **culture**. People having control of and the ability to monitor their energy storage gives them a sense of security. Consequently, they would behave accordingly. For example, they would not mind the extra generation or consumption at certain times, as they know exactly how much energy is stored. Their energy consumption activities would change as well. Also, they may be keen to learn more about TES technology as it is installed locally.

The **literacy** dimension implies that information about the system should be available and used in the best way if consumers are to be in charge. On the other hand, if the TES system is centralized, consumers and producers should have enough information about the functionality of TES systems and how to use storage in an optimal way. Further, as with any other large-scale utility, TES systems will have a positive impact on the **employment** situation, hence will be at a high level for energy security.

As with all of the energy storage technologies, TES needs to be covered in the national **policy** of who owns the storage facilities and who owns the energy stored in the facilities. Further, if the facility is government based, the performance data and decision-making should be given to those who benefit from the storage facility. However, the governance of distributed TES systems should be given to the corresponding owners after they are given suitable certificates to cope with any danger TES might cause.

The big TES reservoirs can be targets for **military** actions or **cyber security** attacks due to their strategic impact on the energy system. That is the case of centralized systems with high energy density. However, if the TES systems are distributed among buildings, any military action can result in catastrophic results if the used TES technology has a high temperature. Therefore, these technologies (distributed TES with high temperature) get a low score for their energy security military dimension. In contrast, distributed TES can be run always manually with no need to be connected to the Internet. This gives them an advantage from a cyber security point of view over the centralized system. To this point, this summarizes the energy security analysis for TES systems.

6. Batteries

6.1. State of the art

The operational principle of batteries is shown in Fig. 7. Batteries consist of a number of electrochemical cells connected in series or parallel. They produce electricity from an electrochemical reaction. A cell has two electrodes (anode and cathode) with an electrolyte. The electrolyte can be solid, liquid or viscous [28, 29]. A cell converts the energy between electrical and chemical energy. When discharging, the electrochemical reactions takes place at the anodes and the cathodes simultaneously. To the external circuit, electrons are provided from the anodes and are collected at the cathodes. When charging, the reverse reactions happen and the battery is recharged by applying an external voltage to the two electrodes[11].

Batteries are used in different applications, such as energy management, power quality and transportation systems. Battery systems can usually be constructed roughly within 3 to 12 months [18], or even within 60 days as demonstrated by Tesla [30]. The location is flexible, housed inside a building, close to the facilities where needed, or even in mobile devices such as in electric cars and mobile phones. Currently, some barriers confront batteries. For example, there may be low cycling times, limited availability of some raw materials, or disposal or recycling issues due to toxic chemical materials and closed loops of rare materials [31, 32]. Furthermore, many types of batteries cannot be completely discharged due to their lifetime, depending on the cycle Depth-of-Discharge (DoD). The most common battery types are Lithium-ion (Li-ion) batteries, Lead–acid batteries, Sodium–sulphur (NaS) batteries, Nickel–cadmium (NiCd) batteries, Nickel–metal Hydride (NiMH) battery, Sodium nickel chloride battery (also known as ZEBRA battery) [11].

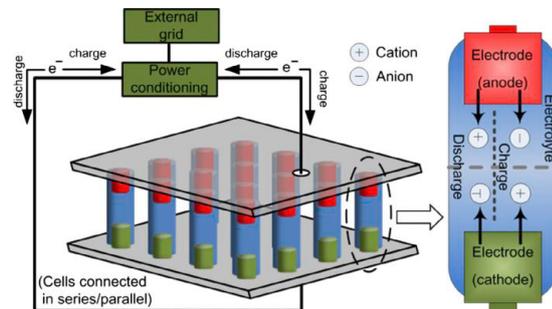


Fig. 7. Battery scheme [11]

6.2. Energy security analysis

To start the energy security analysis, the dimensions are discussed one by one. Starting with the **availability** dimension, batteries score differently based on their type. Because there are many different types of materials that can be used to build batteries on large or small scales, some of these materials, e.g., Sodium, are abundant in the environment and can be obtained easily. However, the most common type of batteries is Li-ion [10], which is scarce

in the environment. The availability of Lithium may be low in the second half of this century, and in the next decades there might be a problem with enough extraction [33]. A similar situation can be seen for Cobalt, which is also needed for Li-ion batteries in mobile applications, in particular battery electric vehicles, due to the higher achievable energy density.

Furthermore, more consumers are turning to electricity self-supply [34], which means more consumers, called prosumers, may need batteries systems. The transition to renewable energy based systems requires more storage systems to cope with the different generation patterns inherited in the renewable energy systems [17, 35]. This results in a high score in the availability dimension from the consumers' perspective. In addition, the technology for manufacturing batteries is globally available. For all of this, apart from the lithium availability, the availability dimension for batteries is at a neutral level.

Considering the **diversity** of resources, batteries do not get a high score for some materials but do for some others. For example, if the batteries are based on sodium, the diversity level is high. Sodium is available around the globe in different places and access to this resource is possible, providing different alternatives for manufacturing these batteries. Then comes the diversity of energy carriers. From an overview on batteries, the diversity of materials is on the high end. Many different alternatives are developed that can be used to build different battery types. Next, the diversity of consumers is also at a high level. Residential, commercial and industrial sectors all can use batteries as energy storage. Having the transformation into renewable electricity based energy systems with many electrical vehicles means a boost for the diversity levels.

The material **costs** differ from one battery technology to another, but the cost trend clearly indicates a fast cost reduction due to high learning and growth rates [36, 37]. Thus, the cost dimension is at a high level. Further, the cost of disruption is also at a high level of energy security. Batteries are usually small modular units that are used in a decentralized system, or small units that are put together to form storage plants in distributed and centralized systems. For this, if distortion is to take place, replacing the damaged parts is not difficult. This reduces the cost of possible disruptions. Therefore, the cost dimension is at a high level of security. However, if the battery system uses toxic materials, the cost of disruption can rise to account for health or environmental impacts. Furthermore, as most batteries do not depend on systems with highly pressurized substances, the cost of securing batteries is low, thus the score for energy security becomes higher.

Batteries have shown their capability for more **technological and efficiency** advancement. Many different approaches and materials are used, and the latest developments with higher efficiencies are in place. This gives batteries a high level of energy security. On the other hand, the efficiency of the batteries is different based on the used material and technology. Therefore, the score for this parameter differs based on what technology is used. However, an advantage of the total efficiency is the use of electricity as the input and output of the storage. No mechanical conversion is needed. This increases the efficiency in general and puts batteries at a high level.

Moving on to the **location** dimension, batteries can achieve a high level of energy security. Batteries can be installed locally on small, distributed scales or in large-scale centralized systems. In addition, electric vehicles that are getting more attention nowadays, including advanced battery systems that are distributed in a decentralized way. This gives batteries a high level of security. Unlike centralized battery systems where batteries are put together to form a large-scale storage capacity for high demand, decentralized systems minimize the land used for storage. Therefore, the level of energy security depends on whether batteries are distributed or concentrated in one geographic location.

The lifetime, key for the **timeframe** dimension, of most of the batteries is long enough to have the applicable timeline be long, thus at a high level of security. Further, the length of events that happen to a batteries system can last long, e.g., a power supply cut for long periods of time. This puts batteries at a low level of energy security especially if batteries are connected to an energy source that cannot be controlled by consumers, e.g., batteries in electric vehicles. However, on the other hand, if the event is sudden, batteries can function efficiently after a very short period of time, measured in seconds. Thus, the length of the effect is short, hence the level of energy security is high.

The same concept is also applied for **resilience**. Batteries can adapt fast to the changing situation of electricity generation. Therefore, battery systems are at a high level for the resilience dimension.

Next is the discussion about the **environment** dimension. First, battery materials need to be taken from natural resources, and, depending on the type of the battery system, these resource can be difficult to exploit or easy.

Therefore, the extraction rate of these materials is different for one type to another. However, with the high expansion of the use of batteries in the transition to renewable energy based systems, the extraction rate is increasing for these materials. Thus, the energy security level from this perspective is at a low level. After that comes the impact of using batteries systems on the environment. Batteries can have toxic materials for the ecosystems of the planet, such as HF, a product of the widely used LiPF_6 salt, and the cyclic and linear carbonates solvents e.g., Dimethyl carbonate (DMC) [38]. The typical practice has been trying to recycle battery materials and then reuse them. However, concerns about the safety of battery material disposal drive the energy security level of this dimension to a low level. Furthermore, many batteries types have limitation on the operating temperature. This puts batteries at a low level of environmental change impact. For these reasons, batteries based on their type can have real issues with the environment dimension of energy security.

Toxic materials of batteries in a decentralized system represent a substantial risk on the **health** of people nearby the battery storage. In addition, as the disposal of batteries has been a concern for the environment, it is also for the health of individuals. In the normal practice of batteries, the toxicity of the materials is mitigated in a way that allows people to use them in a daily life, e.g., mobile phones and laptops. This can give the notion of their safe operation and a high level of energy security even though there is use of toxic materials. On the other hand, healthier people would have more energy-based activities that occur during a lack of energy generation, therefore, their use of battery systems increases. This puts the relationship into proportional terms, and results in a high level of energy security in regards to the health dimension.

It can be easily noticed that **culture** has been highly affected by the use of distributed batteries. How people communicate and preserve things has been enhanced by access to energy stored in portable devices. The impact of batteries with different types and sizes results in the culture dimension of energy security achieving a high level. In addition, people's culture of using certain technologies that rely on batteries drives for more development of battery technologies.

Moving to the **literacy** dimension, despite the wide usage of batteries in people's lives and their high growth rate, detailed information about batteries, their materials and their practicalities are not widely observed. Information is available on the Internet, but this information is not presented in a way to bring the literacy dimension to a high level. In addition, the lack of disposal practice of batteries by individuals shows a lack of use of information. These things put batteries at a low level of energy security in the literacy dimension.

Further, the **employment** dimension is at a high level for battery technologies. Manufacturing and installation of batteries as assistance to distributed decentralized renewable energy systems play significant roles in providing employment in the energy sector [35].

Political decisions are needed to shape people's use of batteries. Regulations that restrict batteries with poor manufacturing and hazardous materials have to be in place, and existing laws blocking the use of batteries have to be adjusted. In addition, governance of the use of batteries has to be granted totally to the battery owners. This can be applied to distributed systems or to a larger scale for centralized systems.

For the **military** and **cyber security** dimensions, the discussion has two parts. The possibility exists of large-scale battery systems to become a target of a military act. This puts the military dimension at a low level of security. On the other hand, for cyber security, unlike many storage technologies, energy inside the batteries is stored in the material's capacity. A cyber-attack cannot affect batteries if they have low connectivity to the Internet. That gives a high level of cyber security because of the possibility to preserve the energy offline. However, although in theory batteries can be disconnected from the Internet, in practice most batteries are connected for various reasons, e.g., monitoring. Therefore, they can be targets for cyber-attacks, thus the score of cyber security is at a low level. The second part is the impact of distributed battery systems on the society. As batteries can hold dangerous chemical materials, they may be used to build flammable and explosive devices, which drive the security level down for the military dimension. Furthermore, batteries distributed on a wide range with high connectivity to the Internet can be manipulated through many parts of the battery's system, e.g., inverters. Thus, manipulation can make batteries drain faster and thus lose their strategic values.

7. Adiabatic Compressed Air Energy Storage (A-CAES)

7.1. State of the art

CAES is a technical approach based on the mechanical conversion of gaseous air. It is commercially available and known as a utility-scale storage technology. When electricity is in excess, the surplus energy drives a reversible motor/generator unit in order to run a set of compressors to start injecting air (usually from the environment) into a storage vessel or cavern in a process called compression mode [39]. The storage can be an underground cavern or above ground tanks. The energy is stored in the form of high-pressure air. When electricity is needed, the stored compressed air is released and heated. The heat source can be from fuel combustion or recovered heat from the compression process, but heat should be recovered for high efficiency. Then, when the compressed air is released, its energy is captured by turbines. The release of the pressurized air is implemented during a process called generation mode. The waste heat from the exhaust can be recycled by a recovery unit [11]. In A-CAES, the heat from the compression mode is captured and stored separately in an extra TES facility. A-CAES was introduced by Pacific Northwest National Laboratory (PNNL) as the most promising technology among various types of second generation CAES [40, 41]. Fig. 8 shows a representation of an A-CAES plant.

A-CAES systems can have small and large capacities with moderate speeds of response. The uses of large-scale A-CAES plants involve grid applications for load shifting and frequency control, as well as bulk energy storage in order to store electricity globally for seasonal variation [42]. A-CAES is suitable for variable renewable energy, e.g., wind power [43, 44] and is the least cost utility-scale bulk storage system that is currently available apart from PHS [45]. The major barrier for A-CAES was to find appropriate geographical locations [11]. With advancing topography mapping, finding appropriate locations is no longer a barrier, but affects the investment cost. Relatively low round trip efficiency of almost 43% [18] is another barrier for CAES compared to PHS and battery technologies. The A-CAES has a higher efficiency of 70% [11, 42] because of the integration of a TES subsystem (no fuel combustion is involved in the discharging mode). As CAES is an outdated technology due to the low efficiency and the use of fossil fuels, A-CAES has been studied and the results clearly show that this sort of energy storage can integrate with renewable energy to fulfil energy demands in the future [42].

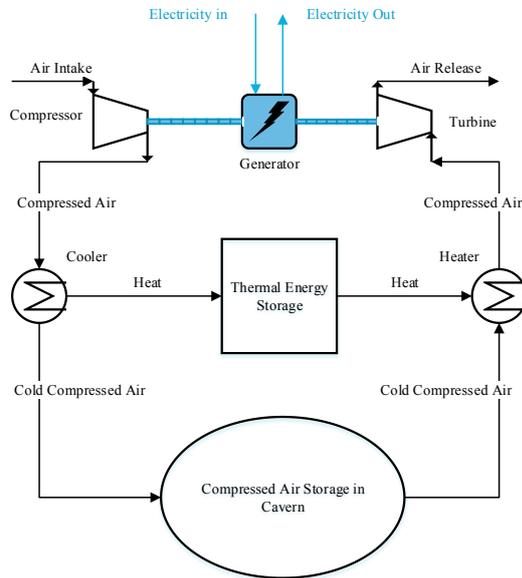


Fig. 8. Schematic diagram of A-CAES in single-stage configuration

7.2. Energy security analysis

As air is used in A-CAES, the score for the **availability** dimension is very high, as air is abundantly accessible. However, on the other side of the equation, the specific needs for storing compressed air comes with a cost related to availability. Also, A-CAES gets a high score when it comes to the availability of appropriate locations to act as the underground cavern.

A-CAES shows low performance in the **diversity** dimension. Although in theory many different gases can be used to run A-CAES, the practice has been to use air. This makes A-CAES rely on one substance (air). Furthermore, the need for certain pressure and temperature conditions for the storage reduces the room for more diversity. Although researchers have been investigating other geological structures, so far the choices are limited.

The **cost** dimension is affected primarily by deciding on the location of an A-CAES plant, which has a high share of the investment cost. On the positive side, air is almost free globally, which results in a high level for the cost dimension. However, the cost of disruption results in a lower level if a natural disaster, e.g., earthquake, destroys the geographical cavern and the whole A-CAES plant needs to be built somewhere else, with a new investment cost, including finding an alternative location. Unlike the cost of disruption, securing the system will not have a high cost if underground facilities can be seen as naturally protected.

For the **technology and efficiency** dimension, technology advancement in A-CAES has potential, and there are ways of reducing costs. Further, A-CAES has a moderate cycle efficiency, thus efficiency is at a high level. In addition, as was noticed for PHS, A-CAES has a high energy density. The compressed air inside the cavern has high energy but is stored in a specific volume. Thus, A-CAES is more efficient and scores high in this dimension.

The **location** dimension has some limitations and risks. A-CAES has to be installed in specific geographical formations, such as salt deposits and hard or porous rocks. Although the surface land can be used for other purposes, which gives a positive score for this dimension, the fact that the needed specific geography can be far from human settlements means there are less possibilities for more distribution of the locations. Furthermore, A-CAES has a long

timeframe in which A-CAES plants can be operational. However, sudden events during installation can have negative impacts lasting for a very long time. This is also to be considered for the resilience dimension. A-CAES has a low adaptive capacity to face natural events that affect the plant. However, as for frequency, voltage control and seasonal variation, A-CAES shows high performance in adapting to the situation, as expected for energy storage systems.

The **environment** dimension shows a high score for A-CAES. The effect from the heating part of CAES has high impact on the environment if fossil fuel is used. Negative impacts on the environment from fossil fuels cause the environment dimension to worsen. In addition, polluted air as an input from the environment to CAES has a role to play in the efficiency. The need for a filtration step or the need for more energy processing of the particles in the air mean that the environment affects the CAES plants negatively. In contrast, A-CAES is at a high level of energy security when it comes to the environment. Life cycle assessment analyses on A-CAES in combination with wind show a positive impact on the environment [46].

The **health** dimension shows a high score. Most of the materials used for A-CAES have low negative impact on people. An exception can be considered for the compressed air. If a failure happens in the piping system, compressed air can be dangerous for workers around the leakage.

The next in the dimensions list is **culture**. As an energy storage that regulates the load and allows for the use of energy in periods of no generation, people will change their activities based on the new possibilities to have energy at various times. That is a positive change in the culture attained by A-CAES. However, this requires a well-informed society, which can be attained if care is taken about the **literacy** dimension. In addition, knowledge of how to run A-CAES needs to be with enough experts in order to provide the highest possible performance. Although A-CAES plants do not require high numbers of employees, which means low performance in the **employment** dimension, the needed workers should be educated and trained to a high enough level. This leads to the next dimension, where **policy** can make sure this work force is found in the society where A-CAES systems are built. Also, regulations and governance of A-CAES requires citizens who benefit from these systems to be consulted and their will of how to govern A-CAES plants should be followed.

Moving to the **military** dimension, energy intensive A-CAES plants can be a target for military operations that aim to take down energy infrastructure. Although effects are less in comparison to flooding a PHS reservoir, A-CAES can still be a target because of its impact on the energy system. The same can be discussed for the cyber security dimension. If A-CAES installations are controlled with high connectivity to the Internet, an attack does not need to be physical. A **cyber-attack** can result in a failure in the of an A-CAES plant. In addition, increases in the temperature or the pressure can result in pipes being destroyed and installations falling apart. For that, cyber security requires skilled IT personnel to be available in order to have high-energy security.

8. Gas and liquid storage

8.1. State of the art

Storing energy stored in chemical bonds within a material-based containment is one of the most common approaches as a simple and efficient technology [47]. Gas storage, mainly for methane, is currently practiced by compressing the gas at 207 bar and placing it in a pressure vessel, which requires costly multistage compression [48]. Alternatively, gases can be adsorbed in a porous material under a lower pressure requirement, e.g., 35 bar [48]. Usually, vessels are storage tanks that are used to store petroleum products and other liquid products, and there are recent efforts for designing and evaluating these tanks' performance [49]. Apart from the fossil fuels that are obtained from natural resources, nowadays the focus is shifted to the different methods of making the gas and the liquids, especially from renewable energy sources, e.g., traditional biofuels, but also solar fuels [18] or power-to-gas [50]. In this paper, the source of the gases and liquids are not as important as the analysis of the storage technology itself.

For the gas tanks, some standards were set for the characteristics of the vessels [49]. An example of gas storage in tanks is shown in Fig. 9. However, for the porous materials the adsorption approach, research is done to investigate different materials and different operating conditions [51].



Fig. 9. Gas storage tanks, taken from [52]

8.2. Energy security analysis

Starting with the **availability** dimension, availability can be at a high or low level based on what substance is used as the energy carrier. Gases and liquids used to store the energy means a high level of energy security. This has two reasons: the availability of renewable energy on a global scale, and the existence of technology to convert this renewable energy into gases or liquids. Furthermore, although researchers are investigating new porous materials, the availability of these materials is an issue sometimes. Therefore, the availability level decreases. In addition, for availability of means, gas and liquids storage seem to have a high score for this parameter. The reason is the availability of an in-place transporting system to/from the storage facilities. Even with centralised strategic reserves, the system has been built in a way to provide available access to these reserves at the moment they are needed. Even more, with the most available decentralised system of storage, vehicle fuel tanks are an example of a high level of availability of consumers to such energy storage options. Mobility has energy storage systems available to consumers all the time. Therefore, the availability dimension is at a high level.

Then comes the **diversity** dimension, with diversity of sources at a high level. Almost all places on the world can be used to harvest renewable energy, which can be easily then converted into gases and liquids. Also, there is plenty of water to run a water electrolyser to form hydrogen, and there are several different processes to form methane. Although these different options vary in their level of commercial availability, the diversity is achieved by the high number of options. The same analysis is carried out on what materials are to be used. Hydrogen, methane, synthetic oil, gasoline, etc., all can be used in energy storage. Thus, the diversity level for energy carriers is at a high level. Furthermore, the diversity of consumers is at a high level, too. Different fuels are chosen by different consumers. Industry, individuals, governments and corporations all account for the portfolio of this energy storage technology.

The **cost** dimension concerning storage of these fuels is on the cheaper end. Fuel tanks in automobiles, diesel tanks for district heating, jet fuel tanks, and others, provide the cost dimension with a high score when it comes to the price parameter. In contrast, the need for special porous material can affect the score in a slightly negative manner. What really affects the cost dimension is the cost of disruption, which is at a low level. The threat of a non-functioning hydrogen tank is intolerable. If an issue occurs to these chemical storage options, the cost to deal with that incident is high. Oil tankers are an obvious example of how much it costs to deal with a catastrophic event. Thus, to avoid disruption, it has always been an expensive practice to secure these storage technologies. Therefore, this parameter is at a low level of energy security.

Moving on leads to the **technology and efficiency** dimension. Research is taking place to advance the use of storing materials by advancing the characteristics of adsorption and pressure tolerance. This gives a high score for technology

advancement. However, the efficiency of such storage depends on the method used. If tankers are used, efficiency is at a high level. On the other hand, converting these chemicals into electricity goes in different stages based on whether they are burnt or taken into chemical processes. These conversion processes reduce the efficiency and lower the energy security level.

Regarding the **location** dimension, gas and liquid storage has a very high energy-density factor (a lot of energy is stored in a small volume). This puts the location dimension at a low level. Because centralised and decentralised systems can be used, more liberty and freedom of choice exist. In centralised systems where big tankers are used to store chemicals, land use is minimised. This means a low score for this parameter. In contrast, smaller storage vessels can be deployed globally with a decentralised system. Fuel tanks in the cars all over the world are an example of why this dimension gets a high score.

The next dimension is **timeframe**. As some of the storage is meant as strategic reserves, the timeline is long, thus the score of this parameter is at a high level. However, any sudden impact on the storage system can have severe effects for a long time. For example, if an earthquake causes centralised tankers to become empty, it will take a long time to refill all the tanks. This leads to a low score. In contrast, if an event of stress is more chronic, gas and liquid storage can cope with the stress. The fact that energy is stored in the chemical bonds of the substance gives a sense of security that the energy is preserved and can be used whenever needed. These parameters collectively result in a high score for the timeframe dimension. In addition, the same is true for the resilience dimension. Because energy is stored within the substance itself, the storage of these chemicals can adapt to any situation. This gives a high score for this dimension. However, the high risk of destruction by explosion or fire can cause gas storage to have less resilience.

Regarding the **environment** dimension, the first concern is the source of the substance that stores the energy. If it is from fossil fuels that are unfriendly to the environment, the score is low for energy security. However, if the source of the substance is environmentally friendly, this parameter is at a high level. For example, if hydrogen is produced by splitting water into hydrogen and oxygen using renewable electricity, then the process is clean compared to drilling to get fossil natural gas and converting the fossil natural gas via steam reforming to hydrogen. Afterwards, comes the transportation of the energy carriers. This is at a low level of energy security as the risks during the transportation are high. Moving bulk energy carriers in tanks could result in leakage, which may harm the environment. Furthermore, the effects of this storage on the environment is considered on the positive side. Storing these chemicals in one place has a high positive impact on the environment. Then comes the next parameter, the effect of the environment on the storage. Based on the technology used and whether cooling and/or compression are used, the environmental temperature can affect storage. For these reasons, the environment dimension is at a low level.

For the **health** dimension, the issue with these storage technologies is the nature of storing chemical. Most of the time, these chemical substances have dangerous or toxic effects on human health. Therefore, any direct exposure can negatively impact health. This puts the health dimension at a low level. Although healthier humans can utilise more of the storage in their daily lives e.g., driving cars for longer trips, that can only result in a slight increase in the energy security level. Overall, the assessment for the health dimension is at a low level.

Culture has been always affected by oil and gas storage. Bigger gasoline tanks in automobiles meant longer ranges of travel. People also changed some of their behaviour because of available storage of diesel or kerosene for heating. This puts the culture dimension at a high level. In addition, the life people try to achieve drives more development in storage technologies to flourish. All this puts the culture dimension at a high level.

From the culture to the **literacy** dimension, the simplicity of these storage technologies makes some of their information available to the public. In addition, the use of oil and gas inventories and their effect on the global economy make it important for the information to be provided on a second to second basis. Not only that, the information of how much energy is stored is used to speculate on and predict the performance of stock markets. These aspects show a positive relationship, however, in decentralised systems, e.g., gasoline tanks, as many people show a lack of knowledge to the danger of these tanks. Also, the information of what these vessels are made of is not well given to society. Therefore, the relationship to energy security is rather neutral.

From workers in gasoline stations to stock market brokers, this type of energy storage has affected their **employment**. Also, a higher employment rate means a stronger economy, which is reflected by an increase in energy storage capacity. Therefore, the employment dimension is at a high level of energy security.

The next dimension is the **policy** dimension. Because of the high importance of strategic energy storage, policies were shaped to ascertain a specific level of storage capacity. This is applied for the citizens’ benefit in democratic regimes to insure the availability of energy in any crises. Also, regulations were made to meet the targets by specialised agencies for governing the practice. All these factors put the policy dimension at a high level.

As the energy is stored within chemical bonds which are contained within materials, this type of storage has been always a target of **military** acts. It can be a target to destroy energy reserves or a target to seize these reserves. This puts the military dimension at a low level of energy security. In contrast, the use of this energy storage can support military efforts for a longer time. This gives a neutral score for energy security.

The last dimension is **cyber security**. The connectivity is typically low, thus the probability of cyber-attacks is reduced. This puts cyber security at a high level for energy security.

9. Summary of Assessment Findings

A summary of the inter-relations between all the storage technologies and energy security is presented in Table 2. The methodology to construct the summary table is based on the following steps:

- Each technology is summarized for all dimensions.
- Within each dimension, if there is a positive relation with any of its parameters, a plus is given.
- The same is applied if there is a negative relation to energy security because of any of the parameters.
- If the number of the plus elements in a dimension for the specific storage technology is more than the minus elements, the box is coloured in green.
- If the number of minus elements are more than the positive signs, the box is given a red colour.
- If the number of plus and minus elements are equal, the relationship is considered neutral for this dimension and the box is given a yellow colour.
- Then, the total energy security evaluation for each energy security dimension is presented in the last column.
- Green boxes are allocated of a value of +1, red boxes for a value of -1 and neutral boxes for a value of 0.
- The boxes are summed up. If the summation is positive for a storage technology, this technology enhances energy security. The higher the number, the better enhancement of energy security.

Table 2. Summary of energy security analysis. 1 Availability, 2 Diversity, 3 Cost, 4 Technology & Efficiency, 5 Location, 6 Timeframe, 7 Resilience, 8 Environment, 9 Health, 10 Culture, 11 Literacy, 12 Employment, 13, Policy, 14 Military, 15 Cyber Security.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
PHS	++	- +	+-	++	+-	+-	+	+	+++	+	+	+	++	-	-	+5
TES	++++	+++	++- +--	+++ +-	++++	++ -	+	++	+	++	++	+	++	-	-+	+9
Batteries	+++	+-	++ +	++	+++	++	+	---	---	++	---	+	+-	-	+-	+5
A-CAES	+-	-	+-	+++	+-	-	+-	---	+	+	+	+-	++	-	+-	+2
Gas/ Liquid Storage	+- ++	+++	+++	+-	+-	+	+	+- +	+-	+++	+++	++	+++	-	+	+5

10. Conclusions

In this paper, it was found that energy security analysis is important for PHS, TES, batteries, A-CAES and gas/liquid storage technologies. The analysis carried out for the fifteen dimensions of energy security resulted in an overview of the energy security levels of each of the storage technologies. TES achieved the highest score, with +9, then come gas/liquid storage, batteries and PHS, each with +5, and the least secure storage technology is A-CAES, with +2. It is found that all storage technologies have a positive relationship to energy security. However, the

difference of how positive the relationship is attributed to the dimensions analysis for each storage technology. TES has most of the dimensions in positive terms (10 dimensions), with only one dimension making a negative contribution (military) and four dimensions having a neutral relationship to energy security. For batteries, the situations is more in contrast between the dimensions, as most of the dimensions show a positive relationship to energy security (9 dimensions). However, fewer dimensions are in the neutral (2 dimension) range, and the rest are affected by a negative relationship (4 dimensions). The same can be noticed for gas/liquid storage, but with one less positive dimension (8 dimensions). The number of neutral dimensions is higher (4 dimensions), and there is one less negative dimension (3 dimension). Moving on, PHS has 8 dimensions on the positive side, 3 dimensions on the negative side and 4 dimensions on the neutral side. For the least secure storage system, A-CAES, there are 6 dimensions in a positive relationship, 4 dimensions in a negative one, and 5 dimensions in a neutral one.

Some energy storage options have the same number of positive dimensions, but their result ranking is different, which is referred to negative impacts. Furthermore, it is found that the least secure energy storage (A-CAES) has the highest number of neutral dimensions.

The conclusions drawn from this analysis are:

- All energy storage technologies have a positive relationship to energy security.
- Energy security analysis is an important aspect of evaluating energy storage options.
- There is a need to look carefully at the impacts of the chosen energy storage technology on the energy security of the system.
- TES has achieved the highest score in the energy security analysis, followed by gas/liquid storage, batteries, PHS and lastly A-CAES.

Choices of what energy storage to be used is linked to the energy security of the whole system and needs to be based on techno-economic requirements, which in turn provide recommendations for decision makers.

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References

- [1] A. Kunz, "Indian energy security. Nuclear energy policy," in "South Asia Politics (Lectures)," Charles University in Prague, Prague, Czech Republic 2012.
- [2] J. Bielecki, "Energy security: Is the wolf at the door?," *The Quarterly Review of Economics and Finance*, vol. 42, no. 2, pp. 235-250, //Summer 2002.
- [3] S. S. Haghghi, *Energy Security: The external legal relations of the European Union with major oil and gas supplying countries*. London, UK: Bloomsbury Publishing, 2007.
- [4] M. Asif and T. Muneer, "Energy supply, its demand and security issues for developed and emerging economies," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 7, pp. 1388-1413, 9// 2007.
- [5] J. Augutis, R. Krikštolaitis, S. Pečiulytė, and I. Konstantinavičiūtė, "Sustainable development and energy security level after Ignalina NPP shutdown," *Technological and Economic Development of Economy*, vol. 17, no. 1, pp. 5-21, 2011/03/22 2011.
- [6] IEA, International Energy Agency, *World Energy Balances 2016*. Paris, France: Organisation for Economic Co-operation and Development (OECD) Publishing, 2016.
- [7] A. H. Maslow, "A theory of human motivation," *Psychological Review*, vol. 50, no. 4, pp. 370-396, 1943.
- [8] A. Azzuni and C. Breyer, "Definitions and dimensions of energy security: a literature review," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 7, no. 7, p. e268, 2017, Art. no. e268.
- [9] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 785-807, 2015/05/01/ 2015.
- [10] IRENA, International Renewable Energy Agency, "Electricity storage and renewables: Costs and markets to 2030," International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates 2017, Available: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.
- [11] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy*, vol. 137, no. Supplement C, pp. 511-536, 2015/01/01/ 2015.
- [12] T. Economist, "Energy storage - Packing some power," ed. Online at [<http://www.economist.com/node/21548495>], accessed 08.Jan.2018: The Economist, 2012.
- [13] A. Abele, E. Elkind, J. Intrator, and B. Washom, "2020 strategic analysis of energy storage in California," University of California, Berkeley

School of Law, University of California, Berkeley, California, USA, 2011.

- [14] R. Lacal Arántegui, N. Fitzgerald, and P. Leahy, "Pumped-hydro energy storage: potential for transformation from single dams," in "JRC Scientific and Technical Reports," Institute for Energy and Transport, Luxembourg, Luxembourg 2012, vol. EUR 25239 EN Available: <https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/pumped-hydro-energy-storage-potential-transformation-single>.
- [15] J. Farfan and C. Breyer, "Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator," *Journal of Cleaner Production*, vol. 141, no. Supplement C, pp. 370-384, 2017/01/10/ 2017.
- [16] D. O. Akinyele and R. K. Rayudu, "Review of energy storage technologies for sustainable power networks," *Sustainable Energy Technologies and Assessments*, vol. 8, pp. 74-91, 2014/12/01/ 2014.
- [17] C. Breyer et al., "Solar photovoltaics demand for the global energy transition in the power sector," *Progress in Photovoltaics: Research and Applications*, 2017.
- [18] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progress in Natural Science*, vol. 19, no. 3, pp. 291-312, 2009/03/10/ 2009.
- [19] A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 2, pp. 318-345, 2009/02/01/ 2009.
- [20] M. F. Demirbas, "Thermal Energy Storage and Phase Change Materials: An Overview," *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 1, no. 1, pp. 85-95, 2006/01/01 2006.
- [21] Y. Ding, L. Tong, P. Zhang, Y. Li, J. Radcliffe, and L. Wang, "Chapter 9 - Liquid Air Energy Storage," in *Storing Energy*, T. Letcher, Ed. Oxford: Elsevier, 2016, pp. 167-181.
- [22] B. Zalba, J. M. Marin, L. F. Cabeza, and H. Mehling, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications," *Applied Thermal Engineering*, vol. 23, no. 3, pp. 251-283, 2003/02/01/ 2003.
- [23] D. Zhou, C. Y. Zhao, and Y. Tian, "Review on thermal energy storage with phase change materials (PCMs) in building applications," *Applied Energy*, vol. 92, pp. 593-605, 2012/04/01/ 2012.
- [24] A. Thess, "Carnot Batteries: Developments and Perspectives of Pumped Heat Electricity Storage," presented at the Energy Storage Europe (ESE) Conference and Exhibition, Düsseldorf, Germany, 2018.
- [25] H. L. Zhang, J. Baeyens, J. Degréve, and G. Caceres, "Concentrated solar power plants: Review and design methodology," *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 466-481, 2013/06/01/ 2013.
- [26] N. P. Siegel, "Thermal energy storage for solar power production," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 1, no. 2, pp. 119-131, 2012.
- [27] J. Michel, "Hamburg considers innovative heat storage scheme," ed. Online [http://energypost.eu/hamburg-considers-innovative-heat-storage-scheme] accessed 1.Feb.2018: Energy Post, 2017.
- [28] J. Y. Song, Y. Y. Wang, and C. C. Wan, "Review of gel-type polymer electrolytes for lithium-ion batteries," *Journal of Power Sources*, vol. 77, no. 2, pp. 183-197, 1999/02/01/ 1999.
- [29] W. Earle Waghorne, "Viscosities of electrolyte solutions," *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, vol. 359, no. 1785, p. 1529, 2001.
- [30] BBC, "Tesla mega-battery in Australia activated," ed. Online [http://www.bbc.com/news/world-australia-42190358], accessed 23.March.2018: BBC, London, UK, 2017.
- [31] D. C. R. Espinosa, A. M. Bernardes, and J. A. S. Tenório, "An overview on the current processes for the recycling of batteries," *Journal of Power Sources*, vol. 135, no. 1, pp. 311-319, 2004/09/03/ 2004.
- [32] A. M. Bernardes, D. C. R. Espinosa, and J. A. S. Tenório, "Recycling of batteries: a review of current processes and technologies," *Journal of Power Sources*, vol. 130, no. 1, pp. 291-298, 2004/05/03/ 2004.
- [33] P. Greim, A. A. Solomon, and C. Breyer, "Availability of lithium for the global transition towards renewable based energy supply with focus on power and mobility," *Submitted*, 2018.
- [34] D. Keiner and C. Breyer, "Modelling of PV Prosumers using a stationary battery, heat pump, thermal energy storage and electric vehicle for optimizing self-consumption ratio and total cost of energy," in *33rd European Photovoltaic Solar Energy Conference*, Amsterdam, The Netherlands, 2017: Modeling, September 25-29.
- [35] M. Ram et al., "Global Energy System Based on 100% Renewable Energy — Power Sector," Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Finland and Berlin, Germany 2017, Available: <http://energywatchgroup.org/wp-content/uploads/2017/11/Full-Study-100-Renewable-Energy-Worldwide-Power-Sector.pdf>.
- [36] N. Kittner, F. Lill, and D. M. Kammen, "Energy storage deployment and innovation for the clean energy transition," *Nature Energy*, Article vol. 2, p. 17125, 07/31/online 2017.
- [37] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, "The future cost of electrical energy storage based on experience rates," *Nature Energy*, Analysis vol. 2, p. 17110, 07/10/online 2017.
- [38] N. P. Lebedeva and L. Boon-Brett, "Considerations on the chemical toxicity of contemporary Li-ion battery electrolytes and their components," *Journal of The Electrochemical Society*, vol. 163, no. 6, pp. A821-A830, 2016.
- [39] S. S. Lee, Y. M. Kim, J. K. Park, S. I. Moon, and Y. T. Yoon, "Compressed Air Energy Storage Units for Power Generation and DSM in Korea," in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1-6.
- [40] B. McGrail et al., "Technoeconomic performance evaluation of compressed air energy storage in the Pacific Northwest," *Pacific Northwest National Laboratory, Richland, USA*, 2013.
- [41] F. R. Zaloudek and R. W. Reilly, "An Assessment of second-generation compressed-air energy-storage concepts," United States 1982-07-01 1982, Available: <http://www.osti.gov/scitech/servlets/purl/5273339>.
- [42] A. Gulagi, D. Bogdanov, and C. Breyer, "A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim," *Energies*, vol. 10, no. 5, 2017.
- [43] S. Succar, D. C. Denkenberger, and R. H. Williams, "Optimization of specific rating for wind turbine arrays coupled to compressed air energy storage," *Applied Energy*, vol. 96, no. Supplement C, pp. 222-234, 2012/08/01/ 2012.
- [44] R. Madlener and J. Latz, "Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power," *Applied Energy*, vol. 101, no. Supplement C, pp. 299-309, 2013/01/01/ 2013.

- [45] A. Gulagi, A. Aghahosseini, D. Bogdanov, and C. Breyer, "Comparison of the potential role of adiabatic compressed air energy storage (A-CAES) for a fully sustainable energy system in a region of significant and low seasonal variations," Dusseldorf, Germany, 2016, pp. 15-17.
- [46] E. A. Bouman, M. M. Øberg, and E. G. Hertwich, "Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES)," *Energy*, vol. 95, pp. 91-98, 2016/01/15/ 2016.
- [47] E. Tzimas, C. Filiou, S. D. Peteves, and J. B. Veyret, "Hydrogen storage: state-of-the-art and future perspective," in "EUR 20995EN," EU Commission, Institute for Energy, Petten, The Netherlands2003.
- [48] T. Düren, L. Sarkisov, O. M. Yaghi, and R. Q. Snurr, "Design of New Materials for Methane Storage," *Langmuir*, vol. 20, no. 7, pp. 2683-2689, 2004/03/01 2004.
- [49] E. Azzuni and S. Guzey, "Comparison of the shell design methods for cylindrical liquid storage tanks," *Engineering Structures*, vol. 101, pp. 621-630, 2015/10/15/ 2015.
- [50] C. Breyer, E. Tsupari, V. Tikka, and P. Vainikka, "Power-to-Gas as an Emerging Profitable Business Through Creating an Integrated Value Chain," *Energy Procedia*, vol. 73, pp. 182-189, 2015/06/01/ 2015.
- [51] H. Furukawa and O. M. Yaghi, "Storage of Hydrogen, Methane, and Carbon Dioxide in Highly Porous Covalent Organic Frameworks for Clean Energy Applications," *Journal of the American Chemical Society*, vol. 131, no. 25, pp. 8875-8883, 2009/07/01 2009.
- [52] M. Tanmay. (2018, 22-March). *Natural Gas Storage Market Projected to Grow at a CAGR of 7.2% for the period of 2015-2020*. Available: <https://businessservices24.com/90541/natural-gas-storage-market-projected-to-grow-at-a-cagr-of-7-2-for-the-period-of-2015-2020/>

Publication III

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Article

Energy Security Analysis for a 100% Renewable Energy Transition in Jordan by 2050

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Abstract: Energy security analysis is a strong tool for policy makers. It allows them to formulate policies that would enhance energy systems by targeting necessary actions. In this study, the impacts of transitioning from a fossil fuels to a renewables dominated energy system on energy security is analysed for Jordan. A Best Policy Scenario was developed for the Jordanian energy system to trace the transition to a 100% renewable energy system. Energy security was analysed for the future system by a qualitative approach utilising colour codes. The results reveal that the primary energy demand increases from 64 TWh in 2015 to 130 TWh in 2050, dominated by electricity and followed by heat and bioenergy. This indicates that a high level of direct and indirect electrification is the key to transition towards a fully sustainable energy system. Renewable electricity generation is projected to increase from 0.1 TWh in 2015 to 110.7 TWh in 2050, with a solar photovoltaic share of 92%. The levelised cost of energy develops from 78 €/MWh in 2015 to 61 €/MWh in 2050. In 2050, this system will have zero greenhouse gas emissions, it will provide plenty of job opportunities and revenue generation. This proposed transition will enhance the energy security level of the Jordanian energy system in five of the six dimensions studied. The five dimensions that will be improved are availability, cost, environment, health, and employment, whereas the dimension on diversity will stay neutral. It can be concluded that Jordan can achieve a 100% renewable energy system by 2050 and such a transition will enhance the energy security level.

Keywords: energy security; 100% renewable energy; sustainable energy transition; energy system modelling; energy policy

1. Introduction

This section presents a literature background on the concepts of energy security and energy transition. Then, the current situation of the Jordanian energy system is addressed. Furthermore, an analysis of energy security of the current system is provided. The last part of this section states the aim of this research and the gap it tries to cover.

1.1. Concepts of Energy Security and Energy Transition

Energy security is a universal concern [1]. Many studies attempt to discuss the topic [2–4] from the view of scientific fields [5], international affairs [6] and national security [7]. The ability of energy security to shape policies and national behaviour [8] makes energy security important. When policies and regulations are prepared, energy security has to be addressed because of its priority [9]. Energy security is a central aim for energy policy [10] because it allows for energy consumers' needs to be covered [11].

Although the concept of energy security is ‘as old as fire’ [12] and the discussion about energy security has a long history, scientific analysis following current research principles and standards are rare before 1975 [13]. In addition, although Ang et al. [1] stated that publications on energy security were rare before 2001, the topic has emerged as one of great importance [14] in the 21st century. The emergence is because energy is the engine for economic growth [3,15] with close links to economy [16,17] and a driver for civilization [18] and society [19]. In general, energy affects every aspect of life [20] and is thus crucial to the survival of a functioning modern society [3,21]. Therefore, enhancing energy security is a key goal of society [2,22–27]. Personal and national energy security are paths to freedom of choice, and thereafter, self-actualization as in Maslow’s hierarchy of needs [28].

There were many attempts to identify energy security throughout history [29–33]. Azzuni and Breyer [34] derived a comprehensive definition of energy security as “the feature (measure, situation, or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats”. This is linked to the 15 dimensions of energy security.

The definition and dimensions according to Azzuni and Breyer [34] are applied to the specifics of this research as follows: **energy security is the status in which the Jordanian energy system functions sustainably in the addressed dimensions freely from any risks**. Six dimensions were selected for investigation: availability, diversity, cost, environment, health, and employment.

1.2. Current Jordanian Energy System

Although Jordan is in the heart of the Middle East [35,36], it has managed to stay stable throughout the political unrest across the whole region. This may be attributed to the absence of fossil oil and gas resources, as it is considered a blessing to have no fossil fuels from a security perspective, since neighbouring countries with fossil fuels have been subject to the energy curse [37–39]. However, the absence of fossil fuels is linked to a high economic cost and financial burden on the Jordanian national budget [35,40], as Jordan has imported almost 96% of its energy needs [41]. Jordan has to pay around 20% of its gross domestic product (GDP) for energy imports [42].

Jordan has access to substantial renewable energy (RE) resources, which are mainly solar energy and wind energy in certain areas [35,40,43–45], that are still to be utilised, e.g., annual direct normal irradiation ranges between 1600–2300 kWh/(m²·a), global horizontal irradiation [46] and wind speeds of 6–8 m/s [35,47]. The current hydropower electricity generation accounts for only around 60 GWh [48], but with a future potential of 400–800 MW hydropower capacity [49] that could generate up to 200 GWh every year [50]. By 2012, biomass made up just 10 MW of capacity with less potential for future development [48]. There are proven reserves of shale oil of about 81,400 TWh_{th} (70 billion tons) [35,51,52]. The current situation for the Jordanian energy system is summarised in Table 1.

Table 1. Jordanian energy system overview for 2018. Data are obtained from [53].

Item	Unit	Value
Population	million	10.31
Energy intensity	MWh/kUSD fixed price	2.7
Energy consumption per capita	MWh	11.0
Electricity consumption per capita	kWh/capita	1701
Population access to electricity	% of population	99%
Total electricity consumption	TWh	17.5
Primary energy consumption	TWh	113
Energy imports	%	94%
Cost of consumed energy *	bUSD (bJOD)	4.25 (3.01)

* Cost of consumed energy comprised mainly the price of the respective fuels.

The Jordanian government approved the following projects [54,55] in 2018 and 2019:

- Start the direct incineration of oil shale for power generation, with an expected electricity generation capacity of 470 MW in 2020;

- Total RE capacity of 1800 MW in 2018;
- Reduce taxes on fossil gas for industries from 16% to 7% to promote industrial competitiveness;
- Agreement with Iraqi government to construct an oil pipeline through Jordanian territories to export oil through Aqaba seaport;
- Reception of 10 direct proposals for electricity storage projects with a capacity of 30 MW;
- Installation of 300 solar PV systems, 8000 solar thermal water heaters and 329 PV systems on mosques.

The Jordanian government aims to have a more diverse and reliable energy system and to increase the share of RE to 15% by 2050 [53], whereas recent research projects pathways for the Middle East leans towards 100% RE by 2050 [56].

1.3. Energy Security Analysis of the Current Situation

An energy security analysis linked to the energy transition enables to identify the best policies for the country and the consequences of these policies. Energy security enhancement is highly needed in the Jordanian context. For the politics in Jordan, enhancing energy security requires a stronger financial system and more stable governments. Energy security policies are seen to be interconnected with policies related to economic growth and stability, reducing poverty, the raising of living standards, political stability and the provision of public services [57].

Energy security analysis can be done qualitatively by addressing various aspects and dimensions of energy security. Alternatively, energy security can be assessed quantitatively by an indicators-based approach as proposed in the literature [58–61]. There is less research about energy security measurement in Jordan with clear methods of how energy security is evaluated well.

Existing research on energy security in Jordan needs to be further developed to overcome gaps, such as the absence of an energy security analysis that covers all the aspects and dimensions of the issue. Moreover, there is a gap in the measurable quantitative analysis of energy security. As the focus of energy security tends to be linked to geopolitics, fossil-based energy systems or renewables, Jordan is no exception with the literature presented by Alshwawra et al. [62]. They analysed energy security changes with historical events, but as it was mentioned earlier, their approach was limited to geopolitics in the realm of the fossil energy system.

In principle, energy security can be enhanced by more domestic supplies, but this may be limited, as can be seen from oil-rich countries. Komendantova et al. [63] used policy as a proxy for energy security concerns. They found that concerns for energy security, such as a reliable energy supply, safety considerations, and costs of electricity are more dominant for policy consideration. However, there was no real analysis of energy security for the current energy system. El-Anis [57] analysed energy security from the perspective of nuclear energy and its policies, and concluded that nuclear energy can ensure a more diverse system and less reliance on energy imports. It may be true that such a domestic resource might bring these benefits, however energy security also depends on several other dimensions. For instance, Ramana and Ahmad [64] found that nuclear energy will not be beneficial to the overall energy security because apart from diversifying the energy mix and reducing imports, the environmental impacts, cost structure and other dimensions of energy security would be negatively affected.

A quantitative analysis on energy security was done by the World Energy Council (WEC) [42], ranking Jordan in 108th place for the year 2019 with a value of 48%. However, this analysis does not disclose its methods of how energy security is measured. To the knowledge of the authors, the only publication that measures energy security in Jordan quantitatively was carried out by Azzuni and Breyer [65]. They found that the energy security level was at 40.5% for Jordan, ranking 118 out of 183 countries in the world. Jordan's best achievement has been found in the health dimension with a performance of 82%, which is attributed to a high level of expenditure in the healthcare sector.

In contrast, Jordan suffers the most in the availability dimension with 0.3%, as the current energy system is based on imported fossil fuels.

These studies reveal the low energy security level in Jordan, with substantial potential for improvement by an energy transition scheme towards a 100% RE system.

1.4. Aim and Novelty of This Research

This research aims to propose an energy transition pathway towards a 100% RE system in Jordan by 2050, and analyse how the energy security is enhanced as a consequence. This research contributes to the discussion of the feasibility of 100% RE systems, together with providing a detailed pathway of how to achieve such a sustainable future by 2050. Moreover, the novelty of this research lies in its unique approach of analysing impacts of a future energy system on energy security. Furthermore, this study investigates the relationship between the decarbonisation of the energy system and energy security in a qualitative approach based on a comprehensive framework. In addition, it provides clear recommendations for sustainable policy adoption in one of the developing countries, Jordan. This study provides an outlook of sustainable energy use, where access to energy is secured for all people while mitigating the effects of energy use on the environment by eliminating greenhouse gas (GHG) emissions. The applied LUT Energy System Transition model uses energy economics to optimise the lowest cost mixture of energy technologies in the energy system to build a future 100% renewable energy system.

In Section 2, the methods for the energy transition scenario and the energy security analysis are introduced. The results of the energy transition scenario are presented and discussed in Section 3. Discussion about the energy security benefits and the impact of a 100% RE system transition on energy security are addressed in detail in Section 4. Section 5 presents the conclusions and the respective consequences on energy security.

2. Methods and Data

In this section, the detailed methods and data formulation are described. A Best Policy Scenario for the period from 2015 to 2050 is defined. The last part of this section details the methods for the energy security analysis.

2.1. LUT Model Overview

The LUT Energy System Transition model [66,67] was employed to investigate the feasibility of the energy transition in Jordan. This model is an optimisation tool, which defines cost-optimal energy system structures under several technical and financial assumptions across the power, heat, transport and desalination sectors. The heat and electricity demand for the industry sector are considered as a part of the heat and power sectors, respectively. The model works on an hourly resolution for the transition period from 2015 to 2050 in 5 year time intervals. The target function of the model is to achieve a minimal annualised cost of the energy system at each step of the transition.

Figure 1 presents the process flow of the LUT Energy System Transition model. A detailed description of the model is given by Bogdanov et al. [67] for the power sector alone, by Bogdanov et al. [68] for the power and heat sectors integrated, and by Ram et al. [69] for the power, heat, transport and desalination sectors. The schematic block diagram for the integrated power and heat sectors is shown in Figure 2. The respective block diagrams for the transport and desalination sectors are presented in the Supplementary Material (Figures S3–S5).

The optimisation was carried out in two stages. In a first step, the demand for prosumers has to be met in hourly resolution for the residential, commercial and industrial sectors, through the respective installed capacity of solar PV and battery storage, as well as the individual heating capacities. Prosumers' demand is limited to 20% of the total demand by 2050, whereas up to 50% of total generation of prosumers can be fed into the grid [67]. In a second step, the demand for all sectors has to be met in every hour of the applied year. The optimisation is conducted for the power and heat sectors as

an integrated case, while the transport and desalination sectors are simulated individually. The RE installed capacity is limited to a maximum of 20% growth in every 5 year time step to eventually achieve a 100% RE-based energy system by 2050. Additionally, no new nuclear and fossil-based power plants are allowed to be installed after 2015. The existing capacities, however, can remain until the end of their actual lifetime. Gas turbines can still be active in the system, since sustainably produced synthetic natural gas and biomethane can be converted via gas turbines.

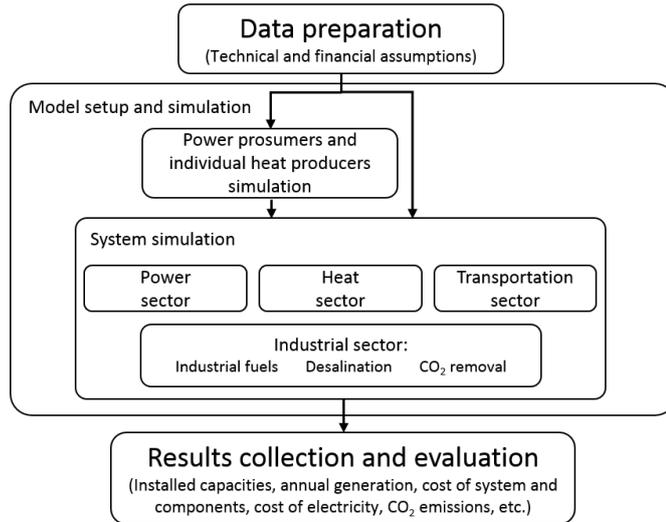


Figure 1. Fundamental structure of the LUT Energy System Transition model [67,69].

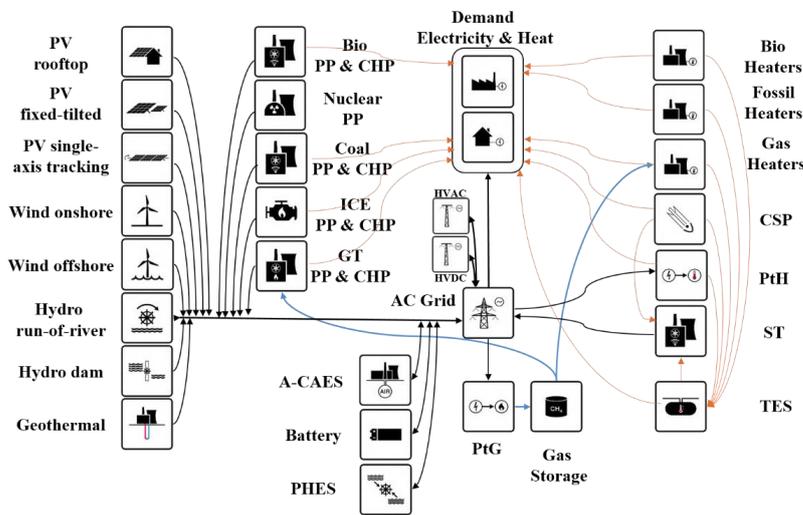


Figure 2. Schematic of the LUT Energy System Transition model for the power and heat sectors [68]. Abbreviations: A-CAES—adiabatic compressed air energy storage, CHP—combined heat and power, CSP—concentrated solar thermal power, GT—gas turbine, ICE—internal combustion engine, PHEs—pumped hydro energy storage, PP—power plant, PtG—power-to-gas, PtH—power-to-heat, PV—photovoltaic, ST—steam turbine, TES—thermal energy storage.

2.2. Country Data and Assumptions Used in the Model

The current energy demand across various sectors is collected and the future demand projected. The respective hourly demand profiles are generated and set as input data in the model. The power sector demand profile was taken from Toktarova et al. [70] in order to generate the respective synthetic load profiles from 2015 to 2050. The power load profile included the cooling demand provided by air conditioning as discussed in Toktarova et al. [70]. Heat demand is classified into four categories: space heating, domestic hot water heating, industrial process heat, and biomass for cooking. In terms of temperature, heat demand was divided into three groups: low, medium and high. It is projected that biomass for cooking will decline as the transition gets closer to the end. This projection can be justified as the energy system becomes more efficient and all residences in the country will have access to clean energy at the latest by 2050. There are four types of transport mode in the system: road, rail, marine and aviation. Each of the transport modes includes passenger and freight as a sub-category. Transport sector data were taken from Khalili et al. [71]. The impact of smart charging and vehicle-to-grid concepts was excluded from this study. The desalination demand was collected from Caldera et al. [72]. The projected desalinated water demand is related to the municipal, industrial and agricultural sectors. The final energy demand by sectors and energy form is shown in Figure 3. The detailed data are tabulated and provided in the Supplementary Material (Tables S1–S7 and Figures S1 and S2).

The historic weather data for the year 2005 was applied, as explained in Bogdanov et al. [67]. The resource profiles in high spatial and temporal resolutions for solar PV, concentrating solar power (CSP), wind energy and hydropower were prepared. The sustainable potential of bioenergy [73] and geothermal energy [74] were collected and used as an upper limit. The current installed power plant capacities were structured by technologies and commissioning year, in an annual resolution from 1960 to 2015 (end of 2014), according to Farfan and Breyer [75]. Access to this level of data helps to better account for power plant capacities that have to be phased out at the end of their lifetimes. Furthermore, technical and financial assumptions for all the technologies used in the model were gathered from different sources and provided in the Supplementary Material (Tables S8–S10).

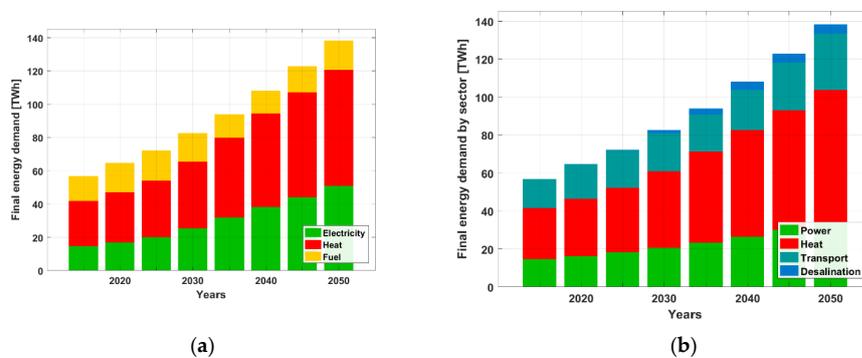


Figure 3. Development of the final energy demand by the energy form (a) and by the sector (b) for Jordan.

2.3. Scenario Definition

The LUT Energy System Transition model can be employed to analyse a wide variety of scenarios across different global regions. The objective of this study was to emphasise on a transition towards an entirely renewable energy-based energy system, which results in reaching zero GHG emissions in the energy sector at the latest by 2050, which is in line with the ambitious target of the Paris Agreement [76] and the sustainable development goals of the United Nations [77] with further justification by the Intergovernmental Panel on Climate Change, IPCC Special Report on 1.5 °C [78]. The Best Policy Scenario fulfils these criteria, wherein the demand for the power, heat, transport and the desalination

sectors has to be met by 2050, using a mix of RE, energy storage and other flexibility options such as power-to-X (PtX) technologies. The transition was planned from the current unsustainable energy system towards a fully renewable-driven energy system by 2050 in Jordan.

The financial and technical assumptions for all the technologies involved in the modelling were obtained from different sources, and are presented in the Supplementary Material (Tables S8–S10). They include the learning curves of all the key technologies, which were considered to have a direct or indirect impact on the future costs since they were a crucial element for determining the cost-optimal energy transition pathways. The simulation was then carried out using the modelling setup of the LUT model, including all the critical aspects of the power, heat, transport and desalination sectors. Here, 108 energy technologies throughout the different sectors were integrated.

2.4. Method for Energy Security Analysis

This research focuses on a soft qualitative analysis of energy security, following the conceptual dimensionalisation according to Azzuni and Breyer [34]. The connections between these dimensions and energy security was established with strong argumentations of the nature of the connections and their relationships to energy security. An analysis of the future 100% RE system in Jordan from an energy security perspective will follow the dimensions identified as the most important ones from previous research [34].

Energy transition towards a 100% renewable energy system affects the availability dimension on the level of resources, means and consumers. For the diversity dimension, the transition will provide insights on how diverse the energy supply will be, based on what energy carriers, energy sources and energy use exist. The cost dimension comprises energy prices and their stability due to the energy transition. The impact of such a transition on the environment and the health dimensions will be addressed in detail, followed by the dimension of employment.

The analysis was carried out by addressing the parameters of each dimension. If a parameter or an aspect of a dimension was positively affected, then this dimension obtained a positive sign. The same qualitative analysis was carried out for the negative impacts of the energy transition on energy security. If the consequences of the transition negatively influenced aspects within a dimension, then a negative sign was given. The overall evaluation of a dimension was a numerical sum of the positive and negative signs.

A colour code was used to visualise the impact of a 100% RE transition on energy security for each analysed dimension. The colour depends on how many positive or negative impacts each dimension will obtain throughout the analysis. If the total number of positive impacts is higher than that of the negative ones, then the colour is given for that dimension as green, if lower it is given red and if positive impacts and negative impacts are equal then the dimension is coloured yellow. Each positive impact is represented by a plus symbol and each negative impact is presented by a minus symbol.

3. Results

Simulation results to attain a fully sustainable energy system across the power, heat, transport, and desalination sectors in Jordan by 2050 show that a transition towards a 100% RE energy system for Jordan would be technically feasible and economically viable, based on the input data considered. The energy supply would come from local and distributed renewable resources. Consequently, it implies that the Jordanian energy system could reduce its direct GHG emissions to zero by 2050, while at the same time gaining energy independence.

The results are structured as follows: Section 3.1 presents an overview of the sustainable future energy system in Jordan by 2050. The results for power and heat are presented in Section 3.2, whereas the transport sector results are presented in Section 3.3, and the desalination sector is presented in Section 3.4. For the cost structure and capital expenditures, Section 3.5 shows the attained results. Sections 3.6 and 3.7 present GHG emission reduction and employment opportunities, respectively, in relation to the energy transition towards a 100% RE system in Jordan by 2050.

3.1. Development of the Future Energy System

The results for primary energy demand by the form of energy and sector are presented in Figure 4. The need for primary energy generation will increase until 2050 due to strong growth in the demand for energy services. At present, fossil fuels are able to cover the primary energy demand of around 90 TWh, which is less than 113 TWh, the figure listed in Table 1, since non-energetic fuel demand, conversion losses in refineries, effects of import and export and others are not part of this study. The primary energy demand will increase to slightly more than 140 TWh by 2050. Much of this energy demand can be provided via large electrification in the country, as shown in Figure 4a. Among the sectors, demand for the transport sector increases the most, which transitions from a fossil-based system towards a transport sector with high levels of direct electrification and synthetic fuels powered by indirect electrification. The demand for the power and heat sectors experiences a slight increase in primary energy from 2015 to 2050, whereas desalination demand grows due to the projected high water stress in the coming decades.

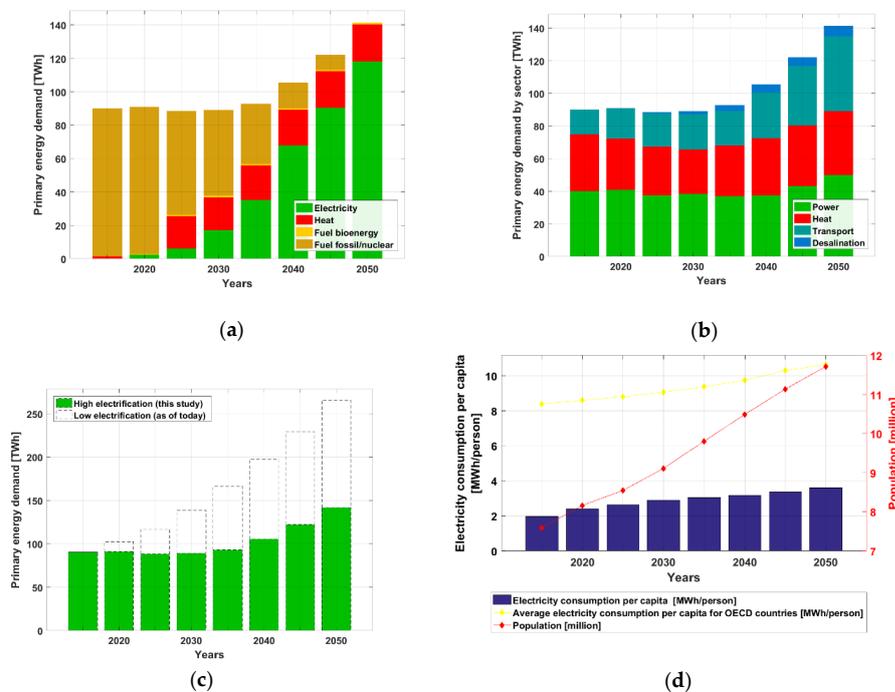


Figure 4. Development of the primary energy demand by the form of energy (a), sector-wise (b), the efficiency gain in primary energy demand (c) and the electricity consumption per capita (d) through the transition for Jordan. The displayed population, taken from the UN [79], excludes non-permanent refugees.

From the total primary energy demand of around 140 TWh in 2050, renewable electricity contributes 85%. The remaining 15% comes from renewable energy-based heat and bioenergy. Primary renewable electricity generation grows considerably from less than 1 TWh in 2015 to around 120 TWh in 2050, as shown in Figure 4a, dominated by solar PV and supported by wind energy. High electrification as a result of an effective policy in Jordan can make a substantial difference over the transition. As indicated in Figure 4c, almost half of the primary energy demand is required compared to a business-as-usual or

low-electrification condition. This shows one of the positive effects of the high penetration of RE and comprehensive electrification, as well as a right policy in the country.

3.2. Power and Heat Sectors

The total electricity generation capacity increases drastically from less than 5 GW in 2015 to nearly 40 GW in 2050. Solar PV dominates the total electricity capacity in 2050, mainly driven by fixed-tilted PV with around 60% of total installed capacity. In the initial periods of the transition until 2035, the share of fixed-tilted PV is insignificant, while onshore wind and single-axis tracking PV emerge starting from 2025. In the later part of the transition, the energy system is mainly run by solar PV, which is due to the great potential and availability of this resource across Jordan, as well as its continued cost reduction. Although the share of onshore wind and solar PV is almost comparable in 2030, the cost competitiveness of solar PV in comparison to wind energy makes PV a more attractive option from 2035 onwards. Other RE technologies, such as CSP, geothermal and bioenergy, complement solar PV and wind power, especially during the peak hours, and also when none of these resources are available. The contribution of fossil fuels goes down through the transition to zero by 2050. A small installed capacity of gas remains in the system, but the fuel shifts from fossil gas to synthetic natural gas powered by renewables and biomethane.

In the heat sector, heat pumps play an integral role contributing to over half of the capacity mix from 2030 to 2045, and even higher in 2050, as given in Figure 5. The majority of heat pump capacity comes from the individual heat sector by 2050, and the remaining fossil fuels are phased out in the last period to achieve a fully sustainable energy system. In addition, some shares of direct electric heating, non-fossil gas, solar thermal heat, CSP solar field, geothermal heat, and biomass-based heating contribute to the total heat generation by 2050. In contrast, heat generation that mainly comes from oil and coal-based heating in 2015 decrease considerably over the transition, and finally to zero by 2050.

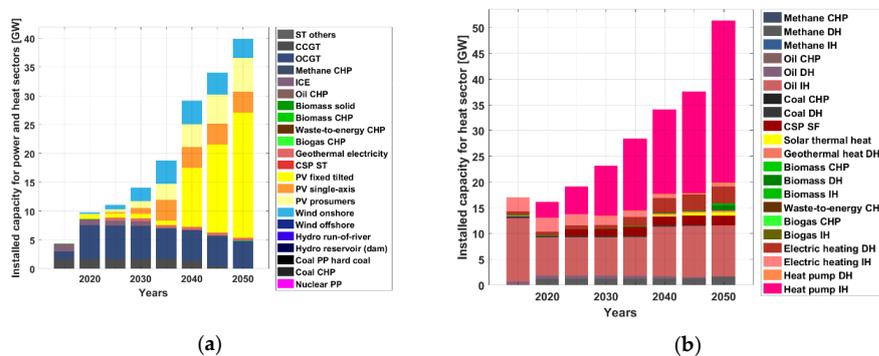


Figure 5. Development of the electricity generation capacity (a) and the heat generation capacity (b) in the integrated heat and power sector from 2015 to 2050 for Jordan.

The respective figures and tables for electricity and heat generation are provided in the Supplementary Material (Table S11, Tables S14–S17 and Figure S6).

The role of energy storage is vital through the transition, especially with the great contribution of solar PV and wind energy. As the sun might not shine and the wind may not blow during every hour of the day, electricity can be stored via energy storage technologies during the hours when the generation is more than the demand. The stored energy can be utilised in the absence of sufficient energy. This phenomenon can be well seen towards the end of the transition, where a higher penetration of solar and wind energy is observed. As shown in Figure 6a, the installed capacity of batteries start emerging from 2025, with an installed capacity of around 1 GWh_{cap}, to approximately 67 GWh_{cap} in 2050. A higher share of PV induces larger energy storage capacities for diurnal balancing. Adiabatic

compressed air energy storage (A-CAES) contributes to the total electricity storage capacity, starting from 2035 until 2050. Electricity storage output is dominated by large-scale batteries, prosumer batteries and A-CAES, in total around 31 TWh_{el} by 2050, as given in the Supplementary Material (Figure S7).

Similarly, heat storage plays a crucial role in covering the heat demand in Jordan. As presented in Figure 6b, gas storage dominates the storage technologies in terms of the total installed capacity. The initial heat storage capacity is installed in 2025, where thermal energy storage for district heating accounts for the entire capacity with around 4 GWh_{th}. From 2040 onwards, a massive capacity of gas storage is added with nearly 900 GWh_{th}, and it increases to almost 2900 GWh_{th} by 2050. With regards to the heat storage output, both thermal energy storage and gas storage are key elements to cover more than 14 TWh_{th} of the heat sector demand during all hours by 2050, as shown in the Supplementary Material (Figures S7, S11 and S12).

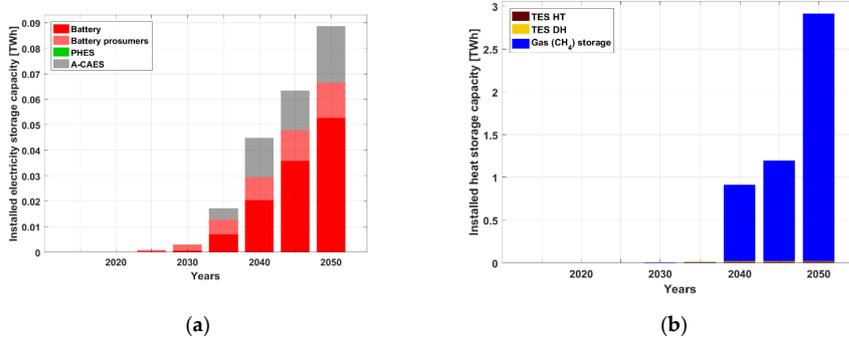


Figure 6. Development of the electricity storage capacity (a) and the heat storage capacity (b) in the integrated heat and power sector from 2015 to 2050 for Jordan. Abbreviations: HT—high temperature, DH—district heating.

3.3. Transport Sector

Final energy demand for the transport sector was around 15 TWh in 2015, which increases gradually from 2020 to 2040. The demand soars towards the end of the transition period with slightly less than 30 TWh in 2050. Electricity utilisation grows in the transport sector, from almost zero in 2015 to more than 10 TWh in 2050. Towards the end of the transition, sustainably produced hydrogen, methane and biofuels contribute considerably. By 2050, more than half of the demand is covered by these three resources. The transport sector shows an electricity demand of roughly 43 TWh by 2050. The substantial demand for renewable electricity-based synthetic liquid fuels emerges from 2040 onwards up to 2050, as shown in Figure 7b. The same trend can be observed for the case of hydrogen, growing from less than 1 TWh in 2030 to around 10 TWh in 2050. The contribution of hydrogen and renewable electricity-based synthetic liquid fuels was mainly to satisfy the demand for the marine and aviation transport modes in the final steps of the transition, and some remaining demand from the road and rail transport modes.

Installed electricity generation capacity for the transport sector upsurges from roughly zero at the beginning of the transition to around 25 GW in 2050, as shown in Figure 8a. From the total installed capacity, the fixed tilted and single-axis tracking PV are the predominant technologies with small shares of onshore wind, as these two technologies are the least costly electricity sources in Jordan. The majority of capacity addition occurs from 2040 onwards, where the contribution of single-axis tracking PV increases. High direct and in particular indirect electrification levels in the transport sector lead to a climb in installed capacities for the last three periods of the transition, as illustrated in Figure 8b. Electricity generation from solar PV started from 2020 with around 80 GWh. This amount increases to about 7 TWh in 2035 and further rises to 45 TWh in 2050. Fixed tilted and single-axis

tracking PV account for 55% and 44% of the total electricity generation in 2050, respectively, with the remaining 1% coming from onshore wind.

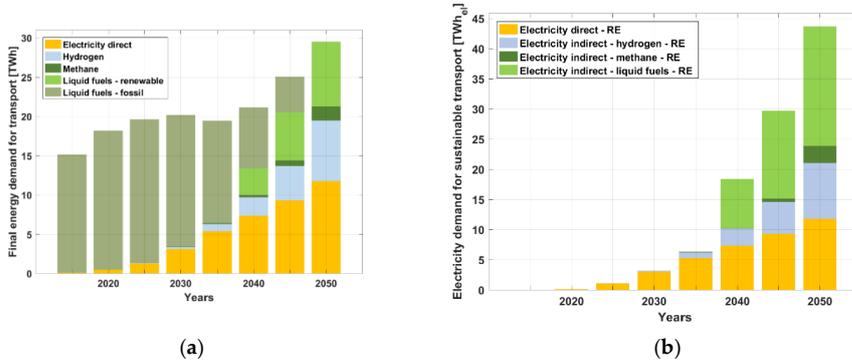


Figure 7. Final energy demand for transport (a) and the electricity demand for sustainable transport (b) during the energy transition for Jordan.

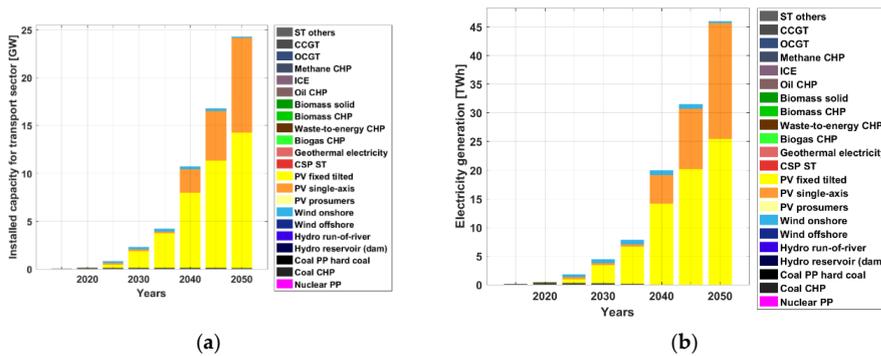


Figure 8. Installed power generation capacity (a) and the electricity generation (b) for the transport sector from 2015 to 2050 for Jordan.

Another crucial aspect that can play an important role for shifting away from fossil fuels towards high electrification of the transport sector is the production of hydrogen and synthetic fuels. As shown in Figure 9, the installed capacities of fuel conversion technologies increase drastically from about 4 GW_{output} in 2040 to more than 12 GW_{output} in 2050. Water electrolysis consists of the highest share of fuel conversion capacities through the transition, followed by hydrogen liquefaction units, Fischer–Tropsch synthesis plants and to a lesser extent liquefied natural gas (LNG) units, converting renewable electricity-based synthetic natural gas or biomethane, if available, into LNG. In addition, the required heat during the synthetic fuels production, which is mainly for CO₂ direct air capture (DAC), can be supplied via recovered process heat. This measure makes the energy system more efficient, since the heat that would be wasted is otherwise reutilised by the CO₂ DAC units. Total heat management reaches 6 TWh_{th} by 2050, which comprises 1.6 TWh_{th} of the recovered heat and 4.4 TWh_{th} of excess heat.

Additional tables and figures for installed generation capacities for fuel conversion and energy storage are given in the Supplementary Material (Tables S12 and S18–S20 and Figures S8, S9 and S13).

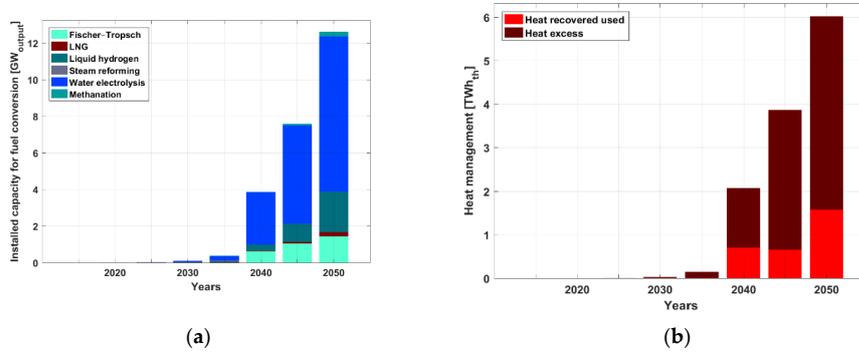


Figure 9. Installed capacity for fuel conversion (a) and heat management for the production of synthetic fuels (b).

3.4. Desalination Sector

Jordan is one of the most water-stressed countries in the Middle East. As can be seen in Figure 10a, almost half of the total water demand in 2050 can be met by desalinated water. The entire desalination capacity comes from the seawater reverse osmosis (SWRO), which is one of the most promising desalination technologies [80]. SWRO is another Power-to-X application, since low-cost electricity is converted into clean water. A small amount of water storage starts contributing by 2040 and remains almost unchanged until the end of the transition. In terms of the levelised cost of water (LCOW), capex contributes to almost half the cost in 2015, in a period when fossil fuels are still the main supply of energy for running the desalination plants. However, the overall LCOW declines towards the end of the energy transition, as the capex and opex decrease. The LCOW falls from 1.1 €/m³ in 2015 to 0.6 €/m³ in 2050. The share of RE-installed capacity climbs from practically zero in 2015 to approximately 4 GW in 2050. As shown in Figure 11a, gas turbines are the predominant contributors until 2025, whereas solar PV and wind energy emerge from 2030 onwards. A massive amount of fixed tilted PV is installed in 2035, with a capacity of 1 GW, and it continuously increases up to 3 GW by 2050. With regards to total electricity generation in the desalination sector, combined cycle gas turbine (CCGT) plays a key role in the first periods of the transition, whereas RE capacities dominate the second half of the transition, as they are the lowest cost energy sources through the energy transition (Figure 11b).

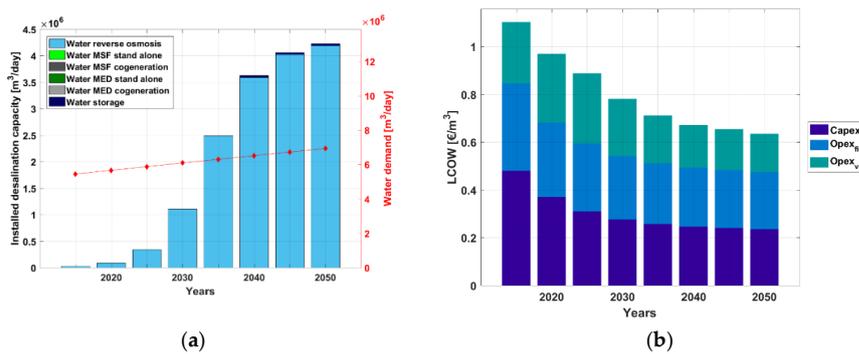


Figure 10. Installed desalination capacity (bar graph, left axis) and the total water demand (line plot, right axis) (a), and the levelised cost of water (LCOW) (b) during the energy transition for Jordan. Abbreviations: MSF—multi-stage flash distillation, MED—multiple-effect distillation.

Additional figures for the LCOW by main cost categories and seawater desalination production by technology are given in the Supplementary Material (Tables S13, S21 and S22 and Figures S14 and S15).

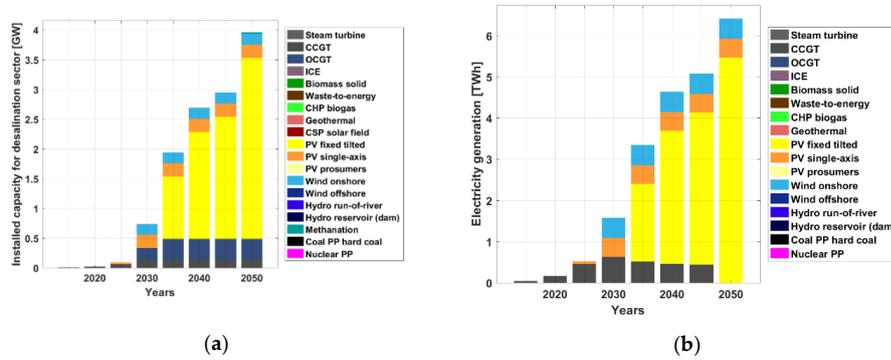


Figure 11. Installed electricity generation capacity (a) and the electricity generation (b) for the desalination sector from 2015 to 2050 for Jordan. Abbreviations: CSP: concentrated solar thermal power, CCGT—combined cycle gas turbine, OCGT—open cycle gas turbine.

3.5. Cost Structure and Investments

The total annual energy system cost increases during the energy transition, from nearly 6 b€ in 2015 to around 8.5 b€ in 2050 (Figure 12a). Higher investments are particularly needed in the heat sector, followed by the transport, power and desalination sectors. This indicates that fuel imports will fade out through the transition as high shares of RE start contributing and the country becomes independent from energy imports. Additionally, as shown in Figure 12b, after a rapid decrease from around 105 €/MWh in 2015 to 80 €/MWh in 2020, the levelised cost of energy decreases gradually in the following years up to 2040 and reaches 60 €/MWh. Then, it almost stabilises towards the end of the transition. In the last period of the transition, the levelised cost of energy again increases slightly by 4%. Since a tremendous amount of RE capacity is to be integrated into the energy system, the share of fossil fuel and GHG emission cost goes down towards the end of the transition and finally turns to zero in 2050. At the same time, capital expenditures continue to grow due to high-investment requirements for introducing solar PV and wind energy, as the predominant RE sources, complemented by further energy system components, in particular Power-to-X technologies, as shown in the Supplementary Material (Figure S10). The sectoral cost breakdowns are presented in the Supplementary Material (Figures S11–S14).

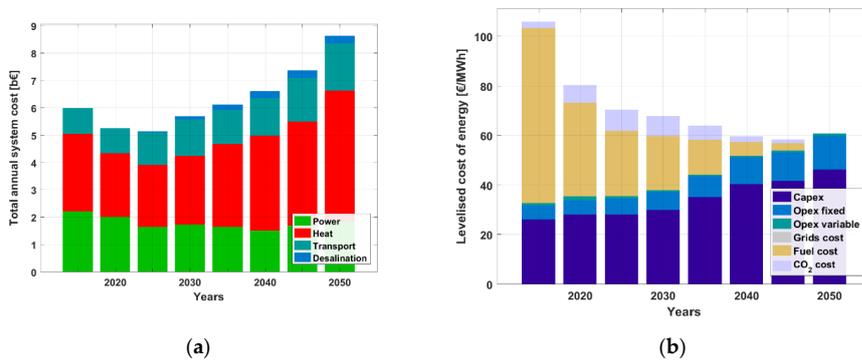


Figure 12. Total annual energy system cost (a) and the levelised cost of energy for all the sectors combined (b) from 2015 to 2050 for Jordan.

3.6. GHG Emissions

One of the positive impacts of transitioning to a 100% RE-based energy system is the defossilisation of the energy system. It means the amount of GHG emissions will be reduced from around 24 MtCO_{2eq} in 2015 to zero in 2050. As illustrated in Figure 13, heat and power sectors account for the main part of the GHG emissions for most of the first half of the transition, whereas most of the GHG emissions come from the transport sector in the second half of the transition. The respective figures for each sector are provided in the Supplementary Material (Figure S16). As shown, the amount of GHG emissions continuously declines for both the power and heat sectors, while it takes longer for the transport and desalination sectors. In the transport sector, after an increase from 3.8 MtCO_{2eq} in 2015 to 4.7 MtCO_{2eq} in 2025, the GHG emissions fall to 4.3 MtCO_{2eq} in 2030. Then, it decreases sharply in the last few steps of the transition. Similarly, GHG emissions in the desalination sector decrease gradually from 2030 to 2045, after a rapid increase from 2015 until 2030. The rise in the first half of the transition is due to an increase in the capacities of gas turbines in the energy system, while their utilisation is reduced towards the end of the transition and brought to zero emissions by substituting fossil gas with synthetic methane and biomethane.

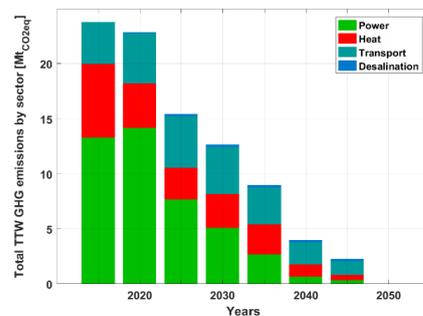


Figure 13. Total GHG emissions by sector during the energy transition from 2015 to 2050. The tank-to-wheel (TTW) approach [71] indicates that the emissions of the final conversion are regarded, while further emissions may occur in the upstream value chain.

3.7. Employment Opportunities

Jordan has come a long way in terms of infrastructure development since its independence in 1946, and it now boasts effective and modern facilities in telecommunications, power and electricity, water, and transport infrastructure [81]. It also has a growing RE sector and as highlighted by the results, a transformation in the energy system across the power, heat and transport sectors has various benefits. Unemployment in Jordan remains stubbornly high, even during the recent high economic growth years. Unemployment rates, especially among youth, have remained in the double digits over the last decade at around 12% [81]. In this regard, job estimations on the basis of the results of this study and adopting the method from Ram et al. [82] show that the energy transition in Jordan has huge employment benefits. The total number of direct energy jobs across Jordan is observed to increase from just around 20 thousand in 2015 to more than 105,000 by 2050, as indicated in Figure 14 (left). Power and heat sectors create the most jobs through the transition, complemented by jobs in the storage, transmission and distribution technologies as highlighted in Figure 14 (left). In addition, renewable electricity-based synthetic fuel production creates some jobs from 2040 onwards. Jobs created by various technologies across the power, heat, fuels and storage sectors can be found in the Supplementary Material (Figures S17 and S18).

Figure 14 (right), also indicates the distribution of jobs across the different categories during the transition period in Jordan. With the rapid installation of capacities up to 2035, the bulk of new jobs is created in the construction and installation of power, heat and storage technologies. Manufacturing jobs

have a relatively lower share in the initial periods up to 2025, as the share of imports is high. From 2025 onwards, as domestic production capabilities build up, a higher share of manufacturing jobs are observed until 2050 with over 20% of the total jobs. The share of fuel-related jobs continues to diminish from 2020 onwards through the transition period, as fossil fuels are replaced with synthetic fuels, reaching just 1% of the total jobs by 2050. On the other hand, the share of operations and maintenance jobs grows through the transition period up to 36% of total jobs by 2050. Transmission and distribution jobs increase through the transition contributing to about 6% of the jobs by 2050. This means more stable jobs for a region suffering from high unemployment amongst the youth and a growing number of economic migrants. A higher share of investments in developing sustainable power infrastructure could be the right catalyst to create long-term jobs in this region [83]. As Cote [83] highlights, the combined challenges of growing energy demand and labour market pressures present the government of Jordan not only with an opportunity to diversify their energy mix, but also to help mitigate high youth unemployment and assist in creating higher-skilled jobs. The electricity-generation-specific jobs increase initially from 1198 jobs/TWh_{el} in 2015 to 1631 jobs/TWh_{el} in 2025 with the rapid ramp up in RE installations. Beyond 2025, with increasing levels of technology development and automation, specific jobs decline steadily to around 872 jobs/TWh_{el} by 2050, as shown in Figure 14 (right).

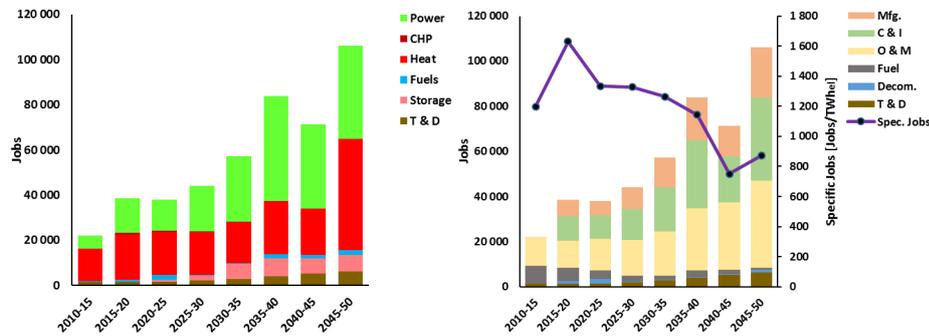


Figure 14. Jobs created by the various energy system technologies (left) and the jobs created based on different categories with the development of electricity-demand-specific jobs (right) during the transition from 2015 to 2050 in Jordan. Abbreviations: Mfg.—manufacturing, C&I—construction and installation, O&M—operation and maintenance, Decom.—decommissioning, T&D—transmission and distribution, Spec. Jobs—electricity-demand-specific jobs.

4. Discussion

4.1. Energy Transition

The results of the energy transition show that not only is it a Best Policy Scenario for a 100% RE system possible for Jordan, but it also is feasible as a low-cost option for the entire energy system. The Best Policy Scenario will result in a reduction of primary energy demand by around half of what would be the primary demand of a business-as-usual projection. This result is due to the high efficiency of electricity-based systems, in comparison to fossil-based systems, linked to low-efficiency combustion processes. Such improvements in efficiency will not only reduce wasted energy, but will also reduce GHG emissions to zero, as was presented in Figure 13. The elimination of GHG emissions was not only due to increased efficiency, but also the source of the energy in use. A 100% RE system in the context of Jordan means the reliance on solar PV and wind energy. Therefore, most of the installed capacities for power and heat generation are PV systems and wind turbines. The elimination of GHG emissions is supported by shifting the transport sector to sustainable solutions, as shown in Section 3.3. Although the energy demand for the transport sector increases in absolute terms, it declines in relative terms per passenger kilometre and tonne kilometre.

The findings of this research clarify a future path for the opportunities associated with RE, that was found in previous research by Jaber et al. [47]. This paper agrees with the opportunities that renewables can bring into the Jordanian energy system; a further step was to show a Best Policy Scenario of how to seize these opportunities and benefit from them to positively impact energy security levels. Results in this research highlight that the renewable energy potential in Jordan, as outlined by Anagreh and Bataineh [84], can pave the way for raising the standards of living according to the Best Policy Scenario. Unlike earlier studies for desalination options with a fossil fuel-based energy system [85], this study provides a detailed desalination capacity installation scheme based on 100% RE. The importance of desalinated water to meet the increasing water demand for one of the most water-stressed regions in the world, Middle East and North Africa (MENA), has been discussed in length by Caldera et al. [72,86,87] and Aghahosseini et al. [88]. Finally, a technically feasible and economically viable pathway is presented, not including nuclear in the energy mix. This is supported by previous research on Jordan by Ramana and Ahmad [64].

A strong initiative to push Jordan for large investments in RE systems is self-sufficiency, and cuts off the reliance on energy imports. A majority of energy production in the country today comes from imports from neighbouring countries. A sudden change in the market or a major conflict due to geopolitical reasons can massively affect the energy supply system in Jordan. Jordan can move towards a high-penetration of RE as an opportunity for socio-economic development in the years to come. Kiwan and Al-Gharibeh [89] discussed the necessity to secure sustainable electricity in Jordan under several scenarios. The results reveal that to achieve a 100% RE-based system for Jordan by 2050, around 25 GW of solar PV, 11 GW of CSP and 5 GW of wind power aligned with 90 GWh of storage capacities are required. The authors stated that a 100% renewable electricity scenario is affordable and diminishes CO₂ emissions and the need for energy imports to zero by 2050. The feasibility of a 100% RE system is confirmed by this research, as well as the solar energy dominance, whereas the role of CSP cannot be confirmed by this research, which is a consequence of low-cost solar PV and the overall cost optimisation for a least costly energy transition pathway. Regarding the resource availability, Anagreh and Bataineh [84] have analysed the potential of solar and wind energy using meteorological and statistical approaches. Their findings show that Jordan has great potential to utilise solar PV and wind energy in various locations. An earlier study by Anagreh et al. [90] proved the excellent potential to implement a wide variety of solar PV and wind projects in the southern part of Jordan.

The energy transition results for Jordan can be compared to research insights on the transition towards a 100% RE system in other countries in the region. Comparable benefits of a 100% RE system in Jordan were concluded for all the countries in the MENA region [88]. An analysis of three different scenarios was conducted for the region and it was found that a 100% RE system was cheaper than a business-as-usual scenario. Similar analyses for different 100% RE scenarios were conducted for individual countries in the region, in particular for Saudi Arabia [86], Turkey [91], Israel [92] and Iran [87,93–95]; all with a comparable conclusion that a 100% RE system is technically feasible and economically viable. It is not only similar to results from the MENA region, but also similar to research done for comparable sun-rich countries in the world, such as Chile [96]. The findings of the current study align with those of the previous research papers on the socio-techno-economic feasibility and applicability of an energy transition with emphasis on the need for political will to execute such scenarios. The next steps would be to study the factors that affect policy making and energy system planning with an emphasis on the specific measures to adopt such a 100% RE scenario.

4.2. Energy Security

In this section, energy security is analysed qualitatively for the dimensions: availability, diversity, cost, environment, health and employment, summarised for all the dimensions with a colour code representation.

4.2.1. Availability and Diversity Dimensions

Availability and diversity dimensions are analysed based on the predefined parameters by Azzuni and Breyer [34]. Availability will be addressed with three parameters and diversity will be addressed with four. Table 2 summarises these parameters:

Table 2. Parameters for the availability and diversity dimensions.

Dimensions	Parameters
Availability	Existence of resources
	Existence of consumers
	Existence of means of transport (access)
Diversity	Diversity of sources
	Diversity of fuels (energy carriers)
	Diversity of means (technologies, transportation)
	Diversity of consumers

As addressed in Figures 4 and 5, the availability dimension of the Jordanian energy system is significantly improved by the energy transition towards a 100% RE system. The first positive impact is the existence of resources. Jordan has substantial RE resources that were not used previously, which changes drastically with the energy transition in a positive way. It is expected that the population will at least double by 2050, which was shown in Figure 4. This development in population means more consumers and more energy use, which is also a positive impact on the energy system. The positive development is not only because of an increased use of energy, but rather because of an increased use of energy per capita, which is also positive. The last parameter of the availability dimension, the existence of means, is affected positively as shown in Figure 5. There are more means to access and harvest energy, and more people have possibilities to attain energy services. Such access can be mirrored from the infrastructure development in the Best Policy Scenario as can be seen from Figures 5 and 8–11, which is also a positive change for this dimension.

Similarly, the parameters within the diversity dimension are positively affected because of the energy transition towards a sustainable and fully RE system. For the first parameter, the diversity of sources or the dependency factor, such a transition makes the energy system more independent from other energy sources, as all the needed energy is supplied domestically. This is a negative attribute for diversity as there will be mainly one type of source if any disaster happens in Jordan, the whole energy system will be down. A variety of sources may be more advantageous to replace a potential energy shortage. In contrast, a higher level of diversity of fuels can be seen from Figures 4 and 5 in 2050 in comparison to the current situation, which is a positive impact, since a 100% RE system leads to a broader use of different fuels for final energy supply. Primary energy will be mainly provided by electricity, which negatively impacts diversity. The third parameter, the diversity of technology and transport, is again positively affected, as the diversity of the use of the various technologies to generate electricity is increased, as can be seen from the installed capacities in Figures 5, 8 and 11. The use of different transportation methods for energy services is another positive effect for diversity. However, as the backbone of the energy system will be dependent on the electricity grid for transporting most of the required energy, this again accounts negatively for the diversity of means. The last parameter for the diversity dimension, the diversity of consumers, seems not to be affected by the energy transition and thus is neither positive nor negative.

4.2.2. Cost Dimension Analysis from the Energy Security Perspective

Since it was found that cost is one of the most important aspects of energy systems [63], three cost parameters of energy security need to be addressed: relationship to energy price, cost of disruption and cost of securing the system [34]. The impact of the energy transition on the first parameter was mixed between positive and negative points. The first point was the end cost to be paid per energy unit.

As was shown in Figure 12, the levelised cost of energy will be lower in 2050 than in 2015, which is a positive side of the transition and thus a positive sign is given. Although the present value of energy cost is 15% higher per capita in 2050 than in 2015, which is a negative sign, energy services improve substantially, and thus indicate higher living standards. The third element of this parameter is positive, since the stability of prices is documented by a low volatility during the transition, as shown for the levelised cost of energy in Figure 12. The overall outlook is positive since subsidies are removed and energy costs reflect the real cost. In addition, energy poverty, which is the situation where individuals spend more than 10% of their income on energy services [97,98], will decrease until 2050 due to higher GDP growth per capita [70] than the increase in energy cost represented in Figure 12. Therefore, another positive sign is given for this parameter.

The second parameter is cost of disruption, which will be affected by the transition towards a 100% RE system. The cost of disruption can be reduced because of a total dependence on local RE sources and therefore increasing energy security, which is a positive effect. Furthermore, the last parameter gets a positive sign as the cost to make the system more secure tends to be lower since a 100% RE system will be more decentralised. Valuable assets will be distributed all over, and thus securing these smaller units is easier than the need to secure big facilities, as is the case for the current fossil fuel-based system.

4.2.3. Benefits of Environment and Health Dimensions

Environment and health dimensions are among the key energy security dimensions. It is one of the primary goals for the Best Policy Scenario to eliminate the negative impacts on the environment from the traditional fossil-based energy system. The parameters of the environment and health dimensions, according to [34], are summarised in Table 3.

Table 3. Parameters for the environment and health dimensions.

Dimensions	Parameters
Environment	Exploration rate and resources' location
	Extraction and transportation methods
	Outcomes from energy use
	Impact resulting from environmental change
Health	Relationship to water
	Impact of people's health on the energy system Impact of the energy system on health of (energy sector workers, consumers, and international society)

The first parameter for the environment dimension can be assessed positively because resources are not depleted faster than the natural ability of regeneration, thus a positive gain for energy security. The next parameter will enhance energy security, as the technologies used to generate electricity, as shown in Figure 5, cause no relevant burden for the environment. The third parameter on GHG emissions, as shown in Figure 13, will develop very positively, due to the phasing out of GHG emissions. The fourth parameter can be also evaluated positively, as the Best Policy Scenario (BPS) aims for limiting global warming to 1.5 °C. The projected increase in temperature is accompanied with more sunshine due to even less clouds in Jordan. The higher share of solar PV in the energy system may lead to even more available energy and a higher level of energy security, which is a positive effect. The last parameter can be evaluated very positively, as water will be used much less for power generation due to drastically reducing the share of thermal power generation [99], and desalination will be based on renewable electricity without relevant water requirements. This parameter is very important for Jordan, as Jordan already suffers from high water-stress levels, so that the BPS will provide innovative solutions for the water issues in Jordan.

The two parameters of the health dimension are expected to show a positive development. The BPS takes into consideration a tremendous improvement in the energy consumption per capita as shown in Figure 4, and it is projected that this transition will make people healthier in general.

Healthier employees and societies will be more productive and efficient, which results in improving the energy security level and is therefore a positive effect. In today's energy system, where 5 million deaths per year and more than 5% of all health-related issues globally are attributed to the energy system [100], the BPS will play a very positive role in eliminating this problem. As shown in Figure 13, GHG emissions from the transport system will be reduced to zero, which also implies that air pollution will be almost eliminated and thus enhances the energy security level. This is a much appreciated positive impact from a 100% RE-based system in contrast to the current system [101]. Fossil fuels are hazardous materials [102], thus the broad electrification will have an additional positive impact on people's health.

4.2.4. Employment Dimension Benefits

The two parameters of the employment dimension are the effect of the energy system on employment and the effect of the employment rate on the energy system. The BPS will result in creating more jobs, as was shown in Figure 14, which is a positive effect. A higher employment rate means more revenue generation opportunities for individuals [103] and more financial resources directed to the energy system with a stronger purchasing power. It is expected that more money will be spent on energy services in the future due to a high employment rate, which is another positive effect.

4.2.5. Summary on Energy Security Dimensions

Summary for the energy security analysis of the BPS is presented in Table 4 with colour codes. Green, for most positive parameters for a dimension, indicates a positive correlation between energy security and the proposed transition towards a 100% RE-based system. Red, if the sum of the assessed parameters per dimension is negative, indicates that the relationship with energy security has deteriorated. Yellow, indicates a neutral impact of the energy transition on energy security.

Table 4. Summary of the energy transition impacts on energy security.

Dimensions	Availability	Diversity	Cost	Environment	Health	Employment
Impact	++++	+++--	+++++--	+++++	++	++

4.3. Limitations and Recommendations for Future Research

Although this study is limited by the pre-assumptions that are used in the model for simulating the future energy scenario, the significance of these limitations seems to be acceptable because the used assumptions are scientifically accepted. Another limitation is the uncertainty of how solar radiation may change in Jordan until 2050. This limitation is of low significance as change in solar radiation is expected to be below a 3% level [104]. Effectively, slightly more solar PV yield could be expected, while a slightly higher temperature level may again slightly decrease that extra yield. The structure of the obtained results is expected to be not affected. The assumption that power transmission lines are built fast enough to cover the whole country can be a limitation, knowing that most of the population in Jordan is concentrated in the big cities, while the rest of the country has a lower population and is mostly desert areas. It could be expected that the electricity demand may be further increased by additional cooling demand, induced by increasing temperature due to climate change effects, as discussed by Emodi et al. [104].

For the current energy system, most of the required data is available to perform a quantitative analysis for energy security according to Azzuni and Breyer [65]. However, for the future energy system, many of these data do not exist yet, and it is hardly possible to project major parts of that data well, so a qualitative analysis is the best compromise.

The applied Best Policy Scenario in order to achieve a 100% RE-based system is not equal to a fully sustainable system, since it is more focused on the used technologies, i.e., faster overall electrification, fast switch to low-cost solutions, fast phase-in of renewables, coverage of clean water and electric vehicles. The transition towards a fully sustainable energy system for Jordan needs additional studies,

which subdivides the country into several nodes based on population distribution and determines the local energy demands, the ability to meet these demands, while minimising the need for transmission lines. Such a valuable improvement in the insights on a national energy transition has been shown for the case of Iran with a first analysis for the country in one node [94] and a second in-depth research in a multi-node resolution [93]. It is also suggested to carry out a comparison of different scenarios to see their relative impact on energy security. An even more sustainable scenario could be to model a system where electricity consumption per capita is equal to the average OECD consumption per capita, which would mean higher standards of living, but also respective policy requirements. The comparison of the impact on energy security from different scenarios enables valuable insights into the scenario that would achieve the highest level of energy security. These scenarios are also to be compared with a Current Policy Scenario to address the needed changes in the policy-making process. Other research for the MENA region [88] clearly indicates that a Current Policy Scenario would lead to higher-energy system cost, while achieving lower sustainability levels.

As the results suggest that there are no major technical and economic barriers to achieve a fully renewable-based energy system in Jordan by 2050, there is still need to address the social acceptance of the respective change and conduct more research on how people would react to such an energy transition.

5. Conclusions

Renewable energy potential in Jordan is quite attractive and a transition towards a 100% RE system is technically feasible and economically viable by 2050. Such a transition towards a highly sustainable energy system will have a multitude of impacts on energy security. The main objectives of this were to propose an energy transition pathway towards a 100% RE system in Jordan by 2050 and to analyse how energy security is enhanced with such a transition.

In order to achieve this goal, multiple steps were implemented in a scientific method. This first step of the method was to simulate a future energy scenario using the LUT model. Then, data was collected from different sources as input data for the model. The calculation method was determined based on the selection of a Best Policy Scenario. Lastly, the methods of energy security analysis were applied by following a comprehensive energy security analysis framework.

The results show that energy demand will increase in absolute terms, but less compared to a business-as-usual scenario, due to improved energy system efficiency. In addition, people will enjoy a higher level of living standards with more traveling and increased transportation services. Furthermore, as water stress and scarcity is one of the biggest challenges Jordan faces nowadays, such a transition can provide all the needed water supply using RE. Such a transition comes along with a GHG emission reduction to zero and employment benefits.

Unlike the current Jordanian energy system, where energy security is at a low level, the Best Policy Scenario will generate positive results for many dimensions of energy security. A major implication of the BPS is zero GHG emissions, enabling the 1.5 °C target of the Paris Agreement. This will drastically enhance the environment and health dimensions of energy security. The BPS allows the energy system to utilise the available renewable resources of Jordan, and thus achieve a higher level of energy security in the availability dimension. Furthermore, the cost dimension will be after all affected positively with a 100% RE system. In addition, the employment dimension will also benefit positively. On the other hand, this transition has a neutral impact on the diversity dimension of energy security.

Future studies should consider modelling additional energy transition scenarios with an even stronger sector coupling of all energy sectors, potentially leading to even higher overall system efficiency and lower cost, the inclusion of non-energetic industrial hydrocarbon demand and higher geo-spatial resolutions. Furthermore, the inclusion of decreased system costs for even higher standards of living and a more diverse mix of energy supply options will highlight the best scenarios that enable Jordan to become one of the first countries around the world with a fully sustainable energy system.

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Abbreviations

A-CAES	Adiabatic compressed air energy storage
CAPEX	Capital expenditures
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CSP	Concentrated solar thermal power
DAC	CO ₂ direct air capture
DH	District heating
GHG	Greenhouse gas
GT	Gas turbine
HDV	Heavy duty vehicle
HT	High temperature
ICE	Internal combustion engine
IH	Individual heating
LDV	Light duty vehicle
LNG	Liquefied natural gas
LUT	LUT University
MDV	Medium duty vehicle
OCGT	Open cycle gas turbine
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditures
PHES	Pumped hydro energy storage
PP	Power plant
PtG	Power-to-gas
PtH	Power-to-heat
PV	Photovoltaic
RE	Renewable energy
SF	Solar field
ST	Steam turbine
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
TTW	Tank-to-wheel
2W	Two-wheelers
3W	Three-wheelers
€	Euro

References

1. Ang, B.W.; Choong, W.L.; Ng, T.S. Energy security: Definitions, dimensions and indexes. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1077–1093. [\[CrossRef\]](#)
2. Vivoda, V. Evaluating energy security in the Asia-Pacific region: A novel methodological approach. *Energy Policy* **2010**, *38*, 5258–5263. [\[CrossRef\]](#)
3. Bielecki, J. Energy security: Is the wolf at the door? *Q. Rev. Econ. Financ.* **2002**, *42*, 235–250. [\[CrossRef\]](#)
4. Jun, E.; Kim, W.; Chang, S.H. The analysis of security cost for different energy sources. *Appl. Energy* **2009**, *86*, 1894–1901. [\[CrossRef\]](#)
5. Löschel, A.; Moslener, U.; Rübhelke, D.T.G. Indicators of energy security in industrialised countries. *Energy Policy* **2010**, *38*, 1665–1671. [\[CrossRef\]](#)
6. Kirchner, E.; Berk, C.A.N. European energy security co-operation: Between amity and enmity. *J. Common Mark. Stud.* **2010**, *48*, 859–880. [\[CrossRef\]](#)
7. Dyer, H.; Trombetta, M.J. *International Handbook of Energy Security*; Edward Elgar Publishing: Cheltenham, UK; Northampton, MA, USA, 2013.
8. Kovačovská, J. Energy Security in European Conditions. Master's Thesis, Faculty of Social Studies, Masaryk University, Brno, Czech Republic, 2010.
9. Sovacool, B.K. Energy security: Challenges and needs. *Wiley Interdiscip. Rev. Energy Environ.* **2012**, *1*, 51–59. [\[CrossRef\]](#)
10. Narula, K. Comparative assessment of energy sources for attaining Sustainable Energy Security (SES): The case of India's residential sector. *Int. J. Sustain. Energy Plan. Manag.* **2015**, *5*, 27–40. [\[CrossRef\]](#)
11. Johnson, C.; Boersma, T. The politics of energy security: Contrasts between the United States and the European Union. *Wiley Interdiscip. Rev. Energy Environ.* **2015**, *4*, 171–177. [\[CrossRef\]](#)
12. Valentine, S.V. Emerging symbiosis: Renewable energy and energy security. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4572–4578. [\[CrossRef\]](#)
13. Augutis, J.; Krikštolaitis, R.; Pečiulytė, S.; Konstantinavičiūtė, I. Sustainable development and energy security level after Ignalina NPP shutdown. *Technol. Econ. Dev. Econ.* **2011**, *17*, 5–21. [\[CrossRef\]](#)
14. Yergin, D. Ensuring energy security. *Foreign Aff. N. Y.* **2006**, *85*, 69. [\[CrossRef\]](#)
15. Kunz, A. *Indian Energy Security. Nuclear Energy Policy*; Charles University in Prague: Prague, Czech Republic, 2012.
16. Magazzino, C. Is per capita energy use stationary? Time series evidence for the EMU countries. *Energy Explor. Exploit.* **2016**, *35*, 24–32. [\[CrossRef\]](#)
17. Magazzino, C. Is per capita energy use stationary? Panel data evidence for the EMU countries. *Energy Explor. Exploit.* **2016**, *34*, 440–448. [\[CrossRef\]](#)
18. Asif, M.; Muneer, T. Energy supply, its demand and security issues for developed and emerging economies. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1388–1413. [\[CrossRef\]](#)
19. Haghghi, S.S. *Energy Security: The External Legal Relations of the European Union with Major Oil and Gas Supplying Countries*; Bloomsbury Publishing: London, UK, 2007.
20. Ciută, F. Conceptual notes on energy security: Total or banal security? *Secur. Dialogue* **2010**, *41*, 123–144. [\[CrossRef\]](#)
21. Dannreuther, R. *Energy Security*; John Wiley & Sons: Hoboken, NJ, USA, 2017.
22. Sovacool, B.K. Evaluating energy security in the Asia Pacific: Towards a more comprehensive approach. *Energy Policy* **2011**, *39*, 7472–7479. [\[CrossRef\]](#)
23. Dunham, I.M.; Schlosser, K. Energy security discourses and environmental protection measures in U.S. federal energy legislation: An introductory exploration. *Extr. Ind. Soc.* **2016**, *3*, 86–94. [\[CrossRef\]](#)
24. Eaves, J.; Eaves, S. Renewable corn-ethanol and energy security. *Energy Policy* **2007**, *35*, 5958–5963. [\[CrossRef\]](#)
25. Jordan, M.; Manley, D.; Peters, R.S.; Stoltz, R. *Goals of Energy Policy: Professional Perspectives on Energy Security, Economics, and Environment*; Our Energy Policy and Sandia National Laboratory: Washington, DC, USA; Sandia National Laboratory: Albuquerque, NM, USA, 2012.
26. International Energy Agency (IEA). *Energy Security and Climate Policy-Assessing Interactions*; 1281720488; Organisation for Economic Co-operation and Development (OECD) Publishing: Paris, France, 2007.
27. Frankl, V.; Višković, A. Energy security, policy and technology in South East Europe: Presenting and applying an energy security index to Croatia. *Energy* **2015**, *90*, 494–507. [\[CrossRef\]](#)

28. Maslow, A.H. A theory of human motivation. *Psychol. Rev.* **1943**, *50*, 370–396. [[CrossRef](#)]
29. Willrich, M. International energy issues and options. *Annu. Rev. Energy* **1976**, *1*, 743–772. [[CrossRef](#)]
30. Miller, L.B.; Lieber, R.J.; Maddox, J.; Mancke, R.; Vernon, R.; Willrich, M. Energy, security and foreign policy: A review essay. *Int. Secur.* **1977**, *1*, 111–123. [[CrossRef](#)]
31. United Nations Development Programme (UNDP). *World Energy Assessment—Energy and Challenges of Sustainability*; United Nations Development Programme: New York, NY, USA, 2000.
32. Bohi, D.R.; Toman, M.A. Energy security: Externalities and policies. *Energy Policy* **1993**, *21*, 1093–1109. [[CrossRef](#)]
33. Narula, K.; Reddy, B.S. A SES (sustainable energy security) index for developing countries. *Energy* **2016**, *94*, 326–343. [[CrossRef](#)]
34. Azzuni, A.; Breyer, C. Definitions and dimensions of energy security: A literature review. *Wiley Interdiscip. Rev. Energy Environ.* **2017**, *7*, e268. [[CrossRef](#)]
35. Jaber, J.O.; Marahleh, G.; Dalabeeh, A. Emissions Reduction Resulting from Renewable Energy Projects in Jordan. *J. Energy Technol. Policy* **2019**, *9*. [[CrossRef](#)]
36. Jaber, J.O.; Jaber, Q.M.; Sawalha, S.A.; Mohsen, M.S. Evaluation of conventional and renewable energy sources for space heating in the household sector. *Renew. Sustain. Energy Rev.* **2008**, *12*, 278–289. [[CrossRef](#)]
37. Sachs, J.D.; Warner, A.M. The curse of natural resources. *Eur. Econ. Rev.* **2001**, *45*, 827–838. [[CrossRef](#)]
38. Mehlum, H.; Moene, K.; Torvik, R. Cursed by resources or institutions? *World Econ.* **2006**, *29*, 1117–1131. [[CrossRef](#)]
39. Van der Ploeg, F. Natural resources: Curse or blessing? *J. Econ. Lit.* **2011**, *49*, 366–420. [[CrossRef](#)]
40. Ammari, H.D.; Al-Rwashdeh, S.S.; Al-Najideen, M.I. Evaluation of wind energy potential and electricity generation at five locations in Jordan. *Sustain. Cities Soc.* **2015**, *15*, 135–143. [[CrossRef](#)]
41. Abu Hamed, T.; Bressler, L. Energy security in Israel and Jordan: The role of renewable energy sources. *Renew. Energy* **2019**, *135*, 378–389. [[CrossRef](#)]
42. World Energy Council (WEC). *World Energy Trilemma Index*; World Energy Council: London, UK, 2019.
43. Malkawi, S.; Azizi, D. A multi-criteria optimization analysis for Jordan’s energy mix. *Energy* **2017**, *127*, 680–696. [[CrossRef](#)]
44. Alali, J. Jordan oil shale, availability, distribution, and investment opportunity. In Proceedings of the International Conference on Oil Shale: Recent Trends in Oil Shale, Amman, Jordan, 7–9 November 2006.
45. Hrayshat, E.S. Analysis of Renewable Energy Situation in Jordan. *Energy Sources Part B Econ. Plan. Policy* **2007**, *3*, 89–102. [[CrossRef](#)]
46. Hrayshat, E.S.; Al-Soud, M.S. Potential of solar energy development for water pumping in Jordan. *Renew. Energy* **2004**, *29*, 1393–1399. [[CrossRef](#)]
47. Jaber, J.O.; Elkarmi, F.; Alasis, E.; Kostas, A. Employment of renewable energy in Jordan: Current status, SWOT and problem analysis. *Renew. Sustain. Energy Rev.* **2015**, *49*, 490–499. [[CrossRef](#)]
48. Steiner, J.R. *Energy Security in Jordan*; Naval Postgraduate School: Monterey, CA, USA, 2015.
49. Weinstein, M. Future Scenarios for Energy Security and Sustainable Desalination in Jordan. Master’s Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2019.
50. Jaber, J.O. Prospects and Challenges of Small Hydropower Development in Jordan. *Jordan J. Mech. Ind. Eng.* **2012**, *6*, 110–118.
51. Jaber, J.O.; Amri, A.; Ibrahim, K. Experimental investigation of effects of oil shale composition on its calorific value and oil yield. *Int. J. Oil Gas Coal Technol.* **2011**, *4*, 307–321. [[CrossRef](#)]
52. Besieso, M. Jordan’s commercial oil shale exploitation strategy. In Proceedings of the 27th Oil Shale Symposium, Golden, CO, USA, 15–19 October 2007.
53. Ministry of Energy and Mineral Resources (MEMR). *Annual Report 2018*; MEMR: Amman, Jordan, 2018. Available online: https://www.memr.gov.jo/ebv4.0/root_storage/ar/eb_list_page/56dcb683-2146-4dfd-8a15-b0ce6904f501.pdf (accessed on 10 June 2020).
54. Ministry of Energy and Mineral Resources (MEMR). *Energy 2018—Facts & Figures*; MEMR: Amman, Jordan, 2018. Available online: https://www.memr.gov.jo/ebv4.0/root_storage/en/eb_list_page/brchure_2018.pdf (accessed on 10 June 2020).
55. Ministry of Energy and Mineral Resources (MEMR). *Energy 2019—Facts & Figures*; MEMR: Amman, Jordan, 2019. Available online: https://www.memr.gov.jo/ebv4.0/root_storage/en/eb_list_page/brchure_2019.pdf (accessed on 10 June 2020).

56. Breyer, C.; Bogdanov, D.; Gulagi, A.; Aghahosseini, A.; Barbosa, L.S.N.S.; Koskinen, O.; Barasa, M.; Caldera, U.; Afanasyeva, S.; Child, M.; et al. On the role of solar photovoltaics in global energy transition scenarios. *Prog. Photovolt. Res. Appl.* **2017**, *25*, 727–745. [CrossRef]
57. El-Anis, I. The political economy of energy security and nuclear energy in Jordan. *Cent. Eur. J. Int. Secur. Stud.* **2012**, *6*, 13–35.
58. Augutis, J.; Krikstolaitis, R.; Martisauskas, L.; Peciulyte, S. Energy security level assessment technology. *Appl. Energy* **2012**, *97*, 143–149. [CrossRef]
59. Kanchana, K.; Unesaki, H. ASEAN energy security: An indicator-based assessment. *Energy Procedia* **2014**, *56*, 163–171. [CrossRef]
60. Kruyt, B.; van Vuuren, D.P.; de Vries, H.J.M.; Groenbergh, H. Indicators for energy security. *Energy Policy* **2009**, *37*, 2166–2181. [CrossRef]
61. Radovanović, M.; Filipović, S.; Pavlović, D. Energy security measurement—A sustainable approach. *Renew. Sustain. Energy Rev.* **2017**, *68*, 1020–1032. [CrossRef]
62. Alshwawra, A.; Almuhtady, A. Impact of Regional Conflicts on Energy Security in Jordan. *Int. J. Energy Econ. Policy* **2020**, *10*, 45–50. [CrossRef]
63. Komendantova, N.; Ekenberg, L.; Marashdeh, L.; Al Salaymeh, A.; Danielson, M.; Linnerooth-Bayer, J. Are Energy Security Concerns Dominating Environmental Concerns? Evidence from Stakeholder Participation Processes on Energy Transition in Jordan. *Climate* **2018**, *6*, 88. [CrossRef]
64. Ramana, M.V.; Ahmad, A. Wishful thinking and real problems: Small modular reactors, planning constraints, and nuclear power in Jordan. *Energy Policy* **2016**, *93*, 236–245. [CrossRef]
65. Azzuni, A.; Breyer, C. Global Energy Security Index and Its Application on National Level. *Energies* **2020**, *13*, 2502. [CrossRef]
66. Breyer, C.; Bogdanov, D.; Aghahosseini, A.; Gulagi, A.; Child, M.; Oyewo, A.S.; Farfan, J.; Sadovskaia, K.; Vainikka, P. Solar photovoltaics demand for the global energy transition in the power sector. *Prog. Photovolt. Res. Appl.* **2018**, *26*, 505–523. [CrossRef]
67. Bogdanov, D.; Farfan, J.; Sadovskaia, K.; Aghahosseini, A.; Child, M.; Gulagi, A.; Oyewo, A.S.; de Souza Noel Simas Barbosa, L.; Breyer, C. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nat. Commun.* **2019**, *10*, 1077. [CrossRef] [PubMed]
68. Bogdanov, D.; Toktarova, A.; Breyer, C. Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan. *Appl. Energy* **2019**, *253*, 113606. [CrossRef]
69. Ram, M.; Bogdanov, D.; Aghahosseini, A.; Oyewo, S.; Gulagi, A.; Child, M.; Fell, H.-J.; Breyer, C. *Global Energy System Based on 100% Renewable Energy—Power Sector*; Lappeenranta University of Technology: Lappeenranta, Finland; Energy Watch Group: Berlin, Germany, 2017.
70. Toktarova, A.; Gruber, L.; Hlusiak, M.; Bogdanov, D.; Breyer, C. Long term load projection in high resolution for all countries globally. *Int. J. Electr. Power Energy Syst.* **2019**, *111*, 160–181. [CrossRef]
71. Khalili, S.; Rantanen, E.; Bogdanov, D.; Breyer, C. Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World. *Energies* **2019**, *12*, 3870. [CrossRef]
72. Caldera, U.; Breyer, C. Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems. *Energy* **2020**, *200*, 117507. [CrossRef]
73. Bunzel, K.; Zeller, V.; Buchhorn, M.; Griem, F.; Thrän, D. *Regionale und Globale Räumliche Verteilung von Biomassepotenzialen*; German Biomass Research Center: Leipzig, Germany, 2009.
74. Aghahosseini, A.; Bogdanov, D.; Breyer, C. A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions. *Energies* **2017**, *10*, 1171. [CrossRef]
75. Farfan, J.; Breyer, C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *J. Clean. Prod.* **2017**, *141*, 370–384. [CrossRef]
76. United Nations Framework Convention on Climate Change (UNFCCC). *Adoption of the Paris Agreement—Proposal by the President*; United Nations Framework Convention on Climate Change: Paris, France, 2015; Available online: <https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf> (accessed on 10 June 2020).
77. United Nations (UN). *Sustainable Development Goals Knowledge Platform*; United Nations: New York, NY, USA, 2015; Available online: <https://sustainabledevelopment.un.org/sdgs> (accessed on 10 June 2020).

78. International Panel on Climate Change (IPCC). *IPCC—Special Report on 1.5 Degrees*; International Panel on Climate Change: Geneva, Switzerland, 2018; Available online: <http://www.ipcc.ch/report/sr15> (accessed on 10 June 2020).
79. United Nations (UN). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*; Working Paper No. ESA/P/WP.241; The Department of Economic and Social Affairs of the United Nations Secretariat: New York, NY, USA, 2015; Available online: https://population.un.org/wpp/publications/files/key_findings_wpp_2015.pdf (accessed on 10 June 2020).
80. Caldera, U.; Breyer, C. Learning Curve for Seawater Reverse Osmosis Desalination Plants: Capital Cost Trend of the Past, Present, and Future. *Water Resour. Res.* **2017**, *53*, 10523–10538. [[CrossRef](#)]
81. International Labour Office (ILO). *Employment Impact of Infrastructure Investment in Jordan—Employment Research Brief*; International Labour Office: Geneva, Switzerland, 2016; Available online: https://www.ilo.org/wcmsp5/groups/public/---ed_emp/documents/publication/wcms_575884.pdf (accessed on 10 June 2020).
82. Ram, M.; Osario, J.; Aghahosseini, A.; Breyer, C. Job creation during the global energy transition towards 100% renewable energy across the power, heat, transport and desalination sectors by 2050. *Furthcoming* **2020**, *151*, 119682.
83. Cote, S. *Renewable Energy and Employment: The Experience of Egypt, Jordan and Morocco*; King Abdullah Petroleum Studies and Research Center: Riyadh, Saudi Arabia, 2019.
84. Anagreh, Y.; Bataineh, A. Renewable energy potential assessment in Jordan. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2232–2239. [[CrossRef](#)]
85. Østergaard, P.A.; Lund, H.; Mathiesen, B.V. Energy system impacts of desalination in Jordan. *Int. J. Sustain. Energy Plan. Manag.* **2014**, *1*, 29–40. [[CrossRef](#)]
86. Caldera, U.; Bogdanov, D.; Afanasyeva, S.; Breyer, C. Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. *Water* **2018**, *10*, 3. [[CrossRef](#)]
87. Caldera, U.; Bogdanov, D.; Fasihi, M.; Aghahosseini, A.; Breyer, C. Securing future water supply for Iran through 100% renewable energy powered desalination. *Int. J. Sustain. Energy Plan. Manag.* **2019**, *23*, 39–54. [[CrossRef](#)]
88. Aghahosseini, A.; Bogdanov, D.; Breyer, C. Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030. *Energy Strategy Rev.* **2020**, *28*, 100466. [[CrossRef](#)]
89. Kiwan, S.; Al-Gharibeh, E. Jordan toward a 100% renewable electricity system. *Renew. Energy* **2020**, *147*, 423–436. [[CrossRef](#)]
90. Anagreh, Y.; Bataineh, A.; Al-Odat, M. Assessment of renewable energy potential, at Aqaba in Jordan. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1347–1351. [[CrossRef](#)]
91. Kilickaplan, A.; Bogdanov, D.; Peker, O.; Caldera, U.; Aghahosseini, A.; Breyer, C. An energy transition pathway for Turkey to achieve 100% renewable energy powered electricity, desalination and non-energetic industrial gas demand sectors by 2050. *Sol. Energy* **2017**, *158*, 218–235. [[CrossRef](#)]
92. Solomon, A.A.; Bogdanov, D.; Breyer, C. Solar driven net zero emission electricity supply with negligible carbon cost: Israel as a case study for Sun Belt countries. *Energy* **2018**, *155*, 87–104. [[CrossRef](#)]
93. Ghorbani, N.; Aghahosseini, A.; Breyer, C. Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050—Achieving zero greenhouse gas emissions and overcoming the water crisis. *Renew. Energy* **2020**, *146*, 125–148. [[CrossRef](#)]
94. Ghorbani, N.; Aghahosseini, A.; Breyer, C. Transition towards a 100% Renewable Energy System and the Role of Storage Technologies: A Case Study of Iran. *Energy Procedia* **2017**, *135*, 23–36. [[CrossRef](#)]
95. Aghahosseini, A.; Bogdanov, D.; Ghorbani, N.; Breyer, C. Analysis of 100% renewable energy for Iran in 2030: Integrating solar PV, wind energy and storage. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 17–36. [[CrossRef](#)]
96. Osorio-Aravena, J.C.; Aghahosseini, A.; Bogdanov, D.; Caldera, U.; Muñoz-Cerón, E.; Breyer, C. The role of solar PV, wind energy, and storage technologies in the transition toward a fully sustainable energy system in Chile by 2050 across power, heat, transport and desalination sectors. *Int. J. Sustain. Energy Plan. Manag.* **2020**, *25*, 77–94. [[CrossRef](#)]
97. Brown, M.A.; Wang, Y.; Sovacool, B.K.; D’Agostino, A.L. Forty years of energy security trends: A comparative assessment of 22 industrialized countries. *Energy Res. Soc. Sci.* **2014**, *4*, 64–77. [[CrossRef](#)]

98. Rademaekers, K.; Yearwood, J.; Ferreira, A.; Pye, S.; Hamilton, I.; Agnolucci, P.; Grover, D.; Karásek, J.; Anisimova, N. *Selecting Indicators to Measure Energy Poverty*; European Commission, DG Energy: Rotterdam, The Netherlands, 2016.
99. Lohrmann, A.; Farfan, J.; Caldera, U.; Lohrmann, C.; Breyer, C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nat. Energy* **2019**, *4*, 1040–1048. [[CrossRef](#)]
100. Johansson, T.B.; Nakićenović, N. *Global Energy Assessment: Toward a Sustainable Future*; Cambridge University Press: Cambridge, UK, 2012.
101. Epstein, P.R.; Buonocore, J.J.; Eckerle, K.; Hendryx, M.; Stout Iii, B.M.; Heinberg, R.; Clapp, R.W.; May, B.; Reinhart, N.L.; Ahern, M.M. Full cost accounting for the life cycle of coal. *Ann. N. Y. Acad. Sci.* **2011**, *1219*, 73–98. [[CrossRef](#)] [[PubMed](#)]
102. Lovins, A.B.; Lovins, L.H. *Energy Policies for Resilience and National Security*; Council on Environmental Quality, Executive Office of the President: Washington, DC, USA, 1981.
103. Kumar, S.; Goteti, N.S.; Savargaonkar, P. Co-benefit technologies, green jobs, and national innovation systems. In *Managing the Transition to a Low-Carbon Economy: Perspectives, Policies, and Practices from Asia*; Lohani, B.N., Kawai, M., Anbumozhi, V., Eds.; Asian Development Bank Institute: Tokyo, Japan, 2016; pp. 149–173.
104. Emodi, N.V.; Chaiechi, T.; Beg, A.B.M.R.A. The impact of climate variability and change on the energy system: A systematic scoping review. *Sci. Total Environ.* **2019**, *676*, 545–563. [[CrossRef](#)] [[PubMed](#)]



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Article

Global Energy Security Index and Its Application on National Level

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Abstract: Energy security is an international concern for all countries in the world, particularly, for the policymakers looking for the wellbeing of citizens. While proper methods to measure energy security without ignoring the different aspects and multidimensional interplay is necessary, the need for an objective evaluation with numerical indicators is of utmost importance. This research covers these gaps by providing a detailed numerical method to formulate an energy security index that is globally comprehensive, but also nationally applicable to all countries in the world. This implies to include all needed aspects and dimensions of energy security. Results of this research show the global performance of all countries in the world in energy security and the performance of these countries in each of the 15 dimensions that articulate energy security. Germany and the United States performed best in the world, when it comes to overall energy security levels, whereas the Central African Republic and Turkmenistan are on the lowest end of performance. Conclusions show that there is not a single way for development and enhancing energy security but rather different alternatives and options. Countries need to learn from each other to identify what works best for their context and implement these strategies in order to enhance energy security.

Keywords: energy security; index; dimensions; parameters; indicators

1. Introduction

Energy security is an universal concern [1]. Many studies have tried to discuss this topic [2–4] from different point of views like various fields of science [5], international relationships [6] and national security [7]. The ability of energy security to shape policies and national behaviour [8] makes it very important. While policies and regulations are prepared, energy security has to be addressed first because of its relevance [9]. The needs of energy consumers are covered when policymakers aim to ensure energy security [10].

Although, the concept of energy security is ‘as old as fire’ [11] and the discussion has a long history, scientific analysis following current research principles and standards are rare before 1975 [12]. Ang et al. [1] state that publications on energy security were rare before 2001, however, it has emerged as one of the important topics [13] in the 21st century. The emergence of this field is because energy is an engine for economic growth [3,14] with close links to economy [15,16] and a driver for civilisation [17] and society [18]. In general, energy affects every aspect of life [19] and therefore crucial to the survival of the functioning modern society [3]. Therefore, enhancing energy security is a key goal of a society [2,20–25]. Personal and national energy security are paths to freedom of choice, and thereafter, self-actualisation as in Maslow’s hierarchy of needs [26].

Consequently, the question about the needed level of energy security arises. Many answers based on different assessment tools and approaches have been offered [27–31] based on the definitions and dimensions used in the assessment. The analysis of energy security by Azzuni and Breyer [32] is further developed in

this research. Azzuni and Breyer devised 15 dimensions for energy security analysis: **Availability, Diversity, Cost, Technology and Efficiency, Location, Timeframe, Resilience, Environment, Health, Culture, Literacy, Employment, Policy, Military and Cyber Security**. This approach is one of the most comprehensive and detailed approaches. However, as many tried to conceptualise energy security, there is still a need for a proper tool to quantify the level of energy security that allows for better interpretation for policymaking. In addition, there is a need for holistic approaches but detailed enough for all individual countries with a global context as was proposed by Hansen et al. [33].

Quantification is one of the important aspects of social science and many other fields of science. It gives the ability for comparing different situations and status. Also, it allows for decision-makers to address exact options as a direct way to enhance the quantified concept. Therefore, this paper aims to evaluate energy security with an energy security index that covers sustainable development of the energy system.

This index is built on the 15 dimensions and their parameters presented by Azzuni and Breyer [32]. The newly introduced energy security index is designed to overcome one or more existing research gaps of the previous studies, as they had been identified as follows:

1. Not enough dimensions and parameters to cover all the aspects of energy security;
2. No transparency of methods of building the index;
3. Limited data or use of the proposed numerical indicators;
4. Limited application of the index on one country or region, or for a short period of time;
5. Equal weighting approach for all dimensions and parameters within the index;
6. No or limited interpretation of the results into policy recommendations that can enhance energy security.

Examples for research gaps are found in literature [34–36]. Although Wang and Zhou [34] proposed a global framework to analyse energy security, their research lacks many aspects of energy security as they have limited their analysis to only three dimensions. In our research, a more comprehensive use of dimensions is presented. In total 15 dimensions are used and evaluated. This by itself is novel as there is no literature to evaluate all 15 dimensions together with their respective parameters. Furthermore, unlike clustering countries into categories that was presented by Wang and Zhou [34], our novel approach is to represent all countries individually. Our research has more resolution for the national level. Furthermore, the same research gap of limiting energy security to a more simplified concept was noticed from [35,36], where only 6 and 8 indicators were used, respectively, to measure energy security. That is a simplified approach as energy security consists of more aspects that need to be addressed. Overcoming this major limitation by evaluating 15 dimensions, 50 parameters and 76 indicators is one of the novelties of this research. Unlike previous research [35,36] that was limited on a certain country or region, the novelty of this research is to evaluate energy security for all countries in the world.

The above listed research gaps are intended to be overcome by the following advancements:

1. Building an energy security index that is comprehensive and representative: This research is based on the selected 15 dimensions approach with several parameters in each dimensions following the earlier conceptualisation [32]. These dimensions and parameters are to provide a holistic analysis of energy security. The relationship of each of the parameters and dimensions has been fully established and presented in [32]. This research uses the same dimensionalisation, but further develops it to accommodate numerical indicators that can be measured for each parameter and dimension.
2. Representing energy security dimensions and parameters with overarching indicators: The choice of numerical indicators is based on several criteria that are not well established in previous research or at least with limited transparency of how these indicators were chosen. This research chooses the following criteria for numerical indicators:
 - a. Data used from trusted sources;
 - b. Indicator values are available for all countries in the world or at least most of them;

- c. Close proxy to the parameters;
 - d. Indicator values can be in absolute or relative numbers;
 - e. Normalisation should be possible for energy security analysis;
 - f. Availability for current and future scenarios;
 - g. Accounting for sustainability [37] as much as possible.
3. A transparent approach: This research is based on open science. The detailed methods are presented in a maximum level of detail to fully track all the established relationships between dimensions, parameters and indicators of energy security. The building steps of the index are represented with numbers and values.
 4. A weighting procedure: This research in the first phase will follow the same trend of previous credible research of having equal weights for all dimensions and parameters. But this research will build on that first phase to accomplish a complete index that uses a reasonable weighting procedure. The weighting will be based on a survey from experts in the field of energy security, energy policy and sustainability. The survey is planned as a follow-up research.
 5. Policy recommendations: This research will provide recommendations to policymakers of what policies are supportive in order to enhance energy security. With a bigger picture, this research will analyse energy security with energy scenarios that aim to enhance energy security in related countries.

The paper is organised as follows: After the Introduction, the methods of choosing suitable indicators for each of the parameters is presented in the Methods section. In the Results and Discussion section, the final index is presented with its application on selected case countries, in addition, the results of applying the index on the case countries are addressed and discussed in detail with ways to enhance the energy security level. Recommendations for achieving higher energy security level are provided in the Conclusions and Recommendation section.

2. Methods

For each dimension, parameters are assigned, measured or calculated indicators. Then, all values are normalised and standardised to a percentage value. The normalisation of each indicator is based on global values, in order to make the index applicable globally. These percentages for each parameter are then multiplied by their weights. If a parameter affects the ES index positively when increased, it is assigned a positive value. If the increase in a parameter represents a negative impact on energy security, the indicator value is subtracted from unity (100%). After that, the parameters (Y_j) and their weights (W_j) are summed up to form the value of each dimension (X_i). The next step is the aggregation of the dimensions using their weights (V_i) to form the ES index. Details of the methods are presented below for each of the dimensions and its parameters. The overall energy security index is presented in Equation (1), while Equation (2) represents the formula for each dimension

$$\text{Energy Security index} = \sum_{i=1}^n V_i \cdot X_i \quad (1)$$

where V_i is the weight of each dimension and X_i is the value of each dimension.

$$X_i = \sum_{j=1}^m W_j \cdot Y_j \quad (2)$$

where W_j is the weight of each parameter and Y_j is the value of each parameter. Y_j is built by one indicator or an average of several indicators. Values of each indicator are normalised to a percentage

value with the same meaning. If there is more than one indicator for any parameter, then Equation (3) is applied

$$Y_j = \frac{\sum_{n=1}^o I_{n,Y_j}}{n} \quad (3)$$

where I_n is a normalised indicator used for the specific parameter Y_j and o is the number of indicators.

All parameters are given equal weights (W_j) within their dimension because of lack of data for individual weighting. The same is applied to the dimensions which are given equal weights (V_i) in the aggregation of the ES index. If valid justification for specific weighting for the dimensions (X_i) or the parameters (Y_j) exists in the future, a room for future improvement arises. Many other previous studies have used equal weighting when aggregating their energy security index [38–40].

Many indicators are normalised by a max-min approach in linear regression to obtain a percentage indicator with relevance to the global achievement in that indicator. Equation (4) describes the max-min normalisation method. Usually, normalisation takes place if the original indicator is not already in a percentage value.

$$I_{n,Y_j} = \frac{I_a + I_{min}}{I_{max} - I_{min}} * 100\% \quad (4)$$

where (I_{n,Y_j}) is the normalised indicator, (I_a) is the absolute value of the indicator, (I_{min}) is the minimum value in the world for (I_a) and (I_{max}) is the maximum value in the world for (I_a).

Nevertheless, sometimes normalisation is done by linear regression for an optimal-worst relationship of an indicator, this is done for the indicators where relationship to energy security is more complex. Equation (5) shows the conversion from Equation (4) to an optimal-worst normalisation method. Such a choice of optimal-worst normalisation is justified separately for indicators that need such alternations.

$$I_{n,Y_j} = \frac{I_a + I_{worst}}{I_{optimal} - I_{worst}} * 100\% \quad (5)$$

where (I_{n,Y_j}) is the normalised indicator, (I_a) is the absolute value of the indicator, (I_{worst}) is the worst value in the world for this indicator (I_a) and ($I_{optimal}$) is the optimal value in the world for this indicator (I_a).

In case some values do not exist for certain indicators, these indicators are set as empty cells and therefore, do not affect the calculation of the respected parameter. That is in case of indicators used to measure a parameter. In the case there is only one indicator for a parameter, then the value of that parameter is set as the worst value (0%). The list of missing indicators is presented in the Supplementary Material.

The detailed methods for formulating each of the dimensions and their corresponding parameters and indicators are provided in Appendix A.

3. Results and Discussion

3.1. Energy Security Index

The designed energy security index is presented in Table 1 where dimensions, parameters and indicators are detailed, in addition, units and normalisation methods for each indicator are summarised. All notations and abbreviations in Table 1 are explained in detail in Appendix A.

Table 1. Energy security indicators forming the parameters and dimensions for the energy security index.

Dimensions	Parameters	Indicators	Unit	Normalisation
A	A_1	Total available resource of fossil fuel and potential renewables [41,42]	TWh	Max-min
	A_2	Population [43]	Persons	Dividing by the world's population
	A_3	Number of airports [44]	Number	Dividing by the maximum in the world

Table 1. Cont.

Dimensions	Parameters	Indicators	Unit	Normalisation
D	D ₁	Simpsons Diversity Index of sources [41]	Percentage	Already normalised
	D ₂	Simpsons Diversity Index of carriers [41]	Percentage	Already normalised
	D ₃	1: Simpsons Diversity Index of Technologies [45] 2: Simpsons Diversity Index of Transportation [46]	Percentage	Already normalised
	D ₄	Simpsons Diversity Index of consumers [41]	Percentage	Already normalised
Co	C ₀₁	1: Diesel prices [47] 2: Weighted average price of power demand [42]	1: USD/litre 2: €/kWh	Dividing by the maximum in the world
	C ₀₂	Income at risk due to power outage (income loss) [48,49]	€/capita	Dividing by the maximum in the world
	C ₀₃	LCOE total [42]	€/MWh	Max-min
TE	TE ₁	1: Number of patents in force by the filling office [50] 2: Scientific and technical journal articles [51]	Number	Dividing by the highest
	TE ₂	Supply efficiency [42]	Percentage	Already normalised
	TE ₃	Energy intensity level of primary energy [52]	(MJ)/USD ₂₀₁₁ PPP GDP	Dividing by the maximum
	TE ₄	Fuel economy [53]	(Litres of gasoline equivalent)/100 km, WLTC	Max-min
Lo	L ₀₁	Area [54]	km ²	Dividing by the worlds area
	L ₀₂	Distance between production and consumption [55,56]	km	Max-min
	L ₀₃	Energy use per area [57]	kWh/km ²	Dividing by the highest
	L ₀₄	Terrestrial and marine protected areas [58]	Percentage	Dividing by the highest
	L ₀₅	1: Trade (% of GDP) [59] 2: KOF Globalisation index [60]	Percentage	Already normalised
	L ₀₆	Population density [43,54]	Persons/km ²	Dividing by the largest country
	L ₀₇	1: Number of countries with shared borders [44] 2: Seaports infrastructure [44] 3: Total renewable surface water [61]	1: Number 2: Scored number 3: m ³ /(year-km ²)	Dividing by the maximum
	L ₀₈	Industrial added values [62]	USD/km ²	Dividing by the second highest
T	T ₁	Life expectancy at birth [63]	Years	Max-min
	T ₂	1: Electrical outages [49] 2: Average weighted age of power plants [45]	1: Days 2: Years	1: Dividing by the maximum in the world 2: Max-min
	T ₃	Number of years that are needed to achieve 100% renewable electricity output [64,65]	Years	Longest allowed time
R	R ₁	Resilience Index [66]	Percentage	Already normalised
E	E ₁	Ecological footprint (number of earth required) [67]	Number	Max-min
	E ₂	CO ₂ intensity [68]	kg per kWh energy use	Dividing by the maximum in the world
	E ₃	Total GHG emissions excluding land-use change and forestry per GDP [48,69]	MtCO _{2eq} /USD	Dividing by the highest in the world
	E ₄	Temperature anomalies [70]	Celsius	Dividing by the highest in the world
	E ₅	Water stress [71]	Percentage	Already normalised, values more than 100% set to 100%
H	H ₁	1: Health expenditure [72] 2: Mortality rate, infant [73]	1: Percent of GDP 2: Number	1: Optimal value 2: Dividing by the highest in the world
	H ₂	Number of deaths attributed to cancer in population [74]	Percentage	Dividing by the maximum in the world

Table 1. Cont.

Dimensions	Parameters	Indicators	Unit	Normalisation
Cu	Cu ₁	1: Poverty headcount ratio at national poverty line [75] 2: GINI index [76] 3: Population ages 15–64 [77] 4: Coverage of social protection and labour programs [78]	1: Percentage of population 2: Percentage 3: Percentage of population 4: Percentage of population	1: Already normalised 2: Already normalised 3: Max-min 4: Already normalised
	Cu ₂	1: Energy use per capita [57] 2: Air transport, passengers carried per capita [79] 3: Food supply (crops, livestock and fish) [80] 4: Human Development Index [81]	1: kWh/capita 2: Number per capita 3: g/capita/day 4: Percentage	1: Dividing by the maximum in the world 2: Dividing by the maximum in the world 3: Dividing by the highest in the world 4: Already normalised
Li	Li ₁	Citable documents [82]	Number	Dividing by the highest in the world
	Li ₂	1: Expenditure on education as percentage of total government expenditure [83] 2: Research and development expenditure (percentage of GDP) [84]	Percentage	Dividing by the highest in the world
	Li ₃	Percentage of tertiary graduates from science, engineering, manufacturing and construction programmes [85,86]	Percentage	Dividing by the highest in the world
Em	Em ₁	Employment in the power sector [87]	Jobs/TWh _{el}	Max-min
	Em ₂	Unemployment (percentage of total labour force) [88,89]	Percentage	Dividing by the maximum
P	P ₁	1: Democracy index [90] 2: Fragile States Index [91] 3: Political stability/absence of violence and terrorism (percentile ranking) [92] 4: Polity data series [93] 5: Human freedom index [94] 6: Freedom in the world [95]	1: Percentage 2: Score 3: Percentage 4: Score 5: Percentage 6: Percentage	1: Already normalised 2: Dividing by the maximum possible 3: Already normalised 4: Theoretical max-min 5: Already normalised 6: Already normalised
	P ₂	1: Subsidies and other transfers (percentage of expense) [96] 2: Regularity indicator for sustainability (RIES) [97]	Percentage	Already normalised
	P ₃	1: Rule of law [92] 2: Corruption Perceptions Index (CPI) [98]	Percentage	Already normalised
M	M ₁	Energy consumption in military sector [57,99]	kWh	Dividing by the maximum
	M ₂	1: Military expenditure (percentage per GDP) [99] 2: Active armed force (percentage of the population) [100]	Percentage	1: Max-min 2: Dividing on the maximum in the world
	M ₃	1: Share of coal production to the world total [41] 2: Share of oil production to the world total [41] 3: Share of gas production to the world total [41]	Percentage	Dividing by the maximum in the world
	M ₄	1: Energy imports, net (percentage of energy use) [101] 2: Income from net exporting minerals classification [102]	1: Percentage 2: USD	1: Dividing by the highest absolute 2: Dividing by the maximum in the world
Cy	Cy ₁	Individuals using the Internet (percentage of population) [103]	Percentage	Already normalised
	Cy ₂	Global cybersecurity index - technical [104]	Score	Already normalised
	Cy ₃	Global cybersecurity index - capacity building [104]	Score	Already normalised

The design of the energy security index makes it clear that it is absolutely quantified and can account for many aspects of energy security. Unlike earlier research and literature that would propose parameters and indicators that are not possible to quantify and measure for most countries in the world [20], Table 1 shows an analysis for what indicators are included for energy security dimensions and parameters according to the rules stated in the Introduction (Section 1). Table 1 shows how research gaps, that were addressed in the Introduction (Section 1), are now covered in detail by 15 dimensions, 50 parameters and 78 indicators.

Although it might appear that some proxy indicators do not have a direct relationship to energy security, but that is due to the angle perspective energy security is viewed from. As this analytical framework builds the concept of energy security on hierarchical levels (dimensions, parameters, indicators), it is justified to have relevant and suitable proxy indicators for each parameter, together with a justifiable correlation between parameters and dimensions, up to the level of correlation of dimensions and energy security. The relationship between all parameters and dimensions with energy security was well-established in a previous research [32]. Correlations between all indicators and their respective parameters and dimensions are presented in detail in Appendix A. After the energy security index is built and designed, its global application is presented in the following section.

3.2. Global Energy Security

Scientific approaches to measure an energy security index are the key for proper analysis of the situation. Quantitative methods with quantified values of the energy security level will allow for real comparison between countries and their performance. Also, such a representation of an energy security index will provide valuable insights for countries on how to maintain their performance and what can be done to improve the respective energy security level. Furthermore, a global representation of energy security on international maps for the overall energy security and for the 15-individual dimensions will provide relevant policy concept implications for what regions in the world can be clustered for what reason. Figure 1 represents the detailed achievement for all the countries in the world for the overall energy security index. In addition, a colour code for the certainty of the results is embedded in Figure 1.

The overall number of parameters is 50 but for some countries data are unavailable, thus their aggregated ESI suffers from some missing indicators. The number of missing parameters is indicated by colour coded categories so that the uncertainty of the resulting ESI is better visible. Certainty levels are:

- Blue—very good (115 countries): for countries with not more than 5 missing parameters;
- Yellow—good (28 countries): for countries with 6–10 missing parameters;
- Orange—acceptable (22 countries): for countries with 11–15 missing parameters;
- Red—others (64 countries): for countries with more than 15 missing parameters.

The most common reason for missing parameters in the red category is due to either data are for non-sovereign country or the country's population is less than 100,000 as was detailed in the methods. In total there are 64 countries in the red category of which 44 are either non-sovereign or with low population.

The reorientation of the ESI distribution on the global level is also provided by an overview world map with a colour code. Figure 2 shows all countries in the world and their energy security performance, where yellow represents the best energy security level (highest ESI) and the dark blue represents the worst energy security level (lowest ESI).

First, energy security levels are higher in developed countries than in emerging and developing countries. This shows the importance of developmental status which has a strong influence to achieve higher levels of energy security. Therefore, more focus on progressively driving development, can enhance energy security. Second, neighbouring countries do not necessarily have same levels of energy security. This can be attributed to natural features of countries, e.g., resources or its political system, such as the example pairs Finland and Russia, and the United States and Cuba. Third, countries with wars and natural disasters in general have a lower energy security performance, as found for Somalia

and Afghanistan. Fourth, some countries scored a low performance because of the absence of some indicators' values. If some data points are missing for an indicator, the lowest value is assumed for that country. This impacts the whole parameter and thus the corresponding dimension. Therefore, the aggregated ESI value will be lower. Finally, no single feature of a country can determine its energy security performance, but rather the aggregated mix of many variables. For examples, having the largest area in the world alone (Russia), having the highest population alone (China), or achieving the highest GDP/capita (Qatar) does not create the best energy security. Therefore, countries with low performance in energy security should not focus only on a single parameter to enhance, but rather on a broad set of comprehensive improvements to cover many parameters in order to achieve a higher energy security level.

A global overview of each of the 15 dimensions is presented in the following and brief remarks on specific findings.

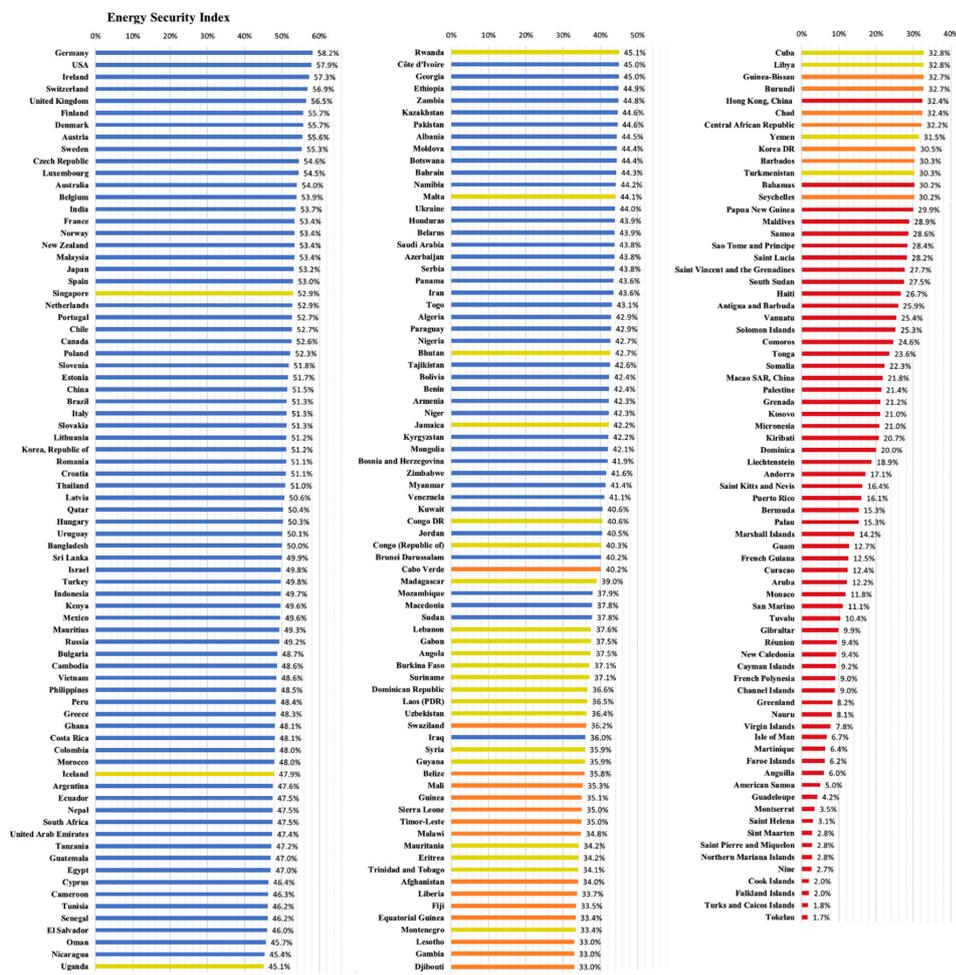


Figure 1. Global energy security levels. The applied colour of the bars indicates the number of missing parameters: blue ≤ 5 , yellow $5 < 10$, orange $10 < 15$, red > 15 .

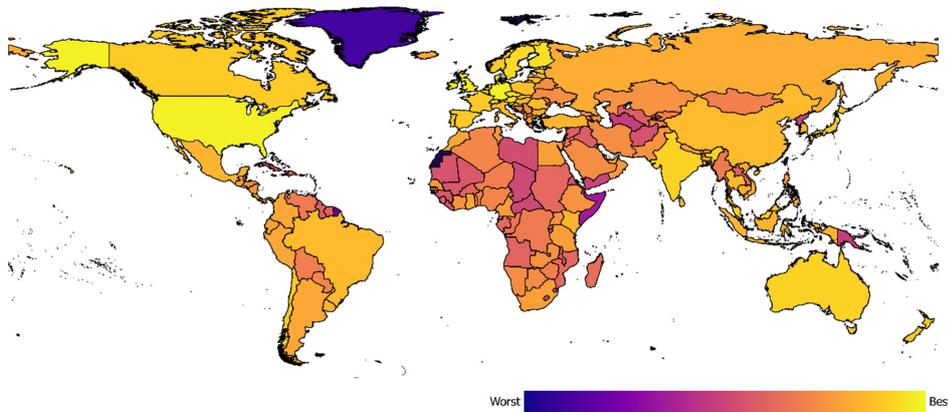


Figure 2. Global view on the energy security index.

3.2.1. Availability

The aggregation of the three parameters of the availability dimension is shown in Figure 3 where the global performance in the availability dimension is presented. Exact values for all countries can be found in the Supplementary Material.

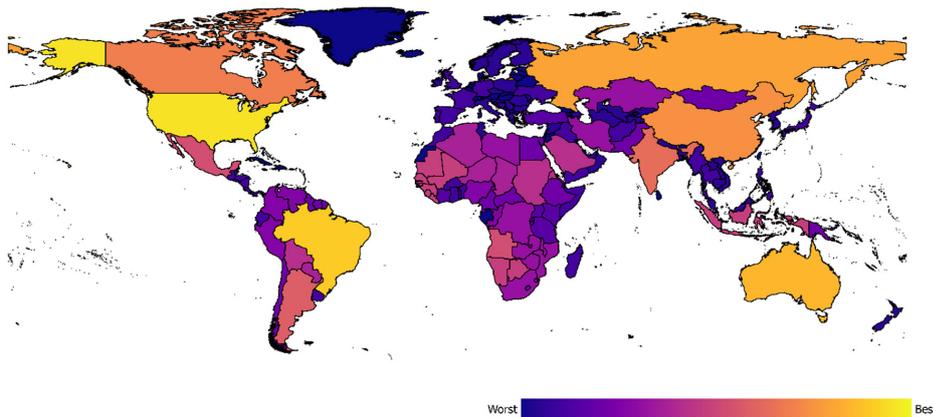


Figure 3. Global view on the availability dimension.

Figure 3 highlights that the United States and Brazil have the highest value for the availability dimension. Reasons for the United States to top this dimension is the abundance of resources together with large demand and easy access. The same applies for Brazil. Many European countries lack access to their own resources and have a small population to increase demands, thus they do not perform well for this dimension. Furthermore, developing countries show better results than some of the developed countries, this can be a good motivation and a driving force to utilise this advantage to progressively improve the overall energy security level. Also, it can be noticed that, area and population can have a correlation with this dimension, as larger countries and more populous ones tend to have a better performance in this dimension.

3.2.2. Diversity

The aggregation of the four parameters of the diversity dimension is shown in Figure 4, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

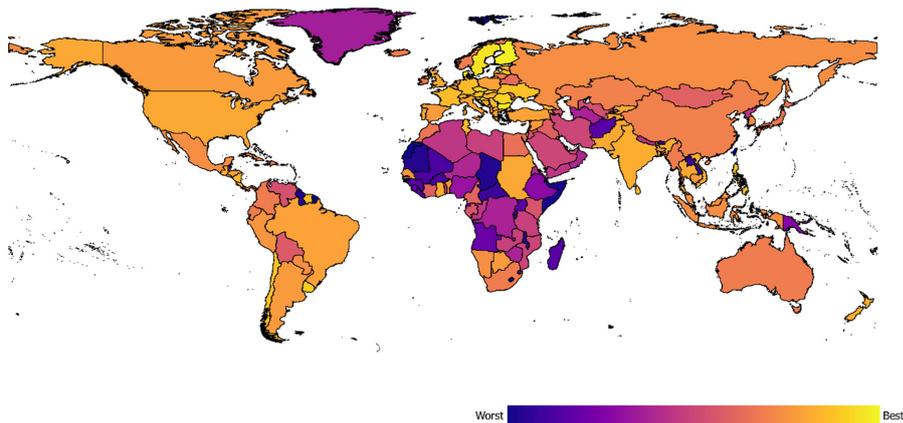


Figure 4. Global view on the diversity dimension.

Finland, Bulgaria and Sweden rank the highest in the diversity dimension as shown in Figure 4. This contributes to the policy these countries follow to balance their energy system elements. In contrast, resource curse seems to strike on some countries where policies are not in place to mediate the economy. The lowest achievement for this dimension is noticed from small islands that need to be dependent on others or African countries that have abundant resources, but their energy system is dependent on one element, e.g., Chad or Lesotho. The best strategy that can be adopted for such countries is to enforce policies to diversify energy system elements.

3.2.3. Cost

The aggregation of the three parameters of the Cost dimension is shown in Figure 5, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

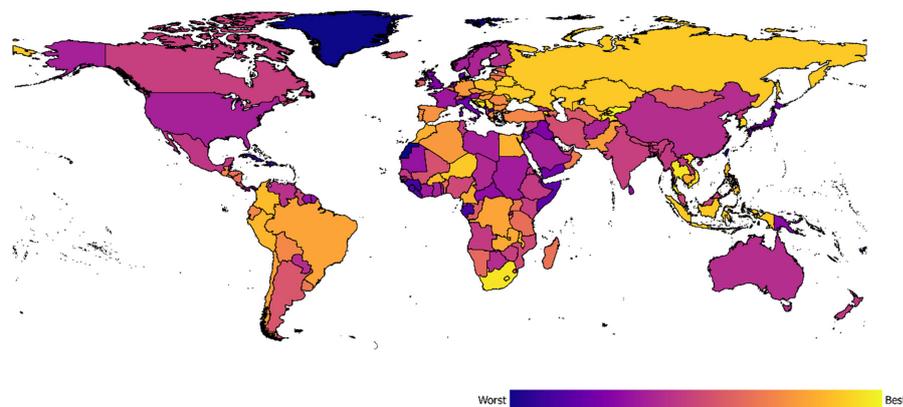


Figure 5. Global view on the Cost dimension.

As for the cost dimension, Kyrgyzstan shows the best performance as can be seen from Figure 5. Although Kyrgyzstan is a land-locked country with relatively small area in comparison to neighbouring countries, its infrastructure and energy cost structure proves to be the best for this dimension. It does not cost much to secure their energy infrastructure, and the income at risk for energy disruption is less. This might be attributed to the fact that Kyrgyz people depend more on traditional way of life than more modern ways. Similar results can be seen for countries such as Lesotho, Thailand and South Africa. In contrast, the United States which scored high in previous dimensions and China with the largest population in the world seem to struggle with the Cost dimension. For the developed world, Germany performs well relatively because of the wide spread of renewable energy.

3.2.4. Technology and Efficiency

The aggregation of the four parameters of the technology and efficiency dimension is shown in Figure 6, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

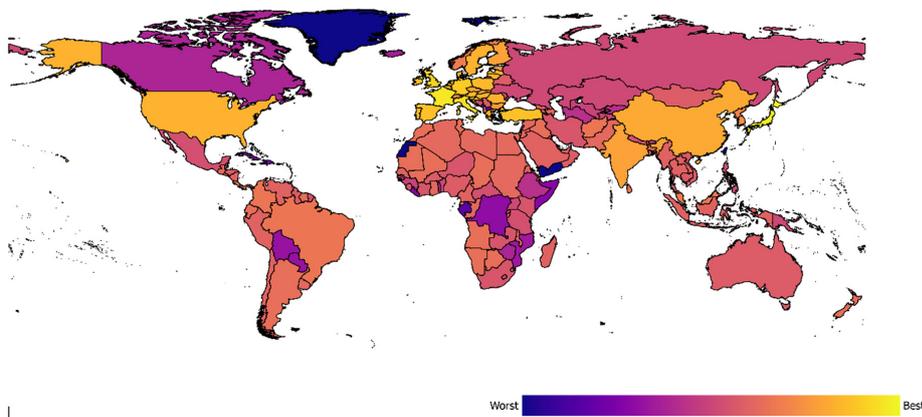


Figure 6. Global view on the technology and efficiency dimension.

Analysing Figure 6 reveals that Japan is leading the world with implementing advanced technologies and thus reaching a more efficient energy system. This is done particularly by reducing the dependency on energy in the economy. A low performance for this dimension can be seen for countries such as Canada where efficiency needs to be improved particularly by enhancing the fuel economy, and technology advancement can be enhanced by generating more patents.

3.2.5. Location

The aggregation of the eight parameters of the location dimension is shown in Figure 7, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Materials.

Although the location dimension might seem to be dependent on factors that are difficult to change, many of the parameters can be enhanced to achieve higher levels of this dimension. This is exactly what Malta, Luxembourg and the Netherlands have done. Figure 7 reveals that these countries have the highest level of performance for this dimension. The trade, infrastructure and geography utilisation are the key elements for their success in this dimension. In contrast, many African countries seem to struggle with this dimension. That is attributed to their industrial intensity, level of globalisation and population density. For these countries, more focus should be on enabling more industrial activities and production facilities in order to have more exports and connections to the global market.

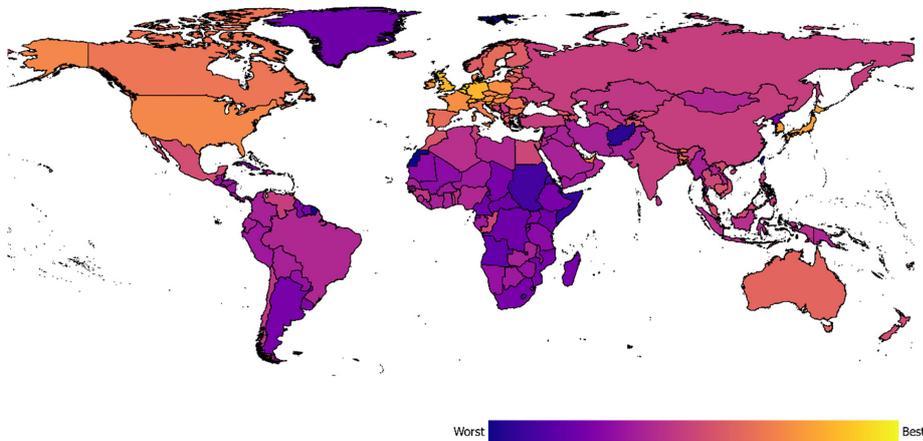


Figure 7. Global view on the location dimension.

3.2.6. Timeframe

The aggregation of the three parameters of the Timeframe dimension is shown in Figure 8, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

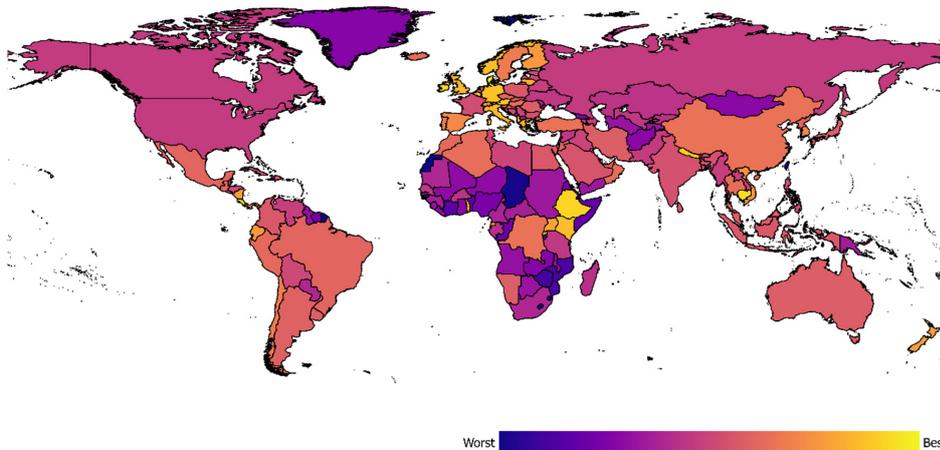


Figure 8. Global view on the timeframe dimension.

For the timeframe dimension it can be noticed that countries with the highest performance are distributed globally, not concentrated in one region. Figure 8 shows Luxembourg, Costa Rica, Denmark, Cambodia and Ethiopia to have the highest score for this dimension. This makes it clear that the infrastructure for these countries can be fixed very fast and the events of disruption for the energy system do not last long. Although life expectancy is not the highest for any of these countries, their energy systems are not affected for a long time with disruption events and impacts on their energy systems are minimised. Some of the developed countries (e.g., the United States and Canada) in addition to many African countries must work harder so that events of disruption will not last long, if they occur the impacts' length of these events is minimised. That can be achieved by having more international and good relationships and by building a more robust energy system.

3.2.7. Resilience

Figure 9 shows the global performance in the resilience dimension. Exact values for all countries can be found in the Supplementary Material.

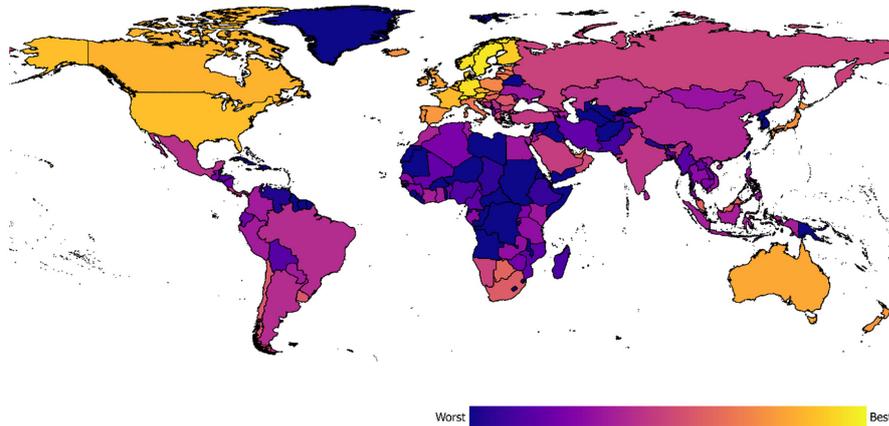


Figure 9. Global view on the resilience dimension.

The resilience index is used to cover the whole resilience dimension. It is shown in Figure 9 that western countries in general have more resilience and more adaptive capacity for their energy systems. Leaders are Switzerland, Luxembourg and Sweden. This can be attributed to the good economy rating of these countries, that they can build alternatives for energy system elements very fast and sustain the flow of their operations as normal. Such leverage is used also to build alternative options in case of emergencies. Rich countries that do well economically but with large area or population do not have necessarily high adaptive capacity e.g., Russia and China.

3.2.8. Environment

The aggregation of the five parameters of the environment dimension is shown in Figure 10, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

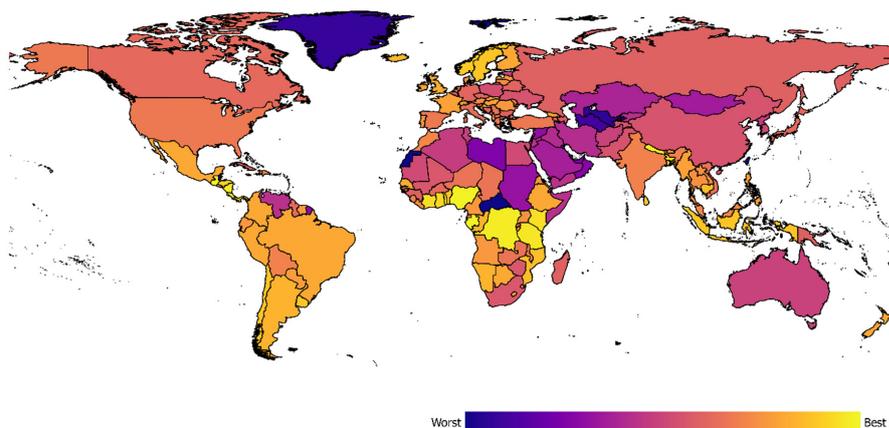


Figure 10. Global view on the environment dimension.

Figure 10 shows many facts of the environment dimension. African countries and countries in Latin America do better in the environment dimension than many developed countries in Europe, North America and Oceania. From Africa, Gabon, Nigeria and Congo DR lead the efforts to keep the environment dimension on the highest values. Same is done by Guatemala and Costa Rica. This proves that European countries claiming to care about environment are behind many African countries. This can be attributed to the lifestyle people live in developed countries that cause high ecological footprints. A simpler lifestyle in Africa proves to have a better relationship with the environment. Another aspect of this dimension is for those countries with the worst achievement for the environment dimension, e.g., Uzbekistan, Kuwait and Turkmenistan. They all have a combination of fossil fuel dependency with a high level of autocratical policy reality and a high level of corruption. This can be also found for many other countries with low achievements in this dimension. Corruption prioritises the benefits of the elite over the environment and the population therefore, decisions are often done with no consideration to the environment.

3.2.9. Health

The aggregation of the two parameters of the Health dimension is shown in Figure 11, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

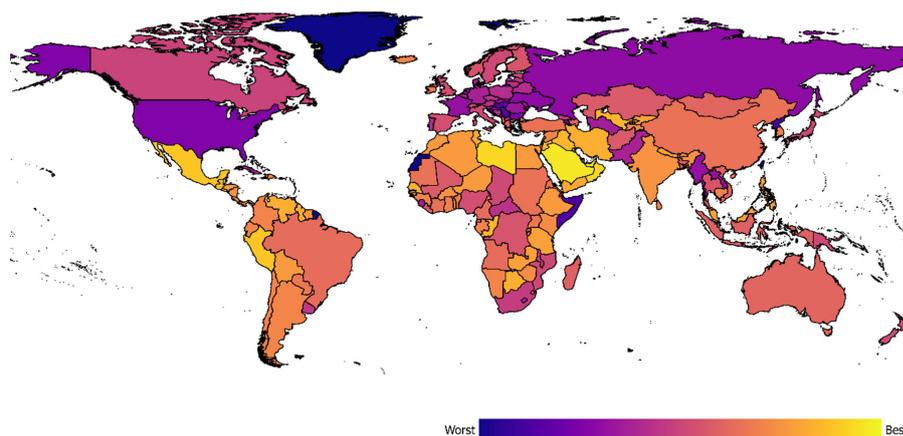


Figure 11. Global view on the health dimension.

The results for the health dimension shown in Figure 11 present Bahrain, Saudi Arabia and United Arab Emirates with the highest performance in this dimension. This is attributed to the expenditure on healthcare in these countries together with the number of deaths attributed to cancer. It also can be explained with the healthy habits of people in these countries, where alcohol consumption is minimal and rich governments that spend lavishly on health infrastructures and medical staff. This is the opposite to other countries where the performance in the health dimension is on a low level, such as the United States and Russia. These two countries spend much of their budget on military-related programmes in addition to the habits of alcohol and drug consumption of the population, plus a health system not equally accessible to all people.

3.2.10. Culture

The aggregation of the two parameters of the Culture dimension is shown in Figure 12, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

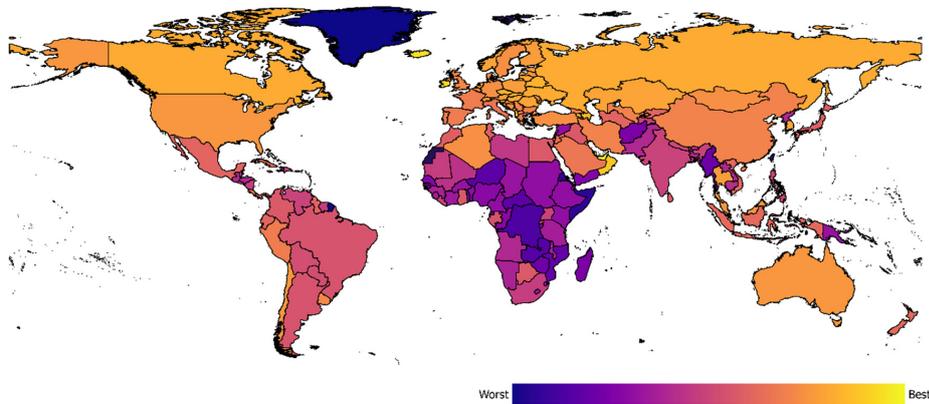


Figure 12. Global view on the culture dimension.

The culture dimension puts Qatar and United Arab Emirates on top of all countries in the world as shown in Figure 12. This can be supported by the fact that people's lives in these two countries are fossil fuel-dependent with a lot of interactions with the energy system. Qatar has the highest energy use per capita in the world. Also, both countries have very high air transport rates relatively to their population. Furthermore, wealthy citizens of these countries with a high percentage of their population in activity age (15–64) contribute a lot to how they affect the energy system and how they use it. In contrast, Congo DR and Zambia and many other African countries are in the lower end of performance in the culture dimension. This is attributed to poverty and less access to air transports.

3.2.11. Literacy

The aggregation of the three parameters of the literacy dimension is shown in Figure 13, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

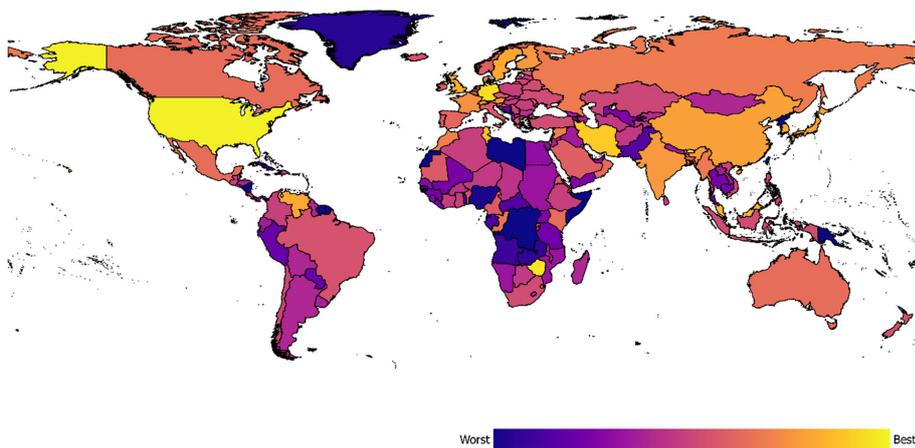


Figure 13. Global view on the literacy dimension.

The United States, Zimbabwe and Germany are the top countries in the Literacy dimension, as shown in Figure 13. It can be noticed from the Supplementary Material that the United States and Germany achieved this high score by the good performance in the information availability. On the other hand, Zimbabwe performs well because of expenditure on education. This makes a strong case for both developing and developed countries. For developing countries in Africa and Latin America, more expenditures on education are needed to improve their energy security. Developed countries in Europe, North America and Oceania, where the education infrastructure is on an advanced level, need to invest more in scientific publications in order to spread knowledge further, and even more to their own people.

3.2.12. Employment

The aggregation of the two parameters of the employment dimension is shown in Figure 14, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

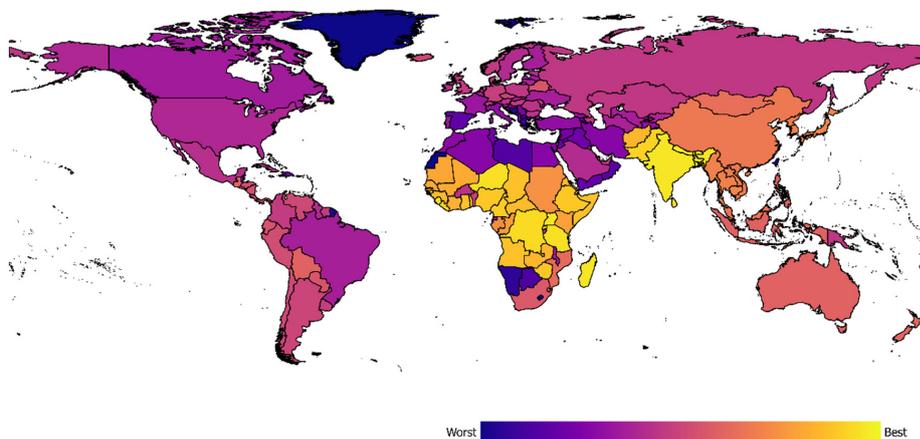


Figure 14. Global view on the employment dimension.

As the employment dimension is concerned about the effect of the energy system on employment and the impact of employment on the energy system, countries with a spacious room for developing their energy infrastructure have the highest scores. Figure 14 highlights Bhutan, Nepal and India have the highest score in the employment dimension. There is a huge opportunity for more employment with the development of renewable energy businesses in these countries. The employment dimension in Europe and the Americas does not seem promising because there seems to be a saturation in energy infrastructure development and a lower number of employment is needed for energy systems development.

3.2.13. Policy

The aggregation of the three parameters of the policy dimension is shown in Figure 15, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

The interplay of geopolitics and respective effects on the policy dimension as shown in Figure 15 points to many aspects. Denmark, Iceland and Finland prove to be on the top of the list of high performance within the policy dimension. These countries have a small population, which seem relatively easy to govern, in addition to a clear political framework to handle matters in hand. In particular, corruption is on low levels which allows for wealth to be more equally distributed in these countries. Countries with a developed political framework to ensure responsibility and power distribution with lower levels of

corruptions achieve high values in the policy dimension. Countries which do not have a good political framework in place because of wars or autocratical regimes score low in this dimension, e.g., Korea DR, Libya and Turkmenistan.

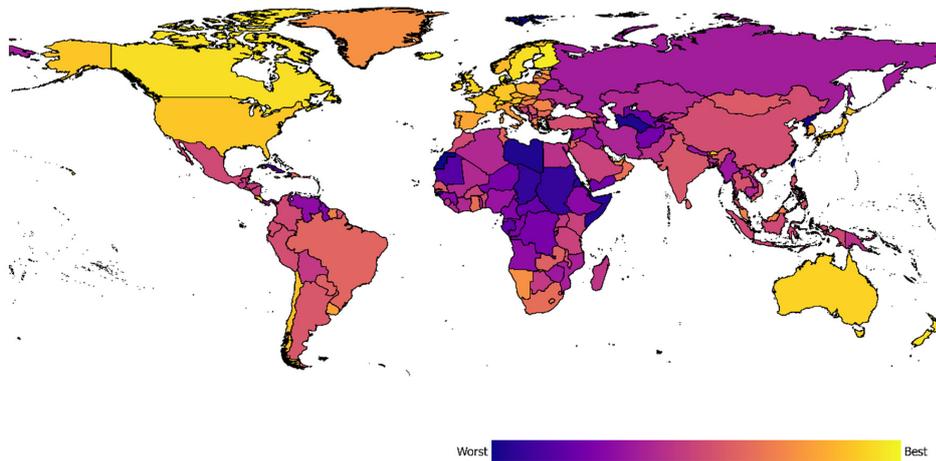


Figure 15. Global view on the policy dimension.

3.2.14. Military

The aggregation of the four parameters of the military dimension is shown in Figure 16 where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Materials.

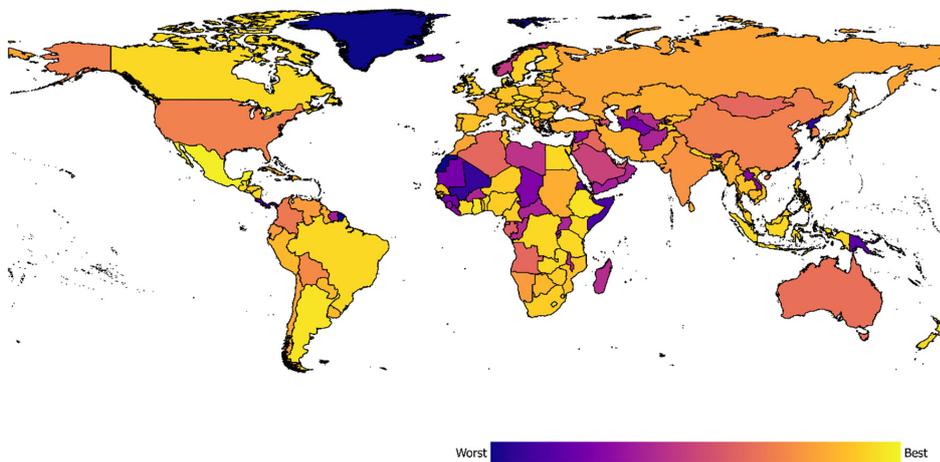


Figure 16. Global view on the military dimension.

Many countries in the world seem to be in a high performance in the military dimension. Two countries in Latin America and two countries in Africa top this dimension. Mexico and Argentina in addition to Ethiopia and Ghana have the highest achievement in this dimension. In contrast, countries being involved in wars together with high dependency on energy resources show a poor performance in this dimension, such as Turkmenistan, Syria and Yemen. Figure 16 reveals rather good values for the

United States and Russia, which would be further improved by reducing their energy consumption for military.

3.2.15. Cyber Security

The aggregation of the three parameters of the Cyber security dimension is shown in Figure 17, where the global performance in this dimension is presented. Exact values for all countries can be found in the Supplementary Material.

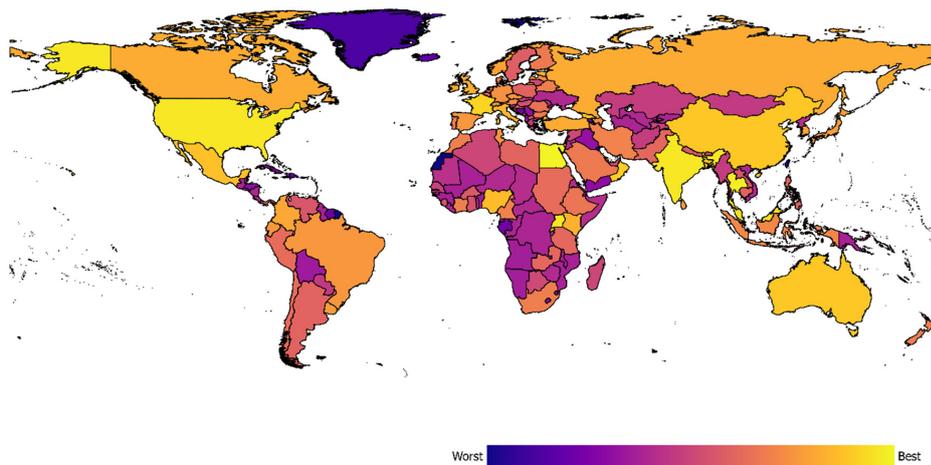


Figure 17. Global view on the cybersecurity dimension.

The last dimension to be analysed is the cybersecurity dimension as presented in Figure 17. Egypt, India and the United States stand out with high performance in this dimension. This is attributed to software use and IT skills. Many African and Asian countries lack connectivity and software use. These countries can invest more in IT education and networks' infrastructure for improving this dimension.

3.3. Energy Security Analysis for Exemplary Countries

In this section, couple of countries are studied in depth for their energy security performance. These countries are chosen to cover a wider spectrum of energy security levels. The highest two countries in the world, Germany and the United States, in addition to two countries, the upper and lower part of the middle of energy security ranking, together with two countries with the lowest energy security level in the world are presented. China and Jordan are chosen from the middle of the list with a rank of 29 and 118, respectively. The Central African Republic and Turkmenistan represents the lowest end of energy security performance.

3.3.1. Germany

Germany has achieved the highest energy security level in the world according to the aggregated ESI. This is attributed to several factors. Figure 18 shows the performance of Germany in each of the 15 dimensions of energy security.

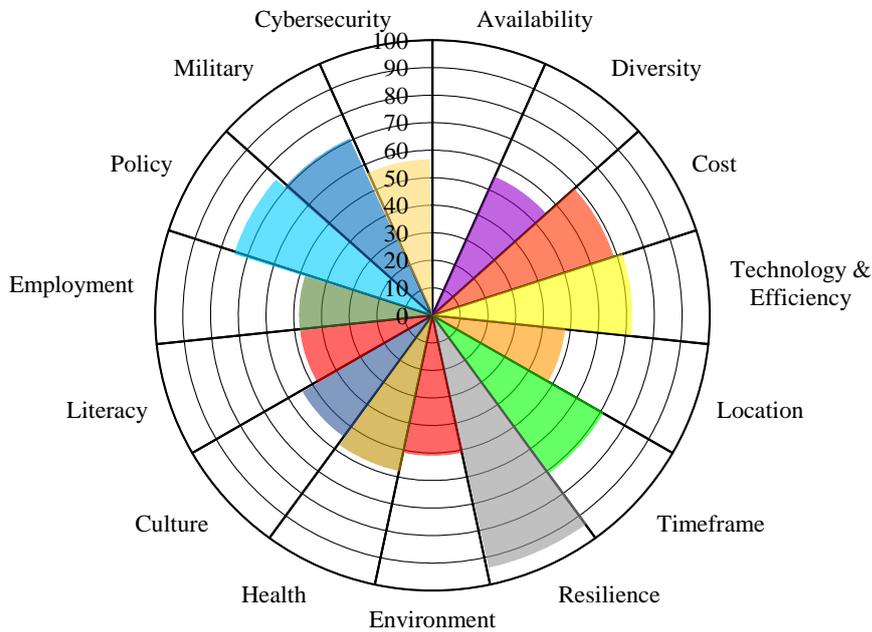


Figure 18. Detailed energy security view for Germany, values 0–100 represent worst to best.

Figure 18 highlights that Germany achieved the highest energy security level in the world by coordinating many of the dimensions. Germany excels in the resilience dimension in which Germany achieved the best performance in comparison to all other dimensions. This high performance in the resilience dimension means that Germany has high adaptive capacity to cope with changes and shocks in the energy system in order to ensure the continuity of a functioning society and system. This high performance in the resilience dimension comes together with the second highest performing dimension, which is the policy. Germany has developed an advanced political system and regulations with regard to the energy system to ensure energy security. Such an achievement within the policy dimension helped to have the resilience performance on the high end. Furthermore, Germany suffers in the availability dimension. This dimension is the worst of all other dimensions for Germany. The impact of the scarce availability in Germany was mitigated by good policies and high adaptive capacity. The performance from Germany shows clearly that lacking in natural resources should not hinder energy security, if political will exists to advance resilience and regulations. Furthermore, Germany has the location and employment dimensions on the worst end. The location dimension is affected hugely by the area of country, its geography and population density. For the employment dimension, Germany is an advanced industrial country where employment is more connected to industries rather than to the energy system, which explains the low achievement in this dimension.

3.3.2. The United States of America

The United States has achieved the second highest energy security level in the world according to the aggregated ESI. This is attributed to several factors. Figure 19 shows the performance of the United States in each of the 15 dimensions of energy security.

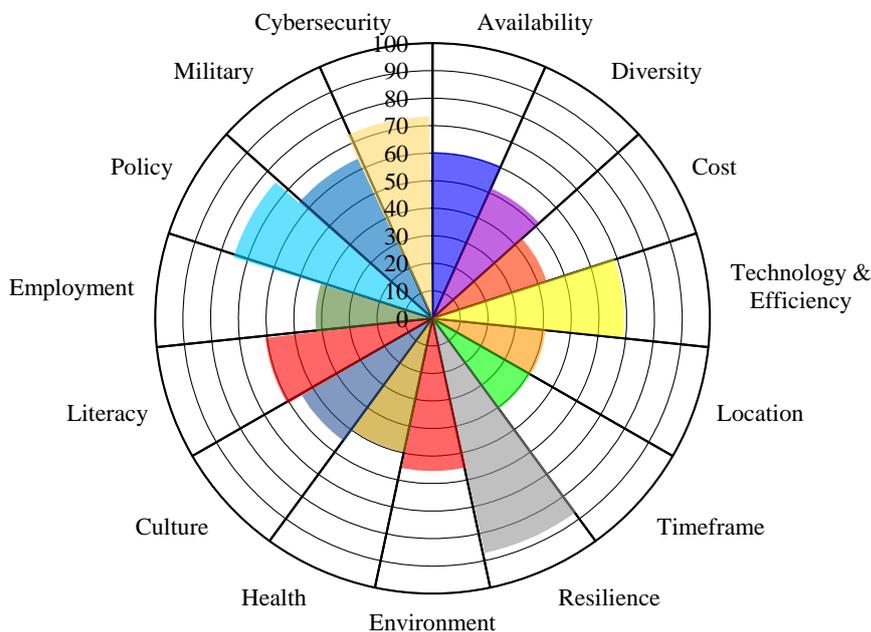


Figure 19. Detailed energy security view for the United States, values 0–100 represent worst to best.

The second highest energy security performance in the world is the United States. However, the route how the United States achieved high performance is different than the previously discussed path of Germany. This proves the point that in order to achieve high energy security levels considering the 15 dimensions approach there are several routes to achieve such high energy security levels. More dimensions are of relevance for energy security than limiting energy security to only availability of resources.

The United States has a more of balanced distribution of the dimensions on a high level. Though, resilience stands again to be the highest dimension followed by policy and cybersecurity. Noticeably, the United States has a higher achievement in the availability dimension than Germany, but still is in the second place of the overall energy security. Implementing similar policies and regulations as Germany for the energy system together with the high level of availability could ensure the United States to climb to rank one in the energy security performance. On the other end, employment and timeframe are the worst of all dimensions for the United States. The reasons that were discussed for Germany still appear to be valid for the United States. Being the most industrialised country, employment in the United States seems to be more connected to industries and companies rather than to the energy system. For the timeframe, the United States needs more than 100 years to achieve a 100% renewable electricity output and the country suffers from old power plants. These two factors made the United States to perform low in this dimension.

3.3.3. China

China has achieved the 29th rank of in energy security according to the aggregated ESI. This is attributed to several factors. Figure 20 shows the performance of China in each of the 15 dimensions of energy security.

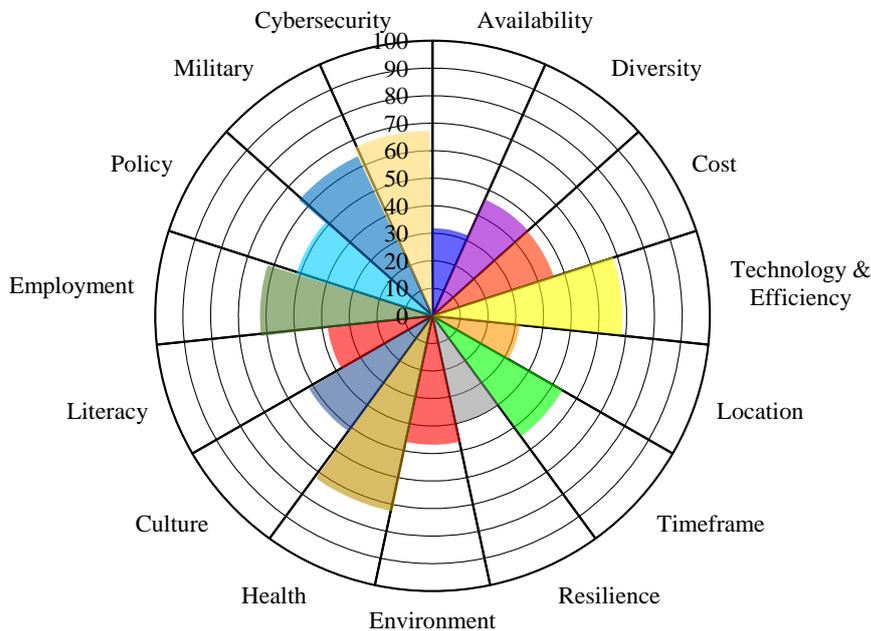


Figure 20. Detailed energy security view for China, values 0–100 represent worst to best.

Moving to the bottom of the high-ranking countries in energy security, turns the attention to China with the rank of 29th in the world. There are many countries in the upper middle of energy security performance, but China was chosen because of being the country with the highest population in the world.

Figure 20 highlights that the best dimension for China is the Health dimension. China seems to spend a lot on healthcare with more healthy people in the workforce. The second remark for China is the high performance in the technology and efficiency dimension together with the cybersecurity dimension. This proves the need for advanced technologies to be implemented if countries want to achieve high energy security levels. Such advancement in technology and efficiency proves necessary because on the other hand China has low achievements in the location and availability dimensions. These natural factors that can be difficult to change are mitigated by advancing other dimensions.

3.3.4. Jordan

Jordan ranks 118th in energy security level according to the aggregated ESI, which places Jordan at the lower end of the middle range. This is attributed to many factors. Figure 21 shows the performance of Jordan in each of the 15 dimensions of energy security.

Moving down the ranks to the lower middle, Jordan stands on 118th of the world energy security levels. Jordan has a very low performance in the availability and literacy dimensions. Jordan has suffered always from scarce energy resources, which has affected the development of the country. Furthermore, literacy needs more attention by spreading knowledge on country level about energy security and energy systems. This can be attributed to the fact that many settlements in Jordan still live in villages with more interests of daily life needs of food and shelter than being involved on country level energy awareness aspects. On the other hand, Jordan pays a lot of attention for the Health dimension with high expenditures levels on healthcare. In addition, the military dimension is on high levels because of the level of immunity Jordan has against the resources curse and being destabilised because of resources availability. This looks like a trade-off for Jordan, less available energy resources make the country to have a higher level of military dimension.

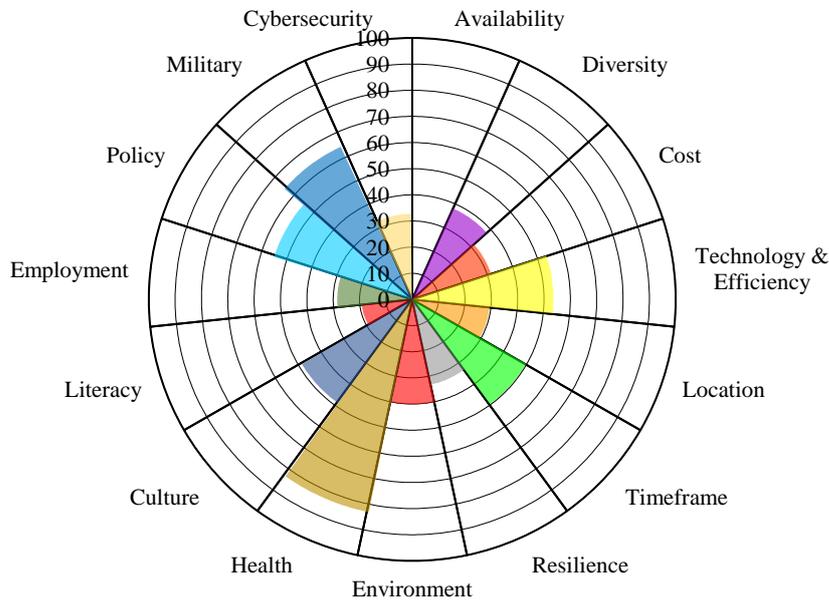


Figure 21. Detailed energy security view for Jordan, values 0–100 represent worst to best.

3.3.5. Central African Republic

On the lowest end of energy security levels in the world stands the Central African Republic. This is attributed to many factors. Figure 22 shows the performance of Central African Republic in each of the 15 dimensions of energy security.

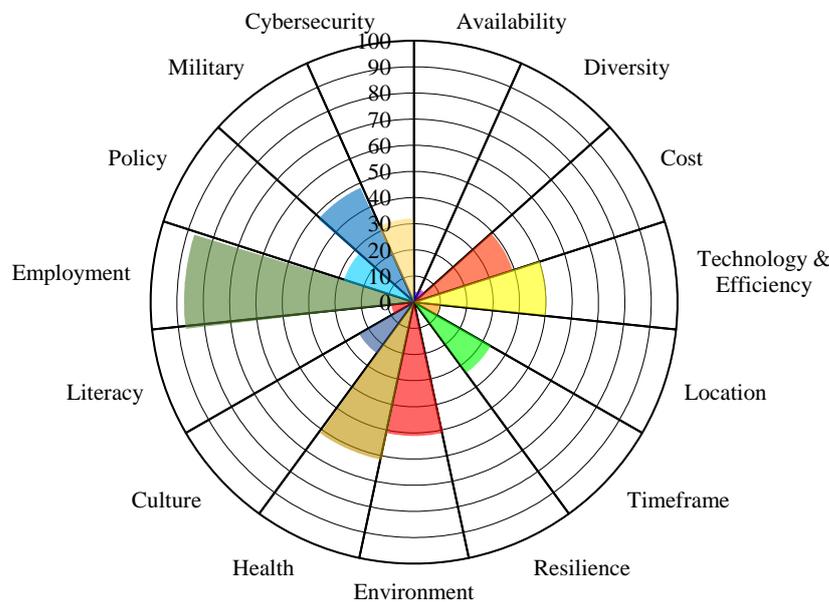


Figure 22. Detailed energy security view for Central African Republic, values 0–100 represent worst to best.

At the lowest end of energy security levels, some countries show different achievements and routes why they ended up in this category. The first example of this category is Central African Republic, where it has performed extremely high in the employment dimension. This means this country has a lot of opportunity to install new energy infrastructure and provide employment in this sector. Furthermore, unemployment is on low levels as most of the population is involved in traditional work in agriculture. On the other hand, many dimensions are on the worst end, for example the diversity dimension. This shows the long way ahead for Central African Republic to implement better practices in order to achieve a higher energy security.

3.3.6. Turkmenistan

The worst energy security level in the world has been found for Turkmenistan. This is attributed to many factors. Figure 23 shows the performance of Turkmenistan in each of the 15 dimensions of energy security.

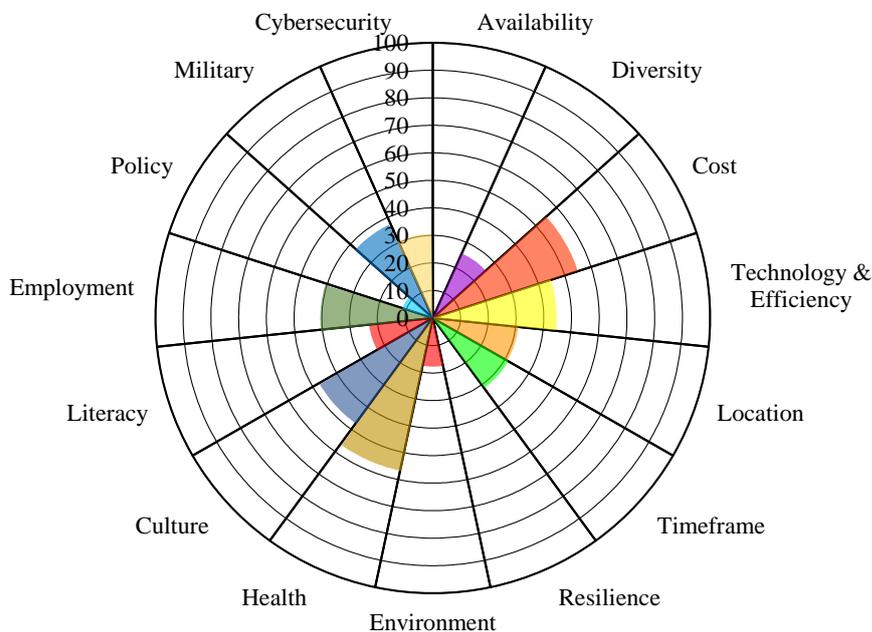


Figure 23. Detailed energy security view for Turkmenistan, values 0–100 represent worst to best.

Although Turkmenistan has very high levels of achievement in the cost dimension, together with the health dimension, it stands in the lowest end of energy security levels in the world. The cost structure for energy services is among the best in the world, owing to own natural gas resources. However, a totalitarian regime with high autocracy levels can make the cost dimension on high performance, but on the expense of other dimensions. That is seen clearly from the policy dimension, where Turkmenistan has one of the worst regimes in the world. This affects most of the other dimensions of energy security.

3.4. Limits of This Research

Although this research is novel with very promising results, some limitations exist. The first limitation is the use of equal weighting of all parameters and dimensions. Reality could be different. However, because of lack of justification of different weights in the present state, this research could be further enhanced by investigating in improved weighting values for all parameters and dimensions.

This can be done by uncertainty and sensitivity analyses as it was done by Augutis et al. [105]. However, because of the large number of indicators (76 indicators), sensitivity analyses would substantially enlarge the length of this research and thus it was not included but rather planned for future research. It was found by Augutis et al. [105] that the average of simulated weights is similar to the use of equal weights, therefore, equal weights have a stronger support.

The second limitation is the static nature of such research. Energy security is analysed for a certain time period. That is attributed mainly to the indicators that were used. Although many of them have past records, but future projection of the indicators needs further research. Once, each indicator can be projected, energy security future scenarios can be applied using this research method. This is of interest since it is expected that the energy system changes structurally from a fossil basis to a solar basis [106]. Since the change from one year to another is negligible, more noticeable changes can be observed on the scale of at least 5–10 years. Therefore, a long-term future extrapolation of data for all indicators is needed as a future research. Once such indicators values are available and justified, ESI projections can be applied for future scenarios.

The third limitation was faced when searching for suitable indicators to represent individual parameters. There are some parameters which were represented by a proxy indicator or a combination of indicators because of the complex nature of these parameters. This shows the need for international efforts to investigate and build indexes in relation to these parameters.

The fourth limitation was the data availability of some indicators for some countries. Although, best efforts have been spent to choose indicators for which data are available for most countries, some indicators have a significant unavailability of data for several countries, though most countries have available data. Future research is needed to investigate the reasons of data unavailability from the sources and build a suitable replacement for these absent data.

4. Conclusions and Recommendations

After going through this intensive analysis of energy security on a global level, several key conclusions can be drawn. First, such detailed evaluation of the global energy security levels with all countries' performance included proves to be a needed research to enable a deeper understanding of the current situation in this regard. This research contributes to close this gap by a novel approach with profound and detailed 15 dimensions for energy security analysis. Second, it is noticed that energy security has many relationships with different aspects. These relationships affect and are affected by energy security. The detailed interaction between these aspects are presented in this research by comprehensive methods and numerical indicators for each of the parameters within each dimension. Third, it is concluded that countries' performances can vary in ways achieving high energy security, since there is not a single recipe but rather there are different paths that can be followed.

Countries vary in their energy security performance from very high achievements, like Germany and the United States, to low performance such as the Central African Republic and Turkmenistan. This is presented on the overall energy security level. Nevertheless, countries also have different achievements in each of the dimensions as has been presented in the Results section. Development pathways and needs for countries are different, so that there is no one solution for all countries, and thus there are multiple ways to transition and enhance the overall global energy system. That means countries need to implement a bunch of smaller steps and learn from other countries what is suitable to their context and test such changes. As was proven in [107], only a directed evolution of the current system is required to guarantee affordability, reliability and sustainability. Each country should focus on what dimension they are lagging and learn lessons from countries that have achieved high results in the respective dimension and implement the best options according to their own circumstances.

The six examples for countries performances in the world showed that lagging in one dimension can be compensated by a higher performance in another dimension and that, such a situation should not hinder development. This point proves the need of a multi dimension evolution of energy security in order to compile a comprehensive analysis. Recommendations are for policymakers and researchers

to study the presented results in detail and formulate strategies to improve energy security both on the country and global level.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1996-1073/13/10/2502/s1>, Excel: energy security. The spreadsheet file in the supplementary material consists of all collected data for all countries and for all indicators. The primary data table shows all these data clustered for 50 parameters and 15 dimensions. The aggregation methods that were described in details in the article (methods, appendix) are implemented in the spreadsheet file and in calculating the ESI for all countries. To adhere to our approach of total transparency, references for data collection for each indicator are also added in the supplementary spreadsheet file. Tables for detailed calculations are provided when needed. Furthermore, lists of missing indicators for each country together with their count is presented.

Author Contributions: A.A. did conceptualisation, methods, validation, formal analysis, investigation, data curation and collection, writing—original draft preparation, writing—review and editing, visualisation; C.B. contributed to conceptualisation, methods, formal analysis and was responsible for supervision, review and editing, project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Appendix A

This Appendix A provides a detailed description of all methods and equations that are used to build the ESI. It includes all the equations and the needed relationships between indicators and parameters in their corresponding dimensions with energy security.

Appendix A.1. Availability

The availability dimension (A) consists of three parameters (A_1, A_2, A_3) and each one is assigned as an indicator or a set of indicators to reflect that parameter in the aggregation. In addition, each parameter is given a weight (W_i). Equation (A1) represents the parameters and their weights. Equal weights for all parameters lead to Equation (A2) with each parameter having a weight of one third.

$$A = W_1 \cdot A_1 + W_2 \cdot A_2 + W_3 \cdot A_3 \quad (\text{A1})$$

$$A = \left(\frac{1}{3}\right) \cdot A_1 + \left(\frac{1}{3}\right) \cdot A_2 + \left(\frac{1}{3}\right) \cdot A_3 \quad (\text{A2})$$

Appendix A.1.1. Existence of Resources

Energy resources are measured by the total available resource of fossil fuel and potential renewables. Fossil fuel resources are obtained from International Energy Agency (IEA) from their global energy balances [41]. Coal, crude oil and natural gas are summed up to form total fossil fuels. The existence of fossil fuel resources is considered as the current total production of total energy primary sources in each country. The renewable energy resources are obtained from the country-specific energy potential of solar photovoltaics (PV), concentrating solar thermal power (CSP), wind energy, hydropower, geothermal energy and bioenergy according to the LUT model data [108]. The indicator of total available energy resources is normalised by a max-min approach presented in Equation (4) for all countries in the world. The maximum was (360,724 TWh) for Australia and (289 TWh) for Lebanon. Countries that have access to more resources obtain also a higher level of energy security, and vice versa. The resultant Equation for this parameter is presented in Equation (A3)

$$A_1 = I_{1,A1} \quad (\text{A3})$$

where $I_{1,A1}$ is the normalised total available energy resources.

Appendix A.1.2. Existence of Consumers

The existence of consumers is measured by a proxy indicator of the population. Data from United Nations for 2015 population in each country is taken [43]. The relationship to energy security for the consumers point of view is directly proportional. The more consumers the energy system has, the more secure it can become. The population is normalised by dividing on the world's population (7.38 billion in 2015) [43] for each country, that means the best energy system to study is the one that covers the whole world, and the least secure energy system is the one with no population. The resultant Equation for this parameter is presented in Equation (A4)

$$A_2 = I_{1,A2} \quad (A4)$$

where $I_{1,A2}$ is the normalised population with normalisation according to Equation (5).

Appendix A.1.3. Existence of Means of Transport

The existence of means of transportation is measured by a proxy of airports number in each country. Data for the number of airports were taken from CIA fact book for 2013 or latest [44]. More airports mean more transportation is taking place, and thus a more secure system. Therefore, the relation is directly proportional. For the normalisation of these absolute numbers, the number of airports in each country is divided by the number of airports in the country with the highest number of airports (the United States with 13513 airports). The absence of airports (zero) is assumed to be the least energy security level. The parameter for the existence of means of transport (A_3) is presented in Equation (A5).

$$A_3 = I_{1,A3} \quad (A5)$$

where $I_{1,A3}$ is the normalised number of airports with normalisation according to Equation (5).

Appendix A.2. Diversity

The diversity dimension (D) consists of four parameters (D_1, D_2, D_3, D_4) and each one is assigned one indicator or more. Equation (A6) represents the parameters and their weights (W_j). Since the weight is distributed equally, each parameter gets a weight of 0.25, as applied in Equation (A7):

$$D = W_1 \cdot D_1 + W_2 \cdot D_2 + W_3 \cdot D_3 + W_4 \cdot D_4 \quad (A6)$$

$$D = \left(\frac{1}{4}\right) \cdot D_1 + \left(\frac{1}{4}\right) \cdot D_2 + \left(\frac{1}{4}\right) \cdot D_3 + \left(\frac{1}{4}\right) \cdot D_4 \quad (A7)$$

In the diversity calculations, the parameters are calculated by using Simpson's diversity index $SIDI$ [109,110]. The formula for $SIDI$ is represented in Equation (A8), and therefore each parameter equals $SIDI$ or the average of $SIDI$ indicators, as applied in Equation (A9):

$$SIDI = 1 - \sum_{i=1}^n Z_i^2 \quad (A8)$$

$$D_j = \text{average}(SIDI_j) \quad (A9)$$

where Z_j is the share of each element in the studied system and j refers to each parameter. For example, if the systems consist of four elements, then the share of each element is obtained by dividing its value over the total sum of all elements. Equation (A10) shows how the shares are calculated:

$$Z_i = \frac{e_i}{\sum_{i=1}^n e_i} \quad (A10)$$

where e_i is the value of each element in the set.

Appendix A.2.1. Diversity of Sources

Diversity of sources regards the relative balance of sources. For instance, if the energy system has only one source, it is less secure than if there are different sources. Two main types of resources were analysed (domestic and imported). Data for 2014 that represent local and imported resources was taken from International Energy Agency IEA [41]. (Z_i) for the two elements (local e_1 and imported e_2) was calculated as in Equation (A10). After that, the diversity of resources was calculated by Equations (A8) and (A9).

Appendix A.2.2. Diversity of Carriers

Energy carriers can be in the form of matter-based chemical materials (fossil fuels, biomass/waste) or in the form of non-matter-based electro-magnetic fields (electricity). Data are derived for the year 2014 [41]. Shares of elements (e_i) (fossil fuels, renewable fuels, heat and electricity) were calculated according to Equation (A10). Fossil fuels include coal, crude oil, oil products and natural gas. Renewable energy includes hydropower, geothermal energy, wind and solar fuels, biofuels and waste. After that, the diversity of carriers was calculated by Equations (A8) and (A9).

Appendix A.2.3. Diversity of Means

Diversity of means consists of two parts: diversity of technology and diversity of transportation. With more technologies forming the energy system, energy security is enhanced. The same concept is applied for transportation options: the more diverse a system is, the more secure it becomes. The total installed capacities of different power generation technologies in 2014 (MW) were taken from Farfan and Breyer [45] for the following elements, (e_i) (gas, oil, coal, nuclear, solar PV, CSP, wind, biogas, biomass, geothermal, hydro run-of-river, hydro reservoir, ocean) and were used to calculate (Z_i) as in Equation (A10). *SIDI* for power generation technologies was calculated using Equation (A8). The second part of this parameter is the diversity of transportation. Shares (Z_i) of elements (e_i) (pipelines, railways, roadways and waterways), all measured in km, were calculated by Equation (A10). The data for each element were taken from Photius Coutsoukis PC [46]. Further, *SIDI* for transportation was calculated from Equation (A8). The diversity of means parameter consists of two indicators, and the arithmetic average of the two is taken into consideration according to Equation (A9) and applied in Equation (A11).

$$D_3 = \frac{(SIDI_{technologies} + SIDI_{transportation})}{2} \quad (A11)$$

Appendix A.2.4. Diversity of Consumers

The last parameter is the consumers' profile. Being able to provide energy services to more diverse users is considered more secure. In this research, analysis of the diversity of consumers is carried out by studying the shares (Z_i) of consumer profiles. Elements (e_i) of industry, transport, residential, commercial and public services, agriculture and forestry, fishing, non-specified, non-energy use were calculated using Equation (A10). Data of energy balances were taken for 2014 [41]. The diversity of consumers was calculated by Equations (A8) and (A9).

Appendix A.3. Cost

The cost dimension (Co) consists of three parameters (Co_1 , Co_2 , Co_3) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. Each parameter is given a weight (W_j). Equation (A12) represents the parameters and their weights. Applying equal weights for all parameters leads to Equation (A13) with a weight of one third for each parameter:

$$Co = W_1 \cdot Co_1 + W_2 \cdot Co_2 + W_3 \cdot Co_3 \quad (A12)$$

$$C_0 = \left(\frac{1}{3}\right) \cdot C_{01} + \left(\frac{1}{3}\right) \cdot C_{02} + \left(\frac{1}{3}\right) \cdot C_{03} \quad (\text{A13})$$

Appendix A.3.1. Energy Price

This parameter is measured by the average of two indicators, after their normalisation. The first indicator is the diesel price (in units of USD/litre) as of mid-November 2014 in each country obtained from [47]. The diesel prices are normalised by dividing by the maximum value in the world (Eritrea with 3.00 USD/litre) and then subtracting from unity to have the lowest price as the most secure result. The second indicator is the weighted average price of electricity in three market segments residential, commercial and industrial (in units of €/kWh) derived from the LUT model [108]. The normalisation is done by dividing by the maximum in the world (Denmark with 0.192 €/kWh) and subtracting from unity, indicating cheap energy prices are best for energy security. Finally, the average of both normalised indicators is obtained in Equation (A14):

$$C_{01} = \frac{I_{1.C01} + I_{2.C01}}{2} \quad (\text{A14})$$

where $I_{1.C01}$ is the normalised diesel price and $I_{2.C01}$ is the normalised electricity price according to Equation (5).

Appendix A.3.2. Cost of Disruption

Income at risk due to power outage as income loss (in units of €/capita) is chosen as the indicator to measure this parameter. Data were calculated by dividing the GDP per capita from [48] by the 365 days in a year, resulting in income per day. That is multiplied by the power shortage in days [49] to be detailed later in the second parameter of the timeframe dimension (section 2.6). The result is lost income due to power shortage (in units of €/capita). The data are normalised by dividing the maximum in the world (Botswana with 930 €/capita) after removing the outliers by the quartile method [111] and then subtracting from unity, indicating that zero loss is the best for energy security and losing more is worse for energy security. This is summarised in Equation (A15):

$$C_{02} = 1 - I_{1.C02} \quad (\text{A15})$$

where $I_{1.C02}$ is the normalised income at risk with normalisation according to Equation (5).

Appendix A.3.3. Cost of Securing the System

A key option to increase the security of an energy system is to lower the levelized cost of electricity (LCOE) on a system level. Low system LCOE indicates a high level of energy security. Total system LCOE of 2015 in each country was obtained from the LUT model [108]. The data were normalised by max-min method (Lebanon with 174.20 €/MWh and both Congo & Congo DR with 38.20 €/MWh) as defined in Equation (4). Lower LCOE means higher energy security level thus subtracting from unity. Equation (A16) shows the mathematical notion for this parameter:

$$C_{03} = 1 - I_{1.C03} \quad (\text{A16})$$

where $I_{1.C03}$ is the normalised total system LCOE.

Appendix A.4. Technology and Efficiency

The technology and efficiency dimension (TE) consists of four parameters (TE_1, TE_2, TE_3, TE_4) and each one is assigned one indicator or a set of indicators to reflect that parameter in the aggregation.

Each parameter is given a weight (W_j). Equation (A17) represents the aggregation of the parameters and their weights. Each parameter is weighted equally with 0.25 leading to Equation (A18):

$$TE = W_1 \cdot TE_1 + W_2 \cdot TE_2 + W_3 \cdot TE_3 + W_4 \cdot TE_4 \quad (A17)$$

$$TE = \left(\frac{1}{4}\right) \cdot TE_1 + \left(\frac{1}{4}\right) \cdot TE_2 + \left(\frac{1}{4}\right) \cdot TE_3 + \left(\frac{1}{4}\right) \cdot TE_4 \quad (A18)$$

Appendix A.4.1. New Technology Advancement

The technology advancement can be measured in many ways. In this parameter two proxy indicators are used to construct how much the technology gets advanced in a country. The first proxy to use is the number of patents in force in each country. The data are taken from World Intellectual Property Organisation for 2016 [50]. The number of patents in each country is normalised by dividing by the country that has the maximum number of patents (the United States with 2,763,055 patents). The more patents a country has accumulated indicates more technology advancement and thus the respective level of energy security. A low number of patents in a country means low energy technology advancement and therefore a low energy security level. The second indicator to be used as a proxy for the technology advancement is the number of scientific and technical journal articles from year 2016 obtained from the World Bank [51]. The more the number of scientific articles originated from a country is interpreted as an indicator for a higher energy security level, and vice versa. The normalisation for this indicator is carried out by dividing the highest value found for a country in the world (China with 426,165 articles), assuming again that a very low amount of scientific articles published indicates a low energy security level. The average of the two indicators is used to determine (TE_1) as presented in Equation (A19):

$$TE_1 = \frac{I_{1,TE1} + I_{2,TE1}}{2} \quad (A19)$$

where $I_{1,TE1}$ is the normalised number of patents and $I_{2,TE1}$ is the normalised number of articles with normalisation according to Equation (5).

Appendix A.4.2. Energy System Efficiency

Supply efficiency for the power sector is the chosen indicator to measure the energy system efficiency. Data were collected from the LUT model [42]. Normalisation is not needed because it is already in percentage. The mathematical notation for this parameter is represented in Equation (A20):

$$TE_2 = I_{1,TE2} \quad (A20)$$

where $I_{1,TE2}$ is the supply efficiency.

Appendix A.4.3. Energy Intensity

Energy intensity is calculated according to the energy intensity level of primary energy in each country (in units of MJ/USD₂₀₁₁ PPP GDP), with data for 2015 derived from the World Bank [52]. The values are normalised by dividing the highest value in the world (Liberia 26.0 MJ/USD₂₀₁₁ PPP GDP), where the highest value of energy intensity represents the lowest level of energy security. The obtained percentage was subtracted from unity. This is expressed by Equation (A21):

$$TE_3 = 1 - I_{1,TE3} \quad (A21)$$

where $I_{1,TE3}$ is the normalised energy intensity with normalisation according to Equation (5).

Appendix A.4.4. Energy Conservation

Energy conservation is an attitude that shows how efficient energy is consumed by people. As a proxy indicator the efficiency of light duty vehicles is considered (in units of litres of gasoline equivalent per 100 km of Worldwide Harmonised Light Vehicle Test Cycle (WLTC)) data for the year 2015. Data are collected from IEA and its Global Fuel Economy Initiative [53]. Average values from the report for EU-28, OCED and global average were used for countries that were not listed specifically by name. Normalisation is done by the max-min approach (Canada with 9.2 and France with 5.2) according to Equation (4) and subtracting from unity as summarised in Equation (A22), referring to more litres needed for 100 km means lower standards for energy conservation and respective more consumption thus a lower level of energy security.

$$TE_4 = 1 - I_{1,TE4} \quad (A22)$$

where $I_{1,TE4}$ is the normalised energy conservation with normalisation according to Equation (4).

Appendix A.5. Location

The location dimension (Lo) consists of eight parameters ($Lo_1, Lo_2, Lo_3, Lo_4, Lo_5, Lo_6, Lo_7, Lo_8$) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. In addition, each parameter is given a weight (W_i). Equation (A23) represents the parameters and their weights. Assuming equal weights for all parameters leads to Equation (A24), applying a weight of 0.125 each:

$$Lo = \sum_{i=1}^8 W_i \cdot Lo_i \quad (A23)$$

$$Lo = \sum_{i=1}^8 \left(\frac{1}{8}\right) \cdot Lo_i \quad (A24)$$

Appendix A.5.1. Energy Systems Boundaries

The energy boundaries parameter of a system is measured by the area in each country. The area in square kilometres is obtained from the World Bank [54]. The assumption for the system boundaries is that, the bigger the area, the higher the energy security level, and vice versa. The normalisation of the area indicator is executed by dividing the area of each country by the area of the whole world (129,733,173 km²), and expressed by Equation (A25):

$$Lo_1 = I_{1,Lo1} \quad (A25)$$

where $I_{1,Lo1}$ is the normalised area with normalisation according to Equation (5).

Appendix A.5.2. Location of Energy Source

To account for the parameter location of energy sources and its importance to energy security, the distance between production and consumption (km) is chosen as an indicator. Crude oil trade movement in 2016 between major players and regions in the world is obtained from BP [55]. The distances between countries are calculated individually for each region or country by using centre estimation presented in [56]. The crude oil movement is multiplied by the distance it is transported. If the country is a net exporter, then the values are for how far its crude oil needs to be transported to consumers as weighted average. If the country is a net importer, then the distance from all sources of crude oil is considered as weighted average. These values are represented by larger regions to an individual country, if the country is not mentioned directly in the data source, otherwise the values are assigned directly to countries. Normalisation is according to the max-min approach (Angola with 11,515 km and Canada with 2332 km) according to Equation (4), by linking long distances to low levels of energy security, thus subtracting the normalised value from unity, as presented in Equation (A26):

$$Lo_2 = 1 - I_{1,Lo2} \quad (A26)$$

where $I_{1.L02}$ is the normalised distance with normalisation according to Equation (4).

Appendix A.5.3. Density Factor (Centralised/Decentralised)

The density factor is expressed by the energy use per area. Primary energy use (in units of kWh_{th} per capita) is derived from World Bank data for the year or later [57]. The value of every country is multiplied by its population (using the same value as for parameter A_3) and divided by the area of the respective country (using the same value as for parameter L_{01}), indicating the energy density (in units of MWh_{th} of primary energy demand per square kilometre). The relation of this indicator to energy security is inversely proportional, i.e., the higher the energy density the lower energy security. After normalising the values by dividing the highest value in the world (Singapore 458,577 MWh/km²), they are subtracted from unity, as represented in Equation (A27):

$$L_{03} = 1 - I_{1.L03} \quad (\text{A27})$$

where $I_{1.L03}$ is the normalised energy density with normalisation according to Equation (5).

Appendix A.5.4. Land Use

This parameter is used as an indicator for terrestrial- and marine-protected areas (in units of percentage of total territorial area). Data are obtained from the World Bank [58] for the year 2017. Data are normalised by dividing the highest value in the world (Slovenia with 55.1%). More protected areas in a country as a percentage of its land is assumed to indicate a better support for energy security, while a very low share of protected land is interpreted the other way around. The parameter is represented by Equation (A28):

$$L_{04} = I_{1.L04} \quad (\text{A28})$$

where $I_{1.L04}$ is the normalised protected areas with normalisation according to Equation (5).

Appendix A.5.5. Globalisation

Globalisation can be measured by proxy indicators, such as international trade in a country as a percentage of GDP. Data were taken from the World Bank [59] for each country for the year 2015. The data were normalised by dividing the maximum value for a country in the world (Luxembourg 438%). More trade means more secure systems, whereas very low levels of trade means a high level of isolation and lowest levels of energy security. The second indicator used is the KOF globalisation index, obtained from KOF (Konjunkturforschungsstelle) Swiss Economic Institute for year 2013 data [60]. There is no need for further normalisation as these values are in a percentage form with relative terms to each other. High values indicate high levels of energy security. The average of the two indicators is used to determine L_{05} , as presented in Equation (A29):

$$L_{05} = \frac{I_{1.L05} + I_{2.L05}}{2} \quad (\text{A29})$$

where $I_{1.L05}$ is the normalised trade and $I_{2.L05}$ is the KOF index with normalisation according to Equation (5).

Appendix A.5.6. Population Settlement and Distribution

This parameter is measured by the population density. It is calculated by dividing the population in a country (using the same value as for parameter A_2) by the area (using the same value as for parameter L_{01}). Normalisation is carried out by dividing the population density in each country by the highest population density in the world (Bahrain 1779 persons/km²), after excluding Singapore.

Higher population density means higher level of energy security. This parameter is represented by Equation (A30):

$$L_{06} = I_{1,L06} \quad (\text{A30})$$

where $I_{1,L06}$ is the normalised population density with normalisation according to Equation (5).

Appendix A.5.7. Geography

The geography parameter consists of a complex relationship to energy security. The average of three indicators is chosen to reflect this complexity in the energy security index. The first indicator is the number of countries with shared borders obtained from [44]. More neighbours mean less security and stability and higher risks. Normalisation is done by dividing over the maximum in the world (China with 14 countries), and then subtracting from unity. The second indicator is the seaports infrastructure, derived from [44] for the year 2015. Evaluation for this indicator is based on the seaports sheet as provided in the Supplementary Material. Each type of infrastructure is given a default point, then the number of these infrastructure in each country is multiplied with the points of its own infrastructure. The types of infrastructure and their points are respectively: Container, Cargo, LNG, Oil, Major seaports, River/lake ports and Cruise; 20, 20, 10, 10, 10, 5 and 5. Normalisation is done by dividing the maximum value in the world (Japan with 500 points), whereas more points for seaports infrastructure means a higher energy security level. The third indicator is the total renewable surface water (in units of m^3/year) for the year 2014 in each country, obtained from FAO [61]. Data are normalised in two steps: First, dividing by the area to get values in units of $\text{m}^3/(\text{year}\cdot\text{km}^2)$; second, dividing by the second highest in the world (Cambodia $2,604,397 \text{ m}^3/(\text{year}\cdot\text{km}^2)$), as the highest is considered an outlier and therefore is given the full score. More water surface area is better for energy security. This parameter is represented by Equation (A31):

$$L_{07} = \frac{I_{1,L07} + I_{2,L07} + I_{3,L07}}{3} \quad (\text{A31})$$

where $I_{1,L07}$ is the normalised number of countries with shared borders, $I_{2,L07}$ is the normalised seaport infrastructure and $I_{3,L07}$ is the normalised total renewable surface water, with normalisation according to Equation (5).

Appendix A.5.8. Industrial Intensity

Industrial intensity is measured by a calculated indicator. Industrial added value (in units of USD) is used as obtained from the World Bank for the year 2015 or latest available for each country [62]. The industrial added values for each country are divided by the area of the respective country (using the same value as for parameter L_{01}). The results represent industrial intensity (in units of USD per km^2). Higher industrial intensity means higher financial utilisation of the area and results in a higher energy security level. Normalisation is carried out by dividing each country's values over the highest value in the world (South Korea 4,811,143), while considering Singapore, Bahrain and Qatar as outliers. This parameter is represented by Equation (A32):

$$L_{08} = I_{1,L08} \quad (\text{A32})$$

where $I_{1,L08}$ is the normalised industrial intensity with normalisation according to Equation (5).

Appendix A.6. Timeframe

The timeframe dimension (T) consists of three parameters (T_1, T_2, T_3) and each one is assigned to one indicator or a set of indicators. Each parameter is given a weight (W_j). Equation (A33) represents the parameters and their weights with equal weights of one third, as summarised in Equation (A34):

$$T = W_1 \cdot T_1 + W_2 \cdot T_2 + W_3 \cdot T_3 \quad (\text{A33})$$

$$T = \left(\frac{1}{3}\right) \cdot T_1 + \left(\frac{1}{3}\right) \cdot T_2 + \left(\frac{1}{3}\right) \cdot T_3 \quad (\text{A34})$$

Appendix A.6.1. Timeline

The timeline parameter is measured by a proxy indicator. The indicator is the life expectancy at birth from the World Bank for the year 2016 [63]. Normalisation is done by the max-min (Japan with 84.0 years and Sierra Leone with 51.8 years) method presented in Equation (4), with high life expectancy meaning higher level of energy security because of a higher opportunity of transferring experience between generations. The parameter is represented by Equation (A35):

$$T_1 = I_{1,T1} \quad (\text{A35})$$

where $I_{1,T1}$ is the normalised life expectancy with normalisation according to Equation (4).

Appendix A.6.2. Length of the Event

The length of an event is measured by the average of two proxy indicators. The first indicator reflects electrical outages (in units of days), expressed as average number of days per year that settlements experience power outages or surges from the public grid. Data are obtained from [49]. Normalisation is done in two steps: First, dividing by the population in the respective country, leading to units of days per capita; second, dividing by the maximum value in the world (Namibia with 7.43×10^{-6} days per person) after removing outliers with the quartile method [111] and then subtracting from unity. Less outage days per capita means a more secure energy system. The second indicator is the average weighted age of power plants for all renewable and non-renewable technologies derived from [45]. Normalisation is done by the max-min (Timor-Leste with 45.35 years and Chad 2.94 years) approach presented in Equation (4). Older power plants are less secure than newer ones, therefore, the normalised value is subtracted from unity. The average of the two indicators is obtained in Equation (A36):

$$T_2 = \frac{I_{1,T2} + I_{2,T2}}{2} \quad (\text{A36})$$

where $I_{1,T2}$ is the normalised power outage and $I_{2,T2}$ is the normalised power plants' age, both with normalisation according to Equation (4).

Appendix A.6.3. Length of the Effect (Struggle or Impact)

The length of any effect on the energy system can be measured in time units. Therefore, the chosen indicator is the number of years that are needed to achieve 100% renewable electricity output. This indicator is calculated from two sets of data, the renewable electricity output (in percentage of total electricity output) for the year 2010 [64] and the renewable electricity output (in percentage of total electricity output) in 2015 [65]. The change rate of renewable electricity output in this 5-years period is calculated by subtracting these two sets of data. The as such obtained rate is used to calculate how long it will take the system to become 100% renewable. Some countries got minus values because they are moving in the wrong direction, i.e., investing more in non-renewable than in renewable power plant capacities. Normalisation is done in several steps: First, any country with a negative value is set to zero, as it implies a major burden for energy security that the country is not moving towards a sustainable and thus renewable electricity supply. Second, the country that needs the least number of years to reach a 100% renewable electricity supply applying this static measure is defined as the most secure and thus rewarded with the highest value. Third, the maximum number of years a country requires for the full transition is used as the worst situation for energy security. Finally, the values are normalised based on the longest found static transition period (50). This parameter is represented by Equation (A37):

$$T_3 = I_{1,T3} \quad (\text{A37})$$

where $I_{1,T3}$ is the normalised number of years to reach 100% renewables, with normalisation according to Equation (5).

Appendix A.7. Resilience

The resilience dimension (R) consists of only one parameter (R_1) and it is assigned to one indicator. In this case the weight (W_j) for the parameter is unity. Equations (A38) and (A39) represent this parameter description:

$$R = W_1 \cdot R_1 \quad (\text{A38})$$

$$R = (1) \cdot R_1 \quad (\text{A39})$$

Adaptive Capacity

Adaptive capacity is measured by an existing index by FM Global called resilience index [66] and applied for the year 2015. Adaptive capacity represents the ability of the energy system in a country or an area to absorb any shocks in the energy system, and still adapt to function as normal or closely to normal. When a system adapts to the changes in e.g., price, supply chain or markets, then it means such a system has adaptive capacity which makes the system more secure. The resilience index is designed in relative form as percentage. There is no need for normalisation for this indicator. The resilience dimension has one parameter, the adaptive capacity, which also has only one indicator, the resilience index. The higher the resilience index the better for the energy security. This parameter is represented by Equation (A40):

$$R_1 = I_{1,R1} \quad (\text{A40})$$

where $I_{1,R1}$ is the resilience index.

Appendix A.8. Environment

The environment dimension (E) consists of five parameters (E_1, E_2, E_3, E_4, E_5) and each one is assigned to one indicator to reflect that the parameter in aggregation. Each parameter is given a weight (W_j). Equation (A41) represents the parameters and their equal weights, 0.2, which leads to Equation (A42) for the parameters:

$$E = W_1 \cdot E_1 + W_2 \cdot E_2 + W_3 \cdot E_3 + W_4 \cdot E_4 + W_5 \cdot E_5 \quad (\text{A41})$$

$$E = \left(\frac{1}{5}\right) \cdot E_1 + \left(\frac{1}{5}\right) \cdot E_2 + \left(\frac{1}{5}\right) \cdot E_3 + \left(\frac{1}{5}\right) \cdot E_4 + \left(\frac{1}{5}\right) \cdot E_5 \quad (\text{A42})$$

Appendix A.8.1. Energy Resources Rate of Exploitation, and Location

The rate of exploitation is measured by the ecological footprint, as discussed by Azzuni and Breyer [32]. The indication of how many planet earths are needed to cover human activities relying on the energy system is a good way of representing this parameter. Data on the ecological footprint are taken from Global Footprint Network [67] for every country for the year 2012. Because many countries use resources more than their natural capacity of regeneration, the normalisation of this indicator was carried out by dividing the national values of each country by the second highest value in the world, Qatar (6.24). The highest value was obtained by Luxemburg (9.1), but it is considered as an unrepresentative outlier. It is obvious that the increase in this indicator means a less secure system. The data are subtracted from unity to show the inverse proportionality, as expressed by Equation (A43):

$$E_1 = 1 - I_{1,E1} \quad (\text{A43})$$

where $I_{1,E1}$ is the normalised ecological footprint with normalisation according to Equation (5).

Appendix A.8.2. Extraction Methods of Energy Supply

The extraction method can be represented as CO₂ intensity of the national energy consumption, which is measured by how much CO₂ (in units of kg) is emitted for energy use (in units of MWh of primary energy). Cleaner fuels and extraction methods result in less CO₂ emissions and thus a more secure energy system. The data for CO₂ intensity in 2014 are derived from the World Bank [68]. The original data were measured in non-SI units (kg per kg of oil equivalent energy use) and have been converted to proper units (kg per MWh). The CO₂ intensity values for each country were normalised by dividing over the maximum in the world (Mongolia) with a CO₂ intensity of 333 kg CO₂/MWh_{th}. The parameter is represented by Equation (A44):

$$E_2 = 1 - I_{1,E2} \quad (A44)$$

where $I_{1,E2}$ is the normalised CO₂ intensity with normalisation according to Equation (5).

Appendix A.8.3. Outcome of Energy Usage

When discussing the environment dimension in the energy system, it is supportive to study the outcome of energy use. Greenhouse gas (GHG) emissions are considered as an indicator of the outcome of the energy system. Data for GHG emissions are retrieved from the World Resources Institute [69] for the year 2012. The data are provided in absolute values of MtCO_{2eq}, however, to make the parameter more sensible, GHG emissions should be related to economic performance. Therefore, the absolute value of GHG emissions for each country was divided by GDP PPP (in USD₂₀₁₁) [48] for the year 2012. The values (in units of kgCO_{2eq}/USD) were then normalised on a global level by dividing each country's value by the value of Mongolia (1.1935 kgCO_{2eq}/USD), which obtained the highest value, applying the quartile method [111] to determine outliers. All values higher than Mongolia were excluded, for example Central African Republic and Gambia. The normalisation resulted in percentage values with an inversely proportional relationship to energy security. The most secure energy system is the one that has the least GHG emissions, so that the values are subtracted from unity, as described by Equation (A45):

$$E_3 = 1 - I_{1,E3} \quad (A45)$$

where $I_{1,E3}$ is the normalised GHG emissions with normalisation according to Equation (5).

Appendix A.8.4. Effects of Climate Conditions and Climate Change on the Energy Security

This parameter comprises effects of climate change on energy security, using temperature anomalies as indicator. Data were collected from NASA [70], and derived with the following criteria: GISS analysis, ERSST_v5, Map type (Anomalies), period Dec–Nov, time interval 2007–2016 (one decade for statistical reasons), base period 1931–1940 (the earliest with full data), and smoothing radius 1200 km. The data created with these criteria were plotted against the world map using QGIS [112]. With a temperature anomaly value for each intersection between a latitude and a longitude, the precision was acceptable. Then the area weighted average for all the data points within the borders of a country was calculated. The area of each data point was almost the same for all the points within a country. The average is assigned to each country as the temperature anomaly. The next step was to normalise these values which was carried out by dividing each country's temperature anomaly by the highest global value (Uzbekistan, 1.791 °C). The result is a percentage normalised value, and the higher the percentage, the more negative the impact from the environment on the energy system reducing security. The values are subtracted from unity, as represented by Equation (A46):

$$E_4 = 1 - I_{1,E4} \quad (A46)$$

where $I_{1,E4}$ is the normalised temperature anomaly with normalisation according to Equation (5).

Appendix A.8.5. Energy-Water Nexus

The last parameter of the environment dimension is energy-water nexus, for the interdependence of water and energy [113–115]. An increase in energy demand typically leads to an increase in water demand in an energy system, and vice versa [116]. Water is typically required for power generation, heating and extraction of natural resources. Water extraction and treatment require energy. A balance is needed between the consumed energy to produce drinkable water and the water needed to satisfy energy demand [117]. Caldera et al. [118] propose renewable electricity-based seawater desalination to achieve the balance, or by proposing future scenarios for water stress [119]. A good indicator for this parameter is water stress, defined as water demand divided by fresh water resources [116]. Data were taken from the United Nations database, describing the level of water stress, as freshwater withdrawal as a proportion of available freshwater resources [71], at a country resolution for the year 2014. Water stress is represented in a relative value, however, further normalisation is needed, because some countries have water stress levels of more than 100%. Dividing by the highest water stress in the world results in a not well-balanced representation. Therefore, the 100% water stress was used as the maximum, and all countries with water stress more than 100% are considered as the maximum unsustainable situation and set to 100% water stress. The minimum for water stress normalisation was considered as zero, which means there is plenty of renewable fresh water. Water stress and energy security forms an inversely proportional relation, so that the indicator is subtracted from unity, as represented by Equation (A47):

$$E_5 = 1 - I_{1,E5} \quad (\text{A47})$$

where $I_{1,E5}$ is the normalised water stress with normalisation according to Equation (5).

Appendix A.9. Health

The health dimension (H) consists of two parameters (H_1 and H_2), and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. Each parameter is given a weight (W_j). This dimension is presented in Equation (A48), and the use of equal weights for the two parameters results in Equation (A49):

$$H = W_1 \cdot H_1 + W_2 \cdot H_2 \quad (\text{A48})$$

$$H = \left(\frac{1}{2}\right) \cdot H_1 + \left(\frac{1}{2}\right) \cdot H_2 \quad (\text{A49})$$

Appendix A.9.1. The Impact of Healthy Individuals and Society on the Energy System

There are two indicators to measure the impact of people's health on the energy system in good approximation: health expenditure as percentage of GDP, and infant mortality rate. The data are taken from the World Bank database for both indicators for the total health expenditures (as percentage of GDP) [72] for the year 2014 and the mortality rate of infants (per 1000 live births) [73] for the year 2016. A higher expenditure as a percent of GDP indicates that there are many unhealthy people in the country and results in fewer resources allocated for energy systems. In addition, it can indicate that the healthcare system is inefficient and thus it needs more improvement. However, this will not change the result of the impact because there are fewer resources channelled to investments in the energy system. Further, no health expenditure at all means that people die because of small health issues. No spending at all means that people do not buy medicine for minor diseases. Therefore, there must be a minimum accepted value for health expenditure. For this reason, Singapore was used as the reference point, with health expenditure per GDP of 4.9%. In linear representation, Singapore's values correspond to the highest. Zero health expenditure as percent of GDP and the highest health expenditure in the world, both, correspond to the worst case in this indicator. The highest health expenditure in the world is observed in the United States of America (17.1%). The second indicator for this parameter is the infant mortality rate. A higher death rate of infants indicates that people are

less healthy, thus their productivity is reduced, and the energy system is affected negatively. An ideal situation is zero deaths of infants which is used for normalising together with the highest mortality rate in the world (Central African Republic of 0.0885 infant deaths per live births). As the relationship between mortality rate and energy security has inverse proportionality, the values for this indicator are subtracted from unity. The average of the two normalised indicators is used to determine the parameter (H_1) as presented in Equation (A50):

$$H_1 = \frac{I_{1,H1} + I_{2,H1}}{2} \quad (\text{A50})$$

where $I_{1,H1}$ is the normalised health expenditure and $I_{2,H1}$ is the normalised infant mortality, with normalisation according to Equation (5).

Appendix A.9.2. The Impact of the Energy System on the Health of Individuals and Societies

For the impact of the energy system on the health of individuals and societies, one indicator is used. It is the number of deaths attributed to cancer. Data for the total number of deaths attributed to cancer are taken from the United Nations database [74] for the year 2015. The data are converted to a percentage by dividing the number of deaths attributed to cancer by the population of each country. The data set is normalised with the max-min approach presented in Equation (4). The maximum was the percentage death rate of Hungary, at a value of 0.169%, and the minimum is set to zero, a level at which no one dies of cancer, assumingly. The higher the deaths attributed to cancer, the stronger indication of negative impacts from the energy system on the health of the society. It is true that death attributed to cancer can be a result of factors other than the energy system, but in this research, it is used as a proxy for the energy system. Therefore, the relation is inversely proportional, and the indicator is subtracted from unity, as represented by Equation (A51):

$$H_2 = 1 - I_{1,H2} \quad (\text{A51})$$

where $I_{1,H2}$ is the normalised cancer deaths with normalisation according to Equation (4).

Appendix A.10. Culture

The culture dimension (Cu) consists of two parameters (Cu_1, Cu_2) and each one is assigned to an indicator or a set of indicators to reflect that parameter in the aggregation. Equation (A52) represents the parameters and their weights (W_j). Applying equal weights for all parameters leads to Equation (A53):

$$Cu = W_1 \cdot Cu_1 + W_2 \cdot Cu_2 \quad (\text{A52})$$

$$Cu = \left(\frac{1}{2}\right) \cdot Cu_1 + \left(\frac{1}{2}\right) \cdot Cu_2 \quad (\text{A53})$$

Appendix A.10.1. Cultural Effects on the Energy System

This parameter of cultural effect on the energy system has many issues to be addressed such as production, connection, consumption, cultural acceptance (NIMBY, Not In My Back Yard). Therefore, different proxy indicators can measure the parameter of cultural effects on the energy system. The first indicator is the poverty headcount ratio at national level (as percentage of population). The data are obtained from the World Bank [75] for the year 2015. Normalisation is done by subtracting the percentage value from unity, because of the inverse proportionality. A lower poverty ratio has more positive impact on the energy system, because people have more money to spend on more efficient choices of energy supplies. Poverty makes people to be more focused on survival rather than better energy security orientation. The second indicator is the GINI index as obtained from the World Bank [76] for the year 2014. The lower the GINI index, the higher the security level, because a lower GINI index means more equal distribution of wealth. Such equal distribution will make people more

content and satisfied with their spending, and the energy market will have better choices for the whole population. Normalisation is done by subtracting the GINI index value from unity. The third indicator is the share of population in the ages between 15 to 64 years (as percentage of total population). The data are obtained from the World Bank [77] for the year 2015. The normalisation of this indicator is carried out by the max-min (United Arab Emirates with 84.9% and Niger with 47.0%) method presented in Equation (4). Higher percentage of the population in this age range means more positive attitude towards the energy system, and thus a higher energy security level. That is because this age category has most of the energy use and they feel to be more responsible towards the energy system. The fourth indicator is the coverage of social protection and labour programmes (as percentage of population). The data are taken from the World Bank [78] for the year 2014. There is no need for normalisation as the indicator is in percentage and a higher coverage indicates a better energy security level. The parameter (Cu_1) is represented by the four indicators, as summarised by Equation (A54):

$$Cu_1 = \frac{I_{1,Cu1} + I_{2,Cu1} + I_{3,Cu1} + I_{4,Cu1}}{4} \quad (A54)$$

where $I_{1,Cu1}$ is the normalised poverty headcount ratio, $I_{2,Cu1}$ is the normalised GINI index, $I_{3,Cu1}$ is the normalised share of population in the ages between 15 to 64 years and $I_{4,Cu1}$ is the normalised coverage of social protection and labour programmes, with normalisation according to Equation (4).

Appendix A.10.2. Energy Conditions Shaping Cultural Aspects

For the energy conditions and how they shape cultural aspects, different indicators are used. The first indicator is the primary energy use. The data are obtained from the World Bank [57] for the year 2015. More energy use is a result of excess energy and ability to purchase, which leads to higher energy security levels. Normalisation is done by dividing by the highest energy use in the world (Qatar 236.0 MWh per capita), assuming that no energy use has the lowest positive impact on energy security. The second proxy indicator is passenger aviation transportation. The data are obtained from the World Bank [79] for the year 2015. Then, numbers of each country are divided by its population to get air transport per capita. Good energy conditions correlate to people travelling more often and using airplanes. The normalisation is carried out by dividing by the maximum number in the world (Ireland with 24073 passengers carried per capita), assuming that no air transport is the lowest level for energy security. The third proxy indicator is food supply, i.e., crops, livestock and fish (in units of g/capita/day). The data are derived from Food and Agriculture Organization of the United Nations (FAO) [80] for the year 2013. Normalisation of food supply is done by dividing by the highest value in the world (Montenegro 3317 g/capita/day). A high supply is the result of good energy conditions and therefore indicates a high energy security level. The fourth proxy indicator is the United Nations Human Development Index (HDI) [81] for the year 2014. There is no need for normalisation, as the HDI is already in a relative percentage. A higher HDI indicates a higher energy security level. This parameter (Cu_2) is summarised by Equation (A55):

$$Cu_2 = \frac{I_{1,Cu2} + I_{2,Cu2} + I_{3,Cu2} + I_{4,Cu2}}{4} \quad (A55)$$

where $I_{1,Cu2}$ is the normalised energy use, $I_{2,Cu2}$ is the normalised passenger aviation transportation, $I_{3,Cu2}$ is the normalised food supply and $I_{4,Cu2}$ is the normalised HDI, with normalisation according to Equation (5).

Appendix A.11. Literacy

The literacy dimension (Li) consists of three parameters (Li_1, Li_2, Li_3) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. In addition, each parameter

is given a weight. Equation (A56) represents the parameters and their weights (W_j), which leads to Equation (A57) for equal weights:

$$Li = W_1 \cdot Li_1 + W_2 \cdot Li_2 + W_3 \cdot Li_3 \quad (\text{A56})$$

$$Li = \left(\frac{1}{3}\right) \cdot Li_1 + \left(\frac{1}{3}\right) \cdot Li_2 + \left(\frac{1}{3}\right) \cdot Li_3 \quad (\text{A57})$$

Appendix A.11.1. Information Availability

The availability of information includes several aspects such as market information and public awareness. This parameter is measured with a proxy indicator for the numbers of citable scientific documents allocated to countries. More citable documents are used as a proxy for more information availability and hence a higher energy security level. Data for citable documents for all countries are taken from Scimago Journal and Country Rank (SJR) [82] for the year 2017. The values were normalised, dividing by the highest number of citable documents in the world (USA 546605 citable documents), as represented by Equation (A58):

$$Li_1 = I_{1,Li1} \quad (\text{A58})$$

where $I_{1,Li1}$ is the normalised citable documents with normalisation according to Equation (5).

Appendix A.11.2. Information Presentation and Provision

To measure how information is presented and provided, proxy indicators are used. The first indicator is the expenditure on education (in units of percentage of total government expenditure) from the World Bank [83] for the year 2016 or later. Higher expenditure on education is interpreted by a higher level of energy security. Normalisation is carried out by dividing the highest value in the world (Zimbabwe, 30.0%), assuming close to zero expenditure to correspond to a very low level of energy security. The second indicator is the research and development (R&D) expenditure (in units of percentage of GDP) from the World Bank [84], for the year 2014 or later. Normalisation of R&D expenditure is done by dividing the highest in the world (South Korea, 4.29%). A higher R&D expenditure is indicated as a higher energy security level, and the indicators representing the parameter (Li_2) are summarised by Equation (A59):

$$Li_2 = \frac{I_{1,Li2} + I_{2,Li2}}{2} \quad (\text{A59})$$

where $I_{1,Li2}$ is the normalised expenditure on education, and $I_{2,Li2}$ is the normalised R&D expenditure, with normalisation according to Equation (5).

Appendix A.11.3. Usage of Energy Information

The energy information usage is approximated by the percentage of tertiary graduates from science, engineering, manufacturing and construction programmes for the year 2015 or later. Data are obtained and combined from United Nations [85,86]. The normalisation of tertiary graduates is done by dividing the highest in the world (Gambia, 54.1%). The higher the percentage the more use of energy information is assumed and thus a higher energy security level is anticipated. The parameter is represented by Equation (A60):

$$Li_3 = I_{1,Li3} \quad (\text{A60})$$

where $I_{1,Li3}$ is the normalised tertiary graduates with normalisation according to Equation (5).

Appendix A.12. Employment

The employment dimension (Em) consists of two parameters (Em_1, Em_2) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. Equation (A61) represents the parameters and their weights (W_j) as summarised by Equation (A62) for equal weights:

$$Em = W_1 \cdot Em_1 + W_2 \cdot Em_2 \quad (A61)$$

$$Em = \left(\frac{1}{2}\right) \cdot Em_1 + \left(\frac{1}{2}\right) \cdot Em_2 \quad (A62)$$

Appendix A.12.1. Effect of Energy Security on Employment Rate

The effect of a secure energy system on employment can be measured by the indicator of employment in the power sector (in units of jobs/TWh_{el}), based on regional distribution derived from [89]. Countries in the same major region are assigned the same value as the sources presents employment aggregate to nine major regions globally. Normalisation of the employment in the power sector is done by the max-min (Afghanistan, 2508 jobs/TWh_{el} and Canada 339 jobs/TWh_{el}) method presented in Equation (4), i.e., the highest number of employments is set best for energy security. This parameter (Em_1) is represented by Equation (A63):

$$Em_1 = I_{1,Em1} \quad (A63)$$

where $I_{1,Em1}$ is the normalised employment in the power sector with normalisation according to Equation (4).

Appendix A.12.2. Effect of Employment Rate on Energy Security

A higher employment rate indicates a higher level of energy security. This parameter is measured by the national unemployment rate (in units of percentage of total labour force) from the World Bank [88,89] for the year 2017. Normalisation is done by dividing the value for every country by the maximum (Solomon Islands 31.4%) and subtracting the result from unity to account for the negative impact of unemployment. This parameter (Em_2) is represented by Equation (A64):

$$Em_2 = 1 - I_{1,Em2} \quad (A64)$$

where $I_{1,Em2}$ is the normalised unemployment rate with normalisation according to Equation (5).

Appendix A.13. Policy

The policy dimension (P) consists of three parameters (P_1, P_2, P_3) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. Equation (A65) represents the parameters and their weights (W_j) leading to Equation (A66) for equal weights:

$$P = W_1 \cdot P_1 + W_2 \cdot P_2 + W_3 \cdot P_3 \quad (A65)$$

$$P = \left(\frac{1}{3}\right) \cdot P_1 + \left(\frac{1}{3}\right) \cdot P_2 + \left(\frac{1}{3}\right) \cdot P_3 \quad (A66)$$

Appendix A.13.1. Political System

The parameter of the political system consists of many issues that need to be addressed such as level of democracy, nature and stability of the political system, citizen's will and internal and external relationships. Thus, different proxy indicators can be used to reflect the relationship between the political system parameter and energy security. The first indicator is the democracy index presented by The Economist Intelligence Unit (EIU) [90] for the year 2016. It is assumed that a higher democracy index leads to a higher energy security level. As the indicator is in units of percentage values for all

countries, no further normalisation is needed. The second indicator is the Fragile States Index (FSI) provided by the Fund For Peace (FFP) [91], used for the year 2016. Higher values for the FSI are interpreted as indicator for a more fragile political system and hence a lower level for energy security. The normalisation is carried out by dividing the FSI values for every country by the maximum in the index (120) and subtracted from unity to represent the inverse proportionality. The third indicator is the political stability/absence of violence and terrorism (in units of percentile ranking) obtained from the World Bank as part of the Worldwide Governance Indicators [92] for the year 2016. Higher stability leads to a higher energy security level. The values are already in a percentile ranking, so that no further normalisation is needed. The fourth indicator is built on the polity data series obtained from The Centre for Systemic Peace (CSP) [93] for the year 2015. The data provide a value from full democracy (10) to a full autocracy (−10) for all countries. These values are normalised by setting 0% to the lowest (−10) and 100% to the highest (10), assuming a full democracy (100%) will correspond to highest energy security level. The fifth indicator is the human freedom index (HFI) where a higher HFI means more human freedom and thus a higher energy security level. The data are retrieved from the CATO institute [94] for the year 2014. Normalisation of this indicator is not needed as it is already in percentage values. The sixth proxy indicator is the freedom in the World index obtained from Freedom House [95] for the year 2017. This indicator does not need to be normalised, as the relationship to energy security is directly proportional, assuming that more freedom leads to a higher energy security level. This parameter is represented by Equation (A67):

$$P_1 = \frac{I_{1,P1} + I_{2,P1} + I_{3,P1} + I_{4,P1} + I_{5,P1} + I_{6,P1}}{6} \quad (\text{A67})$$

where $I_{1,P1}$ is the democracy index, $I_{2,P1}$ is the FSI, $I_{3,P1}$ is the political stability, $I_{4,P1}$ is the polity data series, $I_{5,P1}$ is the HFI and $I_{6,P1}$ is the freedom in the world index.

Appendix A.13.2. Regulations

The parameter of regulations includes the nature of the market (liberalised or controlled), rules and subsidies. Therefore, the parameter of regulations is measured by two proxy indicators. The first indicator traces subsidies and other transfers (in units of percentage of central government expenditures) as retrieved from the World Bank [96] for the year 2016. Subtracting the percentage value from unity was done, so that highest subsidies represent lowest energy security. The second indicator is the Regularity Indicator for Sustainability (RIES) obtained from the World Bank [97] for the year 2016. No further normalisations are needed for this indicator. High indicator values are interpreted for a high level of energy security. This parameter (P_2) is represented by Equation (A68):

$$P_2 = \frac{I_{1,P2} + I_{2,P2}}{2} \quad (\text{A68})$$

where $I_{1,P2}$ is the subsidies and $I_{2,P2}$ is the RIES.

Appendix A.13.3. Governance

The last parameter in the policy dimension is measured by two proxy indicators. The first indicator is the Rule of Law (RoL) (in units of percentile ranking), as obtained from the World Bank from the Worldwide governance indicators [92] for the year 2016. There is no need for further normalisation. A high value indicates a more secure energy system. The second indicator is the Corruption Perception Index (CPI) as obtained from Transparency International [98] for the year 2016. No normalisation is needed as this indicator is available in percentage values. Low values indicate a high level of corruption and thus a low energy security level. This parameter (P_3) is represented by Equation (A69):

$$P_3 = \frac{I_{1,P3} + I_{2,P3}}{2} \quad (\text{A69})$$

where $I_{1,p3}$ is the RoL and $I_{2,p3}$ is the CPI.

Appendix A.14. Military

The military dimension (M) consists of four parameters (M_1, M_2, M_3, M_4) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. Equation (A70) represents the parameters and their weights (W_j), and leads to Equation (A71) for equal weights:

$$M = W_1 \cdot M_1 + W_2 \cdot M_2 + W_3 \cdot M_3 + W_4 \cdot M_4 \quad (\text{A70})$$

$$M = \left(\frac{1}{4}\right) \cdot M_1 + \left(\frac{1}{4}\right) \cdot M_2 + \left(\frac{1}{4}\right) \cdot M_3 + \left(\frac{1}{4}\right) \cdot M_4 \quad (\text{A71})$$

Appendix A.14.1. Energy Use for Military Purposes

The choice of a valid proxy indicator to measure the energy use for military purposes has taken some efforts because of lack of direct data. The indicator is energy use in military sector. Energy use in each country [57] is multiplied with the percentage that accounts for military uses. It was assumed that this percentage is similar to the percentage of military expenditure of GDP [99]. The energy use for military purposes is the multiplication of these two values. Normalisation is done by dividing the maximum in the world (USA 794.4 TWh) indicating that higher energy consumption in the military sector reduces energy security, thus the resulting value is subtracted from unity. This parameter (M_1) is represented by Equation (A72):

$$M_1 = 1 - I_{1,M1} \quad (\text{A72})$$

where $I_{1,M1}$ is the normalised energy use in military sector with normalisation according to Equation (5).

Appendix A.14.2. Militarisation

The militarisation parameter can be measured with two proxy indicators. A higher military expenditure (in units of percentage of GDP) implies more use of military and indicates a lower energy security level. The first indicator is the military expenditure obtained from the World Bank [99] for the year 2017 or later. Normalisation is carried out by the max-min (Oman, 12.0% and Equatorial Guinea, 0.2%) method presented in Equation (4), where the minimum represents the highest energy security level. The second proxy indicator is the number of active armed forces (in units of persons). Data were retrieved from the International Institute for Strategic Studies (IISS) from the military balance [100] for the year 2015. Two steps of normalisation are executed: First, the values for active armed force are expressed as a percentage of the population; second, the normalisation was done by dividing the maximum value in the world (Korea DR, 4.7%). The results are subtracted from unity, because a higher percentage of armed forces in a population means a higher militarisation level and thus a less secure energy system. This parameter is represented by Equation (A73):

$$M_2 = \frac{I_{1,M2} + I_{2,M2}}{2} \quad (\text{A73})$$

where $I_{1,M2}$ is the normalised military expenditure and $I_{2,M2}$ is the normalised number of active armed forces with normalisation according to Equation (4).

Appendix A.14.3. Energy as a Mean in a Military Conflict

To measure how much energy can be used as a political energy weapon, the share of fossil fuel production in a country as a percentage of the total global production is used as a proxy. Three indicators are chosen with the same concept: First, share of coal production to the world total; second, share of crude oil production to the world total; third, share of gas production to the world total. Data for energy balances are taken from IEA [41] for the year 2015. Each of these indicators is normalised by dividing the maximum in the world. Highest share of coal production was for China with 48.4%, highest share

of oil production was for the United States with 13.2% and highest share of gas production was also for the United States with 21.3%. A higher share of the global production means a higher level of energy security as energy has the potential to be used as energy weapon. The average of the three indicators is considered to measure this parameter (M_3) as presented by Equation (A74):

$$M_3 = \frac{I_{1,M3} + I_{2,M3} + I_{3,M3}}{3} \quad (\text{A74})$$

where $I_{1,M3}$ is the normalised share of coal production, $I_{2,M3}$ is the normalised share of oil production and $I_{3,M3}$ is the normalised share of gas production, with normalisation according to Equation (5).

Appendix A.14.4. Destabilisation Factor

Destabilising factors consist of many aspects such as the concept of resources curse, environmental deterioration and economies of violence. To account for energy as destabilisation factor, two indicators are chosen, and their average is calculated to measure this parameter. First, the percentage of net energy imports or net energy exports to the total energy use in every country is used as an indicator. Data are collected from the World Bank [101] for the year 2015. Normalisation is done by dividing the highest absolute (Norway with 581%), both more net export or more net import as a percentage of energy use indicates a less secure energy system. The resulting value is subtracted from unity. The second indicator is the income from net exporting minerals from HS4 international product classification (in units of million USD) [102] for every country for the year 2016. Normalisation is done by two steps: First, dividing by the GDP of every country; second, by dividing over the maximum in the world (Qatar, 15.61% of GDP) and then subtracting the result from unity. A high share of minerals revenue as a percentage of the GDP is less favourable for energy security. This parameter (M_4) is represented by Equation (A75):

$$M_4 = \frac{I_{1,M4} + I_{2,M4}}{2} \quad (\text{A75})$$

where $I_{1,M4}$ is the normalised net energy export/import and $I_{2,M4}$ is the normalised income from net exporting minerals with normalisation according to Equation (5).

Appendix A.15. Cyber Security

The cyber security dimension (Cy) consists of three parameters (Cy_1 , Cy_2 , Cy_3) and each one is assigned to one indicator or a set of indicators to reflect that parameter in the aggregation. Equation (A76) represents the parameters and their weights (W_i) leading to Equation (A77) for equal weights:

$$Cy = W_1 \cdot Cy_1 + W_2 \cdot Cy_2 + W_3 \cdot Cy_3 \quad (\text{A76})$$

$$Cy = \left(\frac{1}{3}\right) \cdot Cy_1 + \left(\frac{1}{3}\right) \cdot Cy_2 + \left(\frac{1}{3}\right) \cdot Cy_3 \quad (\text{A77})$$

Appendix A.15.1. Connectivity and Cyberattacks

The connectivity parameter can be measured with a proxy indicator for individuals using the Internet (in units of percentage of population). The data were retrieved from the World Bank [103] for the year 2016. More Internet users mean more connectivity to the Internet and thus a lower energy security level, therefore, subtracting this value from unity. This parameter (Cy_1) is represented by Equation (A78):

$$Cy_1 = 1 - I_{1,Cy1} \quad (\text{A78})$$

where $I_{1,Cy1}$ is the percentage of individuals using Internet.

Appendix A.15.2. Software Use

To measure the software usage a proxy indicator is chosen in form of the technical aspect of the Global Cybersecurity Index (GCI), as adopted from the International Communication Union [104] for the year 2017. Values are already normalised. The higher the score, the higher the level of energy security. This parameter (Cy_2) is represented by Equation (A79):

$$Cy_2 = I_{1.Cy2} \quad (A79)$$

where $I_{1.Cy2}$ is the normalised $GCI_{\text{Technical}}$.

Appendix A.15.3. IT Skills

To account the IT skills, the Capacity Building Indicator from the Global Cybersecurity Index is adopted from the International Communication Union [104] for the year 2017. Values are already normalised. The higher the score, the higher the level of energy security. This parameter (Cy_3) is represented by Equation (A80):

$$Cy_3 = I_{1.Cy3} \quad (A80)$$

where $I_{1.Cy3}$ is the normalised $GCI_{\text{Capacity,building}}$.

References

1. Ang, B.W.; Choong, W.L.; Ng, T.S. Energy security: Definitions, dimensions and indexes. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1077–1093. [[CrossRef](#)]
2. Vivoda, V. Evaluating energy security in the Asia-Pacific region: A novel methodological approach. *Energy Policy* **2010**, *38*, 5258–5263. [[CrossRef](#)]
3. Bielecki, J. Energy security: Is the wolf at the door? *Q. Rev. Econ. Financ.* **2002**, *42*, 235–250. [[CrossRef](#)]
4. Jun, E.; Kim, W.; Chang, S.H. The analysis of security cost for different energy sources. *Appl. Energy* **2009**, *86*, 1894–1901. [[CrossRef](#)]
5. Löschel, A.; Moslener, U.; Rübhelke, D.T.G. Indicators of energy security in industrialised countries. *Energy Policy* **2010**, *38*, 1665–1671. [[CrossRef](#)]
6. Kirchner, E.; Berk, C.A.N. European energy security co-operation: Between amity and enmity. *JCMS J. Common Mark. Stud.* **2010**, *48*, 859–880. [[CrossRef](#)]
7. Dyer, H.; Trombetta, M.J. *International Handbook of Energy Security*; Edward Elgar Publishing: Cheltenham, UK, 2013.
8. Kovačovská, J. Energy Security in European Conditions. Ph.D. Thesis, Masaryk University, Faculty of Social Studies, Brno, Czech Republic, 2010.
9. Sovacool, B.K. Energy security: Challenges and needs. *Wiley Interdiscip. Rev. Energy Environ.* **2012**, *1*, 51–59. [[CrossRef](#)]
10. Johnson, C.; Boersma, T. The politics of energy security: Contrasts between the United States and the European Union. *Wiley Interdiscip. Rev. Energy Environ.* **2015**, *4*, 171–177. [[CrossRef](#)]
11. Valentine, S.V. Emerging symbiosis: Renewable energy and energy security. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4572–4578. [[CrossRef](#)]
12. Augutis, J.; Krikštolaitis, R.; Pečiulytė, S.; Konstantinavičiūtė, I. Sustainable development and energy security level after Ignalina NPP shutdown. *Technol. Econ. Dev. Econ.* **2011**, *17*, 5–21. [[CrossRef](#)]
13. Yergin, D. Ensuring energy security. *Foreign Aff. N. Y.* **2006**, *85*, 69. [[CrossRef](#)]
14. Kunz, A. *Indian Energy Security. Nuclear Energy Policy*; Charles University: Prague, Czech Republic, 2012.
15. Magazzino, C. Is per capita energy use stationary? Time series evidence for the EMU countries. *Energy Explor. Exploit.* **2016**, *35*, 24–32. [[CrossRef](#)]
16. Magazzino, C. Is per capita energy use stationary? Panel data evidence for the EMU countries. *Energy Explor. Exploit.* **2016**, *34*, 440–448. [[CrossRef](#)]

17. Asif, M.; Muneer, T. Energy supply, its demand and security issues for developed and emerging economies. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1388–1413. [[CrossRef](#)]
18. Haghghi, S.S. *Energy Security: The External Legal Relations of the European Union with Major Oil and Gas Supplying Countries*; Bloomsbury Publishing: London, UK, 2007.
19. Ciută, F. Conceptual notes on energy security: Total or banal security? *Secur. Dialogue* **2010**, *41*, 123–144. [[CrossRef](#)]
20. Sovacool, B.K. Evaluating energy security in the Asia pacific: Towards a more comprehensive approach. *Energy Policy* **2011**, *39*, 7472–7479. [[CrossRef](#)]
21. Dunham, I.M.; Schlosser, K. Energy security discourses and environmental protection measures in U.S. federal energy legislation: An introductory exploration. *Extr. Ind. Soc.* **2016**, *3*, 86–94. [[CrossRef](#)]
22. Eaves, J.; Eaves, S. Renewable corn-ethanol and energy security. *Energy Policy* **2007**, *35*, 5958–5963. [[CrossRef](#)]
23. Jordan, M.; Manley, D.; Peters, R.S.; Stoltz, R. *Goals of Energy Policy: Professional Perspectives on Energy Security, Economics, and Environment*; Our Energy Policy and Sandia National Laboratory: Washington, DC, USA, 2012.
24. International Energy Agency. *Energy Security and Climate Policy—Assessing Interactions*; 1281720488; Organisation for Economic Co-Operation and Development (OECD) Publishing: Paris, France, 2007.
25. Franki, V.; Višković, A. Energy security, policy and technology in South East Europe: Presenting and applying an energy security index to Croatia. *Energy* **2015**, *90*, 494–507. [[CrossRef](#)]
26. Maslow, A.H. A theory of human motivation. *Psychol. Rev.* **1943**, *50*, 370–396. [[CrossRef](#)]
27. Kumar, S. Assessment of renewables for energy security and carbon mitigation in Southeast Asia: The case of Indonesia and Thailand. *Appl. Energy* **2016**, *163*, 63–70. [[CrossRef](#)]
28. Sovacool, B.K. An international assessment of energy security performance. *Ecol. Econ.* **2013**, *88*, 148–158. [[CrossRef](#)]
29. Kanchana, K.; Unesaki, H. ASEAN energy security: An indicator-based assessment. *Energy Procedia* **2014**, *56*, 163–171. [[CrossRef](#)]
30. Lu, W.; Su, M.; Zhang, Y.; Yang, Z.; Chen, B.; Liu, G. Assessment of energy security in China based on ecological network analysis: A perspective from the security of crude oil supply. *Energy Policy* **2014**, *74*, 406–413. [[CrossRef](#)]
31. Phdungsilp, A. Assessing energy security performance in Thailand under different scenarios and policy implications. *Energy Procedia* **2015**, *79*, 982–987. [[CrossRef](#)]
32. Azzuni, A.; Breyer, C. Definitions and dimensions of energy security: A literature review. *Wiley Interdiscip. Rev. Energy Environ.* **2017**, *7*, e268. [[CrossRef](#)]
33. Hansen, K.; Breyer, C.; Lund, H. Status and perspectives on 100% renewable energy systems. *Energy* **2019**, *175*, 471–480. [[CrossRef](#)]
34. Wang, Q.; Zhou, K. A framework for evaluating global national energy security. *Appl. Energy* **2017**, *188*, 19–31. [[CrossRef](#)]
35. Radovanović, M.; Filipović, S.; Pavlović, D. Energy security measurement—A sustainable approach. *Renew. Sustain. Energy Rev.* **2017**, *68*, 1020–1032. [[CrossRef](#)]
36. Badea, A.C.; Tarantola, S.; Bolado, R. Composite indicators for security of energy supply using ordered weighted averaging. *Reliab. Eng. Syst. Saf.* **2011**, *96*, 651–662. [[CrossRef](#)]
37. Child, M.; Koskinen, O.; Linnanen, L.; Breyer, C. Sustainability guardrails for energy scenarios of the global energy transition. *Renew. Sustain. Energy Rev.* **2018**, *91*, 321–334. [[CrossRef](#)]
38. Wu, G.; Liu, L.-C.; Han, Z.-Y.; Wei, Y.-M. Climate protection and China’s energy security: Win-win or tradeoff. *Appl. Energy* **2012**, *97*, 157–163. [[CrossRef](#)]
39. Kamsamrong, J.; Sorapipatana, C. An assessment of energy security in Thailand’s power generation. *Sustain. Energy Technol. Assess.* **2014**, *7*, 45–54. [[CrossRef](#)]
40. Cabalu, H.; Alfonso, C. Energy security in Asia: The case of natural gas. In *Energy Economics and Financial Markets*; Dorsman, A., Simpson, J.L., Westerman, W., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 13–30.
41. International Energy Agency (IEA). *World Energy Balances 2016*; Organisation for Economic Co-Operation and Development (OECD) Publishing: Paris, France, 2016.

42. Breyer, C.; Bogdanov, D.; Aghahosseini, A.; Gulagi, A.; Child, M.; Oyewo, A.S.; Farfan, J.; Sadovskaia, K.; Vainikka, P. Solar photovoltaics demand for the global energy transition in the power sector. *Prog. Photovolt. Res. Appl.* **2017**, *26*, 505–523. [[CrossRef](#)]
43. United Nations (UN). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*; United Nations (UN): New York, NY, USA, 2015.
44. Central Intelligence Agency (CIA). *The World Factbook 2018*. Available online: <https://www.cia.gov/library/publications/the-world-factbook/index.html> (accessed on 8 September 2018).
45. Farfan, J.; Breyer, C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *J. Clean. Prod.* **2017**, *141*, 370–384. [[CrossRef](#)]
46. Photius Coutsoukis (PC). *Countries of the World*. Available online: https://photius.com/rankings/spreadsheets_2015/transportation_2015.xlsx (accessed on 26 October 2017).
47. Wagner, A. *International Fuel Prices 2014*; Federal Ministry of Economic Cooperation and Development BMZ: Bonn, Germany, 2015.
48. World Bank (WB). GDP, PPP (Constant 2011 International \$). Available online: <http://api.worldbank.org/v2/en/indicator/NY.GDP.MKTP.PP.KD?downloadformat=excel> (accessed on 27 October 2017).
49. Nationmaster. Energy-Electrical outages-Days: Countries Compared. Available online: <http://www.nationmaster.com/country-info/stats/Energy/Electrical-outages/Days> (accessed on 15 October 2018).
50. World Intellectual Property Organization (WIPO). *Patents in Force*; WIPO IP Statistics Data Center: Geneva, Switzerland, 2016.
51. World Bank (WB). Scientific and Technical Journal Articles. Available online: <http://api.worldbank.org/v2/en/indicator/IP.JRN.ARTC.SC?downloadformat=excel> (accessed on 30 May 2018).
52. World Bank (WB). Energy Intensity Level of Primary Energy. Available online: <http://api.worldbank.org/v2/en/indicator/EG.EGY.PRIM.PP.KD?downloadformat=excel> (accessed on 4 June 2018).
53. International Energy Agency (IEA). *International Comparison of Light-Duty Vehicle Fuel Economy 2005–2015. Ten Years of Fuel Economy Bench-Marking*; International Energy Agency IEA: London, UK, 2017.
54. World Bank (WB). Land Area. Available online: <http://api.worldbank.org/v2/en/indicator/AG.LND.TOTL.K2?downloadformat=excel> (accessed on 4 June 2018).
55. British Petroleum. *BP Statistical Review of World Energy 2017*; British Petroleum: London, UK, 2017.
56. DistanceFromTo (DFT). *Distance between Cities Places On Map*. Available online: <https://www.distancefromto.net> (accessed on 10 October 2018).
57. World Bank (WB). Energy Use. Available online: <http://api.worldbank.org/v2/en/indicator/EG.USE.PCAP.KG.OE?downloadformat=excel> (accessed on 6 June 2017).
58. World Bank (WB). Terrestrial and marine protected areas (% of total territorial area). Available online: <https://data.worldbank.org/indicator/ER.PTD.TOTL.ZS> (accessed on 9 October 2018).
59. World Bank (WB). Trade (% of GDP). Available online: <http://api.worldbank.org/v2/en/indicator/NE.TRD.GNFS.ZS?downloadformat=excel> (accessed on 14 June 2017).
60. Gygli, S.; Haelg, F.; Sturm, J.-E. *The KOF Globalisation Index-Revisited*; KOF Swiss Economic Institute: Zurich, Switzerland, 2018; Volume 439.
61. Food and Agriculture Organization (FAO). AQUASTAT Main Database. Available online: <http://www.fao.org/nr/water/aquastat/data/query/index.html> (accessed on 11 October 2018).
62. World Bank (WB). Industry, Value Added (Current US\$). Available online: <http://api.worldbank.org/v2/en/indicator/NV.IND.TOTL.CD?downloadformat=excel> (accessed on 9 May 2018).
63. World Bank (WB). Life Expectancy at Birth, Total (Years). Available online: <https://data.worldbank.org/indicator/SP.DYN.LE00.IN> (accessed on 2 October 2018).
64. World Bank (WB). Renewable Electricity Output 2010 (% of Total Electricity Output). Available online: <https://data.worldbank.org/indicator/EG.ELC.RNEW.ZS> (accessed on 27 September 2018).
65. World Bank (WB). Renewable Electricity Output 2015 (% of Total Electricity Output). Available online: <https://data.worldbank.org/indicator/EG.ELC.RNEW.ZS> (accessed on 28 September 2018).
66. FM Global. *Resilience Index 2018 Data*; FM Global: Johnston, RI, USA, 2018.
67. Global Footprint Network (GFN). *National Footprint Accounts, 2016 Edition*. Available online: <http://www.footprintnetwork.org/licenses/public-data-package-free-edition-copy/> (accessed on 21 February 2017).

68. World Bank (WB). CO2 Intensity (kg per kg of Oil Equivalent Energy Use). Available online: <http://api.worldbank.org/v2/en/indicator/EN.ATM.CO2E.EG.ZS?downloadformat=excel> (accessed on 2 March 2017).
69. World Resources Institute. CAIT-country greenhouse gas emissions data. In *CAIT Climate Data Explorer*; World Resources Institute: Washington, DC, USA, 2015; Volume 2017.
70. National Aeronautics and Space Administration (NASA). GISS Surface Temperature Analysis. Available online: <https://data.giss.nasa.gov/gistemp/news/2005/> (accessed on 27 October 2017).
71. United Nations (UN). Level of Water Stress: Freshwater Withdrawal As a Proportion of Available Freshwater Resources. Available online: http://data.un.org/Data.aspx?d=SDGs&f=series%3aER_H2O_STRESS (accessed on 30 October 2017).
72. World Bank (WB). Health Expenditure, Total (% of GDP). Available online: <http://api.worldbank.org/v2/en/indicator/SH.XPD.TOTL.ZS?downloadformat=excel> (accessed on 26 October 2017).
73. World Bank (WB). Mortality Rate, Infant (per 1000 Live Births). Available online: <http://api.worldbank.org/v2/en/indicator/SP.DYN.IMRT.IN?downloadformat=excel> (accessed on 4 December 2017).
74. United Nations (UN). Number of Deaths Attributed to Cancer. Available online: http://data.un.org/Data.aspx?q=cancer&d=SDGs&f=series%3aSH_DTH_CANCER (accessed on 26 October 2017).
75. World Bank (WB). Poverty Headcount Ratio at National Poverty Lines. Available online: <http://api.worldbank.org/v2/en/indicator/SI.POV.NAHC?downloadformat=excel> (accessed on 15 February 2017).
76. World Bank (WB). GINI Index. Available online: <http://api.worldbank.org/v2/en/indicator/SI.POV.GINI?downloadformat=excel> (accessed on 31 January 2017).
77. World Bank (WB). Population Ages 15–64. Available online: <http://api.worldbank.org/v2/en/indicator/SP.POP.1564.TO.ZS?downloadformat=excel> (accessed on 27 June 2017).
78. World Bank (WB). Coverage of Social Protection and Labor Programs (% of Population). Available online: http://api.worldbank.org/v2/en/indicator/per_allsp.cov_pop_tot?downloadformat=excel (accessed on 6 June 2017).
79. World Bank (WB). Air Transport, Passengers Carried. Available online: <http://api.worldbank.org/v2/en/indicator/IS.AIR.PSGR?downloadformat=excel> (accessed on 18 June 2017).
80. Food and Agriculture Organization (FAO). Food Supply-Crops Primary Equivalent. Available online: <http://www.fao.org/faostat/en/#data/CC> (accessed on 2 June 2017).
81. United Nations Development Program (UNDP). Human Development Index. Available online: <http://hdr.undp.org/en/indicators/137506> (accessed on 18 June 2018).
82. SC Imago Journal and Country Ranking (SJR). Citable Documents. Available online: <https://www.scimagojr.com/countryrank.php?year=2017> (accessed on 19 June 2018).
83. World Bank (WB). Expenditure on Education as % of Total Government Expenditure (%). Available online: <http://api.worldbank.org/v2/en/indicator/SE.XPD.TOTL.GB.ZS?downloadformat=excel> (accessed on 18 June 2018).
84. World Bank (WB). Research and Development Expenditure (% of GDP). Available online: <http://api.worldbank.org/v2/en/indicator/GB.XPD.RSDV.GD.ZS?downloadformat=excel> (accessed on 20 March 2017).
85. United Nations (UN). Percentage of Tertiary Graduates from Engineering, Manufacturing and Construction Programmes. Available online: http://data.un.org/Data.aspx?q=graduate&d=UNESCO&f=series%3aFOSGP_56_F500 (accessed on 19 June 2018).
86. United Nations (UN). Percentage of Tertiary Graduates from Science Programmes. Available online: http://data.un.org/Data.aspx?q=graduate&d=UNESCO&f=series%3aFOSGP_56_F400 (accessed on 19 June 2018).
87. Ram, M.; Bogdanov, D.; Aghahosseini, A.; Oyewo, S.; Gulagi, A.; Child, M.; Fell, H.-J.; Breyer, C. *Global Energy System Based on 100% Renewable Energy—Power Sector*; Lappeenranta University of Technology and Energy Watch Group: Lappeenranta, Finland, 2017.
88. World Bank (WB). Unemployment, Total (% of Total Labor Force) (Modeled ILO Estimate). Available online: <http://api.worldbank.org/v2/en/indicator/SL.UEM.TOTL.ZS?downloadformat=excel> (accessed on 16 April 2018).
89. Ram, M.; Aghahosseini, A.; Breyer, C. Job creation during the global energy transition towards 100% renewable power system by 2050. *Technol. Forecast. Soc. Chang.* **2020**, *151*, 119682. [CrossRef]
90. the Economist Intelligence Unit (EIU). Democracy Index 2016. Available online: http://www.eiu.com/public/topical_report.aspx?campaignid=DemocracyIndex2016 (accessed on 6 September 2017).
91. Fund for Peace (FFB). Fragile States Index (FSI). Available online: <http://fsi.fundforpeace.org/library/fragilestatesindex-2016.xlsx> (accessed on 6 September 2017).

92. World Bank (WB). The Worldwide Governance Indicators. Available online: <http://info.worldbank.org/governance/wgi> (accessed on 18 July 2018).
93. Center for Systemic Peace (CSF). Polity Series. Available online: <http://www.systemicpeace.org/> (accessed on 16 June 2017).
94. The CATO Institute. The Human Freedom Index. Available online: <https://object.cato.org/sites/cato.org/files/human-freedom-index-files/hfi-2016-scores-and-rankings-updated-2.xlsx> (accessed on 18 July 2018).
95. Freedom House (FdH). Freedom in the World. Available online: https://freedomhouse.org/sites/default/files/FIW2017_Data.zip (accessed on 18 July 2018).
96. World Bank (WB). Subsidies and Other Transfers (% of Expense). Available online: <https://data.worldbank.org/indicator/GC.XPN.TRFT.ZS> (accessed on 23 July 2018).
97. Banerjee, S.G.; Moreno, F.A.; Sinton, J.; Primiani, T.; Seong, J. *Regulatory Indicators for Sustainable Energy A Global Scorecard for Policy Makers*; The World Bank: Washington, DC, USA, 2016.
98. Transparency International (TI). Corruption Perception Index (CPI). Available online: http://files.transparency.org/content/download/2060/13252/file/CPI2016_FullDataSetWithRegionalTables.xlsx (accessed on 23 July 2018).
99. World Bank (WB). Military Expenditure (% per GDP). Available online: <http://api.worldbank.org/v2/en/indicator/MS.ML.XPND.GD.ZS?downloadformat=excel> (accessed on 26 July 2018).
100. International Institute for Strategic Studies (IISS). *The Military Balance*; International Institute for Strategic Studies: London, UK, 2017.
101. World Bank (WB). Energy Imports, Net (% of Energy Use). Available online: <https://data.worldbank.org/indicator/EG.IMP.CON.S.ZS> (accessed on 10 September 2018).
102. Hausmann, R.; Hidalgo, C.; Bustos, S.; Coscia, M.; Chung, S.; Jimenez, J.; Simoes, A.; Yildirim, M. The Atlas of Economic Complexity. Available online: <http://www.atlas.cid.harvard.edu> (accessed on 3 October 2018).
103. World Bank (WB). Individuals Using the Internet (% of Population). Available online: <http://api.worldbank.org/v2/en/indicator/IT.NET.USER.ZS?downloadformat=excel> (accessed on 27 July 2018).
104. Brahim, S. *Global Cybersecurity Index 2017*; International Telecommunication Union: Geneva, Switzerland, 2017; pp. 1–77.
105. Augutis, J.; Krikštolaitis, R.; Martišauskas, L.; Urbonienė, S.; Urbonas, R.; Ušpurienė, A.B. Analysis of energy security level in the Baltic States based on indicator approach. *Energy* **2020**, *199*, 117427. [[CrossRef](#)]
106. Haegel, N.M.; Atwater, H.; Barnes, T.; Breyer, C.; Burrell, A.; Chiang, Y.-M.; De Wolf, S.; Dimmler, B.; Feldman, D.; Glunz, S.; et al. Terawatt-scale photovoltaics: Transform global energy. *Science* **2019**, *364*, 836. [[CrossRef](#)]
107. Brown, T.W.; Bischof-Niemz, T.; Blok, K.; Breyer, C.; Lund, H.; Mathiesen, B.V. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renew. Sustain. Energy Rev.* **2018**, *92*, 834–847. [[CrossRef](#)]
108. Bogdanov, D.; Farfan, J.; Sadovskaia, K.; Aghahosseini, A.; Child, M.; Gulagi, A.; Oyewo, A.S.; de Souza Noel Simas Barbosa, L.; Breyer, C. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nat. Commun.* **2019**, *10*, 1077. [[CrossRef](#)]
109. Nagendra, H. Opposite trends in response for the shannon and simpson indices of landscape diversity. *Appl. Geogr.* **2002**, *22*, 175–186. [[CrossRef](#)]
110. Simpson, E.H. Measurement of diversity. *Nature* **1949**, *163*, 688. [[CrossRef](#)]
111. Seo, S. A Review and Comparison of Methods for Detecting Outliers in Univariate Data Sets. Ph.D. Thesis, University of Pittsburgh, Pittsburgh, PA, USA, 2006.
112. Open Source Geospatial (OSGeo). QGIS (Quantum Geographic Information System). Available online: <http://qgis.osgeo.org> (accessed on 6 March 2020).
113. Sanders, K.T.; Webber, M.E. The energy-water nexus: Managing water in an energy constrained world. *Earth* **2013**. [[CrossRef](#)]
114. World Economic Forum (WEF). Introduction. In *Water Security: The Water-Food-Energy-Climate Nexus*; Island Press/Center for Resource Economics: Washington, DC, USA, 2011; pp. 1–16.
115. Lohrmann, A.; Farfan, J.; Caldera, U.; Lohrmann, C.; Breyer, C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nat. Energy* **2019**, *4*, 1040–1048. [[CrossRef](#)]

116. World Energy Council (WEC). *World Energy Resources 2013 Survey*; World Energy Council: London, UK, 2013.
117. International Renewable Energy Agency (IRENA). *Renewable Energy in the Water Energy & Food Nexus*; International Renewable Energy Agency (IRENA): Abu Dhabi, Emirates, 2015.
118. Caldera, U.; Bogdanov, D.; Breyer, C. Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate. *Desalination* **2016**, *385*, 207–216. [[CrossRef](#)]
119. Luo, T.; Young, R.; Reig, P. *Aqueduct Projected Water Stress Country Rankings*; World Resources Institute: Washington, DC, USA, 2015.



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