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Michael Child

TRANSITION TOWARDS LONG-TERM SUSTAINABILITY OF THE FINNISH ENERGY SYSTEM

LUT
University

Michael Child

TRANSITION TOWARDS LONG-TERM SUSTAINABILITY OF THE FINNISH ENERGY SYSTEM

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Supervisor	Professor Christian Breyer LUT School of Energy Systems Lappeenranta University of Technology Finland
Reviewers	Professor Peter D. Lund Department of Applied Physics Aalto University Finland
	Professor Eva Heiskanen Consumer Society Research Centre University of Helsinki Finland
Opponent	Professor Peter D. Lund Department of Applied Physics Aalto University Finland

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Abstract

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This dissertation describes the meaning, potential elements and impact of a transition towards the long-term sustainability of the Finnish energy system. Such a transition is possible that would adhere to the goals of the Paris Agreement, aid in mitigating the threat of climate change, and abide by more broad sustainability guardrails that respect known planetary boundaries. Further, this dissertation envisions the components of a sustainable energy system in Finland by 2050 on linguistic, techno-economic and social bases. At the same time, a critical appraisal of the feasibility of such a vision is offered as a stimulant for greater societal discourse on energy related issues in Finland, and around the world.

The purpose of this research is to model and analyse scenarios for Finland from an energy system perspective, taking into account different sustainability dimensions, such as competitiveness, ecology, energy security and society. Research work includes the analysis of renewable energy integration into the Finnish energy system with high amounts of variable renewable electricity generation and new clean energy technologies and concepts. In most cases, the EnergyPLAN modelling tool was used to simulate possible future energy system scenarios for the purpose of comparison. In another case, the linguistic tool of Critical Discourse Analysis was used to negotiate through the meaning of the concept of change in energy systems. In still another, Futures Studies were employed to create a societal vision of a new age of renewable energy.

Results of this dissertation show that a transition towards greater long-term sustainability of the Finnish energy system can occur by 2050 in Finland. Further, it is shown how high shares of renewable energy, appropriate energy storage strategies, and flexibility measures can be employed that can result in an energy system which ensures the economic competitiveness, energy security, and social goals of Finland.

Keywords: Energy system modelling, renewable energy, energy storage, energy transition, prosumers

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Michael Child
July 2018
Lappeenranta, Finland

Ours is essentially a tragic age, so we refuse to take it tragically. The cataclysm has happened, we are among the ruins, we start to build up new little habitats, to have new little hopes. It is rather hard work: there is now no smooth road into the future: but we go round, or scramble over the obstacles. We've got to live, no matter how many skies have fallen.

D.H. Lawrence, opening lines of Lady Chatterly's Lover

Contents

Abstract

Acknowledgements

Contents

List of publications 11

Nomenclature 13

1 Introduction 15
- 1.1 The need for change in global energy systems 15
- 1.2 Sustainable energy futures 16
- 1.3 Implications of the Paris Agreement 16
- 1.4 Planetary boundaries and normative guardrails 17
- 1.5 Sustainability in energy systems 17
- 1.6 The current Finnish energy system 18
- 1.7 Motivation and objectives 21
- 1.8 Scope and limitations of the current research 23
- 1.9 Contribution of research 24
- 1.10 Structure of the dissertation summary 25

2 Future trends for energy systems 27
- 2.1 Low carbon, no carbon and recarbonisation 27
- 2.2 Constraints on energy systems 27
- 2.3 Energy system megatrends 29
  - 2.3.1 Renewable energy 29
  - 2.3.2 Energy storage and system flexibility 31
  - 2.3.3 Electrified mobility 32
  - 2.3.4 Energy efficiency 33
  - 2.3.5 Prosumerism 34
  - 2.3.6 Societal engagement 34
- 2.4 Nuclear energy 35
- 2.5 Carbon capture and storage 35
- 2.6 Carbon capture and utilisation 36
- 2.7 Cost trends in global energy systems 37

3 Methods of studying energy systems 39
- 3.1 The meaning of words and expressions 39
- 3.2 Overview of energy system modelling 40
- 3.3 EnergyPLAN 41
- 3.4 Limitations of energy system modelling 43
- 3.5 Futures studies 45

4 Results 47
4.1 Publication I: the concept of change in energy systems 47
4.2 Publication II: towards sustainability in energy scenarios 48
4.3 Publication III: a recarbonised Finnish energy system 49
4.4 Publication IV: flexible generation and energy storage solutions 51
4.5 Publication V: solar PV in northern latitudes 52
4.6 Publication VI: a sustainable energy system for Åland 53
4.7 Publication VII: towards a peer-to-peer society 55

5 Discussion 57
5.1 General discussion of presented results 57
5.2 Policy implications for Finland 61
5.3 Limitations of the current research 63

6 Conclusions 65

References 68

Publications

List of publications

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

I. Child, M., and Breyer, C. (2016). Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy*, 107, pp. 11-26.
II. 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.
III. Child, M., and Breyer, C. (2016). Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050. *Renewable and Sustainable Energy Reviews*, 66, pp. 517-536.
IV. Child, M., and Breyer, C. (2017). The role of energy storage solutions in a 100% renewable Finnish energy system. *Energy Procedia*, 99, pp. 25-34.
V. Child, M., Haukkala, T. and Breyer, C. (2017). The role of solar photovoltaics and energy storage solutions in a 100% renewable energy system for Finland in 2050. *Sustainability*, 9(8), 1358.
VI. Child, M., Nordling, A., and Breyer, C. (2017). Scenarios for a sustainable energy system in the Åland Islands in 2030. *Energy Conversion and* Management, 137, pp. 49-60
VII. Ruotsalainen, J., Karjalainen, J., Child, M. and Heinonen, S. (2017). Culture, values, lifestyles, and power in energy futures: A critical peer-to-peer vision for renewable energy. *Energy Research & Social Science*, 34, pp. 231-239.

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

Michael Child is the principal author and investigator in Publications I, and III – V. In publication II, much of the original analysis was performed by Mr. Koskinen, and then further developed by Michael Child for publication under the supervision of the other authors. In Publication VI, data collection and modelling was performed by Mr. Nordling under the supervision of the other authors. Michael Child was the principal author of Publication VI, and performed additional data analyses. In Publication VII, Juho Ruotsalainen was the corresponding author and Michael Child made significant contributions throughout the research and writing processes.

Nomenclature

Abbreviations

a	Annum / year	
b	Billion	10^9
BAU	Business As Usual	
BECCS	Bioenergy Carbon Capture and Storage	
BEV	Battery Electric Vehicle	
CCS	Carbon Capture and Storage	
CCU	Carbon Capture and Utilisation	
CDA	Critical Discourse Analysis	
CHP	Combined Heat and Power	
DACCS	Direct Air Carbon Capture and Storage	
EPR	European Pressure Reactor	
ESS	Energy Storage Solution	
EV	Electric Vehicle	
FEC	Final Energy Consumption	
GHG	Greenhouse Gas	
G	Giga	10^9
h	Hour	
ICE	Internal Combustion Enegine	
J	Joule	
k	Kilo	10^3
Li	Lithium	
LULUCF	Land Use, Land Use Change and Forestry	
M	Mega	10^6
oe	Oil equivalent	
P	Peta	10^{15}
PtG	Power-to-Gas	
PtL	Power-to-Liquids	
PtX	Power-to-X	
PV	Photovoltaics	
RE	Renewable Energy	
t	Ton	
T	Tera	10^{12}
TEC	Total Energy Consumption	
USD	United States Dollar	
V2G	Vehicle-to-Grid	
VRE	Variable Renewable Energy	
VUCA	Volatility, Uncertainty, Complexity and Ambiguity	
W	Watt	
WBGU	German Advisory Council on Global Change	

Subscripts

p	Peak
x	Any number

1 Introduction

1.1 The need for change in global energy systems

Change in global energy systems is inevitable. Influenced by several key drivers, it appears obvious that energy systems of the future will continue to evolve and become quite different from today. Currently, energy systems are driven by such forces as increasing energy demands, climate change, economic competitiveness, globalisation, and energy security. Further, technological innovation affects and is affected by each of these key drivers. At certain times, change progresses gradually and rather predictably. At others, it is punctuated by disruptive advances in technology or major societal transitions.

Rifkin (2011) suggests that all great changes in human society are facilitated by developments in energy systems and means of communication. The first industrial revolution, for example, witnessed the emergence of the steam engine, the exploitation of fossil fuels, and the greatly expanded use of the printing press. This was followed by a second industrial revolution in the early to mid-1900s, an age of oil, internal combustion engines, nuclear power, cars, radio, television and telephones. In a similar manner, Heinonen et al. (2015) postulate that a third industrial revolution is currently underway, defined by renewable energy, energy storage technologies, the Internet, and new digital manufacturing technologies. Following the earlier successes of both cars and telephones, the third industrial revolution may be characterised by increasing use of distributed technologies, promoting more decentralised societies and energy systems.

Perhaps the most profound opportunity related to changing global energy systems is the transition towards greater sustainability. Despite the wealth, development and overall prosperity that the age of fossil fuels has brought since the first industrial revolution, Scheer (2002) argues that this will ultimately lead down a long road to self-destruction. This is due to high levels of environmental degradation, dependency on finite resources, and a depreciation of the local and regional impacts of “fossil fuel pyromania”. In addition, Scheer argues that the “global machine” we have created exceeds the margins of safety in which humans can operate. The only alternative, therefore, is a complete and immediate transition towards solar resources, which comprise all forms of renewable energy that are ultimately derived from the sun. A new solar economy can provide for human material and energy needs completely, and could stimulate new development of the economy, aid in maintaining harmony with the environment, and re-establish more resilient cultural and democratic institutions that will ensure a more secure future human society. Scheer’s vision of the future may seem Utopian. However, he argues that it is far less Utopian than the impossible proposition that finite, polluting resources coupled with more concentrated global business structures will ever be enough to provide for all.

1.2 Sustainable energy futures

The transition towards sustainability will not only be techno-economic in nature, so must be viewed through a social filter that accounts for what kind of change people want, and how people and societal structures (institutions, business models, patterns of trade, infrastructures, etc.) influence and are influenced by change. Bai et al. (2016) argue that the scientific community should illustrate pathways towards sustainable by better identifying both plausible and desirable energy futures. Plausibility may be determined by techno-economic modelling, for example, through answering such questions as *Can it be done?* and *Can it be done affordably?*. At the same time, plausibility can be challenged by those with different modelling tools, or by those who make different assumptions about the future. Determining desirability is also a difficult task, as it not only involves answering the important question of *What do people want?*, but the equally important question of *Why do people want it?* (Butler et al. 2015). Moreover, desirability is a difficult concept to determine given the vast diversity of global human society. Different people want different things in different contexts. Diversity of desire can even be seen within an individual depending on whether they are focussing on their own immediate needs, or those of a larger collective (Delina & Janetos 2018). Desire can also be regulated or mandated by law or doctrine.

Given such plurality in determining plausibility and desirability, as well as the fact that the future cannot accurately be predicted, multiple narratives should be created, often called energy futures, that serve as starting points for societal discourse (Bai et al. 2016) about the actual future of energy. As well, visions of the future should be more than technological in nature by including culture, politics and economics (Delina & Janetos 2018). Therefore, showing how society is engaged in a future energy system is imperative (Butler et al. 2015; Soutar & Mitchell 2018; Delina & Janetos 2018; Grunwald 2011). This can enable the anticipation of potential disruptions, expose possible risks and opportunities, and allow for reflexive thought (Grunwald 2011; Delina & Janetos 2018).

Creating multiple visions of energy futures can also be problematic. Grunwald (2011) cautions that the diversity of energy futures could lead to disorientation, and may impede rational decision-making. In addition, it would be difficult to prevent exposure to visions that are driven by ideologies or vested interests. For these reasons, the various visions, scenarios and futures created must be transparent enough to allow for meaningful epistemological scrutiny, and should encourage public debate. Transparency of premises, values, interests, judgements, assumptions, etc. (Grunwald 2011) will be needed to enable collective navigation through divergent and multiple futures of energy that ultimately lead to “public deliberations on how energy futures ought to proceed”.

1.3 Implications of the Paris Agreement

The impending threat of climate change and the need for a coordinated global response were recognized in the landmark Paris Agreement of the 21st Conference of Parties to the United Nations Framework Convention on Climate Change. This response should enable limiting "global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit temperature increase to 1.5 °C" (United Nations Framework Convention on Climate Change 2015) through lower greenhouse gas (GHG) emissions. As contributions from energy-related sectors represent more than three quarters of global GHG emissions, global energy systems are under intense scrutiny. Furthermore, it may be proportionately more difficult, expensive or disruptive to reduce non-energy GHG emissions (e.g. in agriculture or industry). Therefore, meeting the aims of the Paris Agreement before the middle of this century may involve major transitions in global energy systems, perhaps to the point where net-zero emission energy systems are the only legitimate option.

1.4 Planetary boundaries and normative guardrails

Of course, GHG emissions are not the only issue at hand. In order to address the technological, economic, political, institutional and socio-cultural challenges that accompany changes to energy systems, any energy transition must be guided by ethics, sustainability (Berkhout et al. 2012), and the goal must be to increase overall energy system resilience (Folke 2006). Doing so could therefore involve examining energy system impacts from the perspective of the nine planetary boundaries proposed by Steffen et al. (2015) and Rockström et al. (2009). In addition to climate change, these include novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows, freshwater use, land-system change, and biosphere integrity. At the same time, a system of normative guardrails could be observed for energy systems, such as those proposed by the German Advisory Council on Global Change (WBGU 2003). These include climate protection, sustainable land use, protection of marine ecosystems, protection of rivers and catchment areas, and prevention of air pollution. Analysis of and adherence to a wider range of sustainability criteria are further introduced and developed in Publication II.

1.5 Sustainability in energy systems

O'Brien et al. (2009) warn there is a danger that too narrow a focus on GHG mitigation will only reinforce the power and economic structures that are the root cause of climate change. It will also do little to consider the "debts to the past as well as obligation to future citizens". For this reason, a broader criteria of sustainability is required to ensure that societal risk is reduced beyond the scope of climate change. Sustainability must assure that certain levels of risk, cost or damage are intolerable, no matter what short terms gains there are.

Achieving sustainability in energy systems is no easy task. Energy systems are large socio-technical systems that require long term planning, and therefore have a lot of momentum (Hughes 1969). This means that change in energy systems can represent a threat of stranded assets and investments for stakeholders who have vested interests in maintaining the *status quo*. Large power plants operate for decades and require equally large investments. Securing such large investments requires a relatively stable investment landscape. Therefore, change can sometimes be disruptive to investment stability, and represent a threat to economic sustainability. At the same time, it may also represent opportunity for those savvy enough to foresee the outcome of change. For this reason, modelling of future energy scenarios becomes an important tool for investors.

Operationalizing sustainability criteria is also difficult. Planetary boundaries and sustainability criteria must be quantified as biophysical, socio-economic or ethical requirements that can pass muster in real world politics, such as the above mentioned two-degree target. However, the realization of multiple sustainability criteria can be overly complex and may even involve contradictory messages unless they are carefully considered. In this regard as well, modelling of future energy scenarios can aid in advancing the important discourse on energy related issues that will form the basis of future decisions that affect energy system design.

The nature of energy systems also offers a challenge to implementing sustainability. One cannot only focus on energy conversion, but must also consider all the upstream and downstream processes involved when applying sustainability criteria. On the supply side, upstream processes include resource extraction and treatment that result in primary energy. Downstream processes include conversion, distribution and storage technologies that provide a form of final energy that is supplied to end users. Further downstream one may need to consider spent fuel management and plant decommissioning. On the demand side, a useful form of energy may be created by various end user technologies that ultimately provides an energy service (IIASA 2012). The main point is that sustainability criteria can be applied to one or all of the processes involved. Further, descriptions of energy scenarios used for modelling should outline how and where sustainability criteria are applied. In this regard, transparency of scenario assumptions becomes paramount. Establishing a circular economy with no net impacts would be an ultimate goal of a sustainable energy system. The evaluation of such a system could be assured through the lifecycle assessment (LCA) of all system components, including a meaningful system boundary that includes upstream and downstream processes.

1.6 The current Finnish energy system

Although the Finnish energy system appears to be in the midst of a transition towards higher shares of renewable energy, it is motivated by several goals that have remained rather consistent over time. They also appear likely to be the main drivers of future change: reliability, affordability, stability of consumer prices, ability to maintain industrial competitiveness, and responsibility towards international and European efforts to mitigate climate change. Similar to many European energy systems, large amounts of installed generation capacities are nearing their end of life, and so, a rather natural opportunity exists to replace this capacity without the risk of stranded investments. However, discourse in Finland related to energy system visions for the future is far from unanimous despite the rather ubiquitous desire to achieve the same goals. The destination seems clear. The route is not.

Total energy consumption (TEC) in Finland was approximately 388 TWh (1.36 million TJ) in 2016. This included a record high share of renewable energy, at 34%, dominated by wood fuels (26% of TEC) (Statistics Finland 2018). At the same time, wind power grew by 32% and energy extracted from heat pumps by 23% in 2016 over the previous year. In 2016, Finland achieved a 39% renewable energy share of final energy consumption (FEC) well ahead of the target of 38% set as part of its obligation to the European Union (Figure 1).

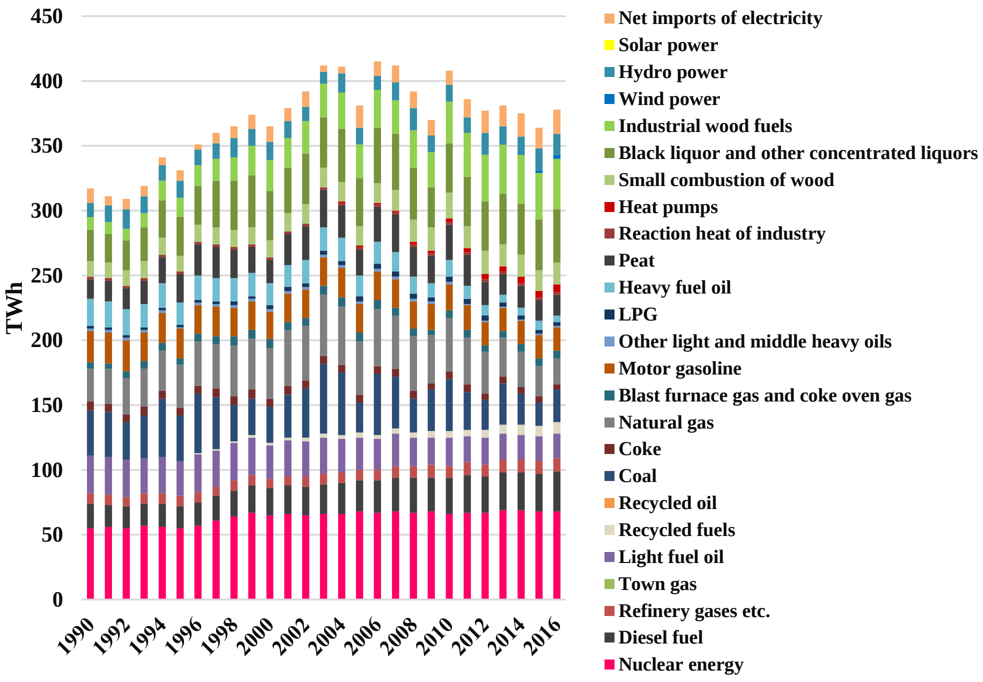

Figure 1. Total energy consumption by source (TWh), 1990-2016. Source: (Statistics Finland 2018)

Electricity consumption totalled 85.2 TWh in 2016. Both TEC and electricity consumption were marginally higher in 2016 than the previous year due to relatively colder temperatures, but an overall downward trend in energy use has existed in Finland since the early 2000s (Figure 2). In 2016, industry and construction accounted for approximately 50% of electricity consumption. Households and agriculture made up 30%. Public services and other consumption represented 17% of electricity consumption, and transmission and distribution losses totalled approximately 3% of consumption. Shares of renewable energy in electricity generation have consistently increased in recent years, with wind power increasing at a rate of 69% (year-on-year) through the first three quarters of 2017 (Statistics Finland 2018).

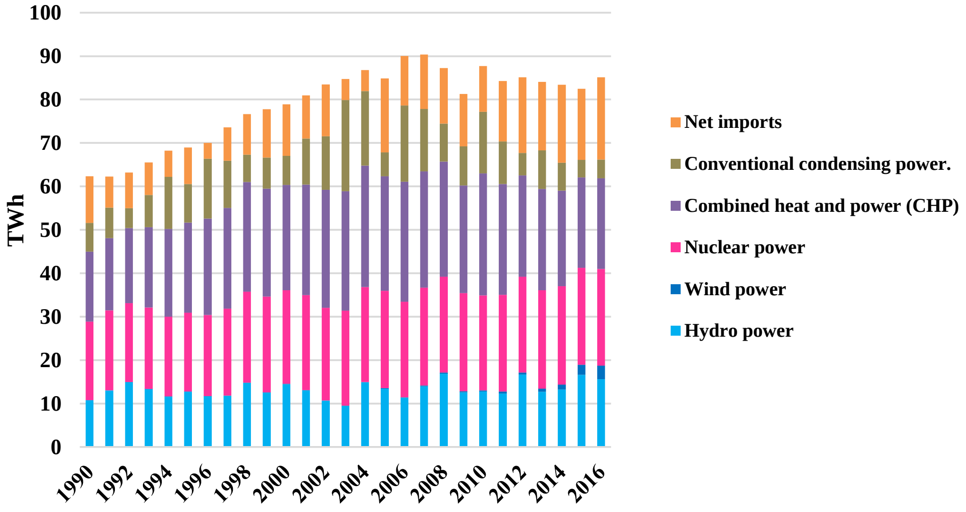

Figure 2. Final electricity consumption by source (TWh), 1990-2016. Source: (Statistics Finland 2018)

Figure 3 shows greenhouse gas emissions for Finland, including land use, land use change and forestry sector (LULUCF). Likewise, a downward trend is seen from the early 2000s onwards (Statistics Finland 2018). This is most prominent in the energy sector, suggesting that reductions may be more difficult in non-energy sectors, and sectoral coupling may offer opportunities for further reductions (T. Brown et al. 2018; Buttler & Spliethoff 2018). As part of the European Union, Finland has committed to 40% domestic reduction in GHG emissions by 2030 compared to 1990 (Latvia and the European Commission 2015). It has been reported that renewable energy was used to generate 47% of Finnish electricity in 2017, and carbon-neutral sources totalled 80% (Finnish Energy 2018). It also appears that the structure of Finnish power generation is rapidly moving towards low carbon technologies, such as hydro, wind, solar, nuclear, and combined heat and power based on bioenergy (ibid.). Gas-based generation technologies, already present in the energy system, could contribute further to decarbonisation through switching from fossil natural gas to sustainable synthetic gas or biomethane.

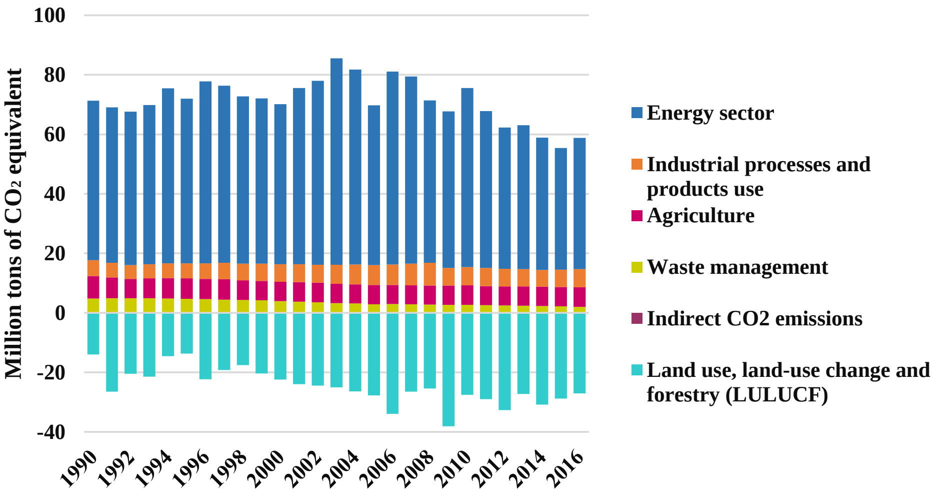

Figure 3. Greenhouse gas emissions and removals (Mt of CO_2 equivalent), 1990-2016. Source: (Statistics Finland 2018)

1.7 Motivation and objectives

As will be demonstrated in Publication II, prominent energy scenario development for the future has failed to adequately account for a wide range of criteria needed for a successful transition towards sustainability. It was also observed that several influential scenarios created for the Finnish energy system contained similar shortcomings, and focussed too narrowly on GHG emission reduction, to the possible detriment of other known, important planetary boundaries. In addition, none of the main scenarios developed for the Finnish energy system had attempted to view results from a futures perspective, or create visions of what life might be like for future generations. Instead, many scenarios of the future seemed too deeply rooted in the techno-economic structures of both the past and the present without offering a sufficient narrative of the future that could blend both objective knowledge with subjective interpretations (Soutar & Mitchell 2018). Moreover, the current debate on the future of energy seemed somewhat focussed on the continuity of present pathways, and lacked any meaningful discussion on a broader range of possibilities, especially those that seemed ‘outside-the-box’. Bai et al. (2016) suggest that sustainability debate should be more inclusive of such visions.

From a techno-economic perspective, it also seemed that assumptions concerning the role of solar PV in Finland, in particular, were rather pessimistic given its rise to prominence globally as a least cost source of sustainable electricity. Specifically, few adequate efforts were made to estimate the future cost of solar PV using a learning curve approach, such as documented in Vartiainen et al. (2017). Haukkala (2015) questioned why solar energy deployment was so marginal in Finland, and postulated that outdated assumptions, vested interests, path dependence and technological lock-in are primarily responsible. It was also stated that an explicit vision for solar energy in Finland was lacking (ibid.). So, a vision needed to be created to allow public debate to include a wider range of possible energy futures and assumptions based on more current information.

Lastly, a wide range of flexibility measures are available to accommodate higher shares of renewables, especially those that are variable in nature, in energy systems (Lund et al. 2015). Yet, one of the most progressive representations of the Finnish energy system at the beginning of this work in 2014 suggested that a maximum share of renewables in gross electricity consumption would be 69-72%, and that an optimal level would be 44-50% (Zakeri et al. 2014). Closer examination revealed that the article makes no mention of battery electric storage in either stationary or BEV applications, other than dismissing all electricity storage systems as “not economically attractive”. This statement was based on a lifecycle assessment of the costs of various forms of storage by the same author (Zakeri & Syri 2015). However, that study was determined to have rather outdated assumptions related to electrical energy storage. For example, the cost of Lithium-ion battery systems was listed as 795 €/kWh, with a range of 470-1249 €/kWh. At the same time, there is no accounting that this cost may be different in the future. However, UBS estimated that, due to economies of scale established by a rapidly expanding EV market, battery costs would be less than 400 €/kWh by 2015, would halve by 2020, and would halve again by 2025, reaching around 100 €/kWh for battery packs (UBS 2014). Nor did the Zakeri et al. (2014) study make significant mention of the relevance of gas storage or the full range of possibilities of Power-to-Gas, which have been identified as currently profitable for niche applications in Finland, and an interesting area for further inquiry (Breyer et al. 2015). PtG technologies were limited to electrolysers producing hydrogen (with associated hydrogen storage) instead of expanding to include methane as an end product. Methane is a gas that could readily be used as part of the well-developed gas infrastructure of Finland. In essence, this is an example of how a modelled scenario of the future seems far too grounded in the present. Other scenarios were needed that could account for alternative futures.

The purpose of this research is to model and analyse scenarios for Finland from an energy system perspective. The analysis takes into account different sustainability dimensions, such as competitiveness, ecology, energy security and society. Research work includes the analysis of renewable energy integration into the Finnish energy system with large amounts of variable renewable energy (VRE) generation, and new clean energy technologies and concepts. Modelling and analysing future energy systems and markets are challenging due to radical changes needed to tackle climate change. At the same time, all dimensions of sustainability need to be regarded, something that may create barriers to development. Especially challenging is the modelling and analysis of those energy systems which include large amounts of variable renewable electricity generation in the system. Therefore, new scenarios need to be created to better analyse the economics, barriers, operational issues, etc. of those systems.

The focus of this work is the transition of the Finnish energy system towards long-term sustainability. This involves modelling an energy system that includes large amounts of variable renewable electricity generation, new energy storage options with synthetic natural gas, new energy demand patterns and demand response, etc. The effects on the power system at an operational time scale are analysed by integrating and further developing existing energy system and market models. A special focus is Power-to-Gas (PtG) technology. Moreover, renewable power methane can be stored for the mid- to long-term and reused in the energy system in several ways, with synergetic benefits to the energy system. Another special focus is on the integration of energy conversion and end-use sectors (i.e., electricity, heat, transport and industry). In the end, it is hoped that this work will support decision making of stakeholders by extending the discourse around energy in Finland to include the possibility of 100% renewable energy supply. When possible, the work endeavours to include the impacts on and influences of energy markets (in particular for the electricity sector), and discusses grid stability issues on a system level.

1.8 Scope and limitations of the current research

Specific research questions are posed in each of the Publications that are included in this dissertation with the exception of Publication VII. However, this research was guided by general research questions that were made more specific in each Publication. First, what are the dominant views on how the change towards sustainability will proceed? The answer to this question is found in Publication I. Second, how might the sustainability of energy systems best be defined? This question is best answered in Publication II. Third, what might be the elements of a sustainable energy system for Finland, and how might those elements interact? These questions are discussed throughout Publication III to VI. Lastly, what might life be like once a transition towards sustainability has occurred? This is the topic of Publication VII.

Much of this research involves the modelling of the Finnish energy system in isolation, without considering the potential roles of imports and exports of energy carriers. Currently, the Finnish energy system is quite dependent on imported energy carriers (e.g. electricity, oil, natural gas), resulting in reduced energy security and a poor trade balance in energetic and financial terms. For this reason, it was deemed reasonable to investigate the possibility of complete energy autonomy within some future scenarios. Of course, there could very well be benefits to maintaining the strong trade relations that have worked well for Finland in the past. In addition, high shares of VRE generation can be balanced by vibrant trade between regions and nations. So, in this regard, the present research represents a rather extreme set of scenarios. The results would no doubt be quite different if the Finnish energy system were modelled as it currently is, interconnected rather well with neighbouring countries. This will be the focus of future work.

For the studies involving the Åland energy system, international trade of sustainable energy carriers was modelled even though high levels of energetic autonomy were sought within scenario designs. However, these energy carriers were limited to the trade of liquid biofuels, which were assumed to be produced for lower cost either on mainland Finland or Sweden. In both cases, power interconnections between neighbouring regions were not part of scenario design.

At several stages of the research process, projections, estimations and assumptions needed to be made about the future. Naturally, this is inherently difficult. However, the process of making these decisions always relied heavily on two solid foundations: the justification of all assumptions through the use of references to credible scientific publications, and the full transparency of all such assumptions through accurate reporting. Far too many studies of energy systems are lacking in this regard (see Publication II), so this work endeavours towards full transparency. The suitability of these assumptions must also be part of the overall discourse on the future of energy in Finland, and it is advisable to interpret all results with appropriate caution.

1.9 Contribution of research

The main contribution of this research is that it can broaden the nature of discourse on energy issues in Finland in both scientific and general contexts. This, in turn, can aid in decision-making about the future of energy in Finland and elsewhere. Furthermore, it can aid several stakeholders by providing insights into what may be possible or feasible for the future. These stakeholders include energy providers, retailers, transmission and distribution companies, and private citizens. This work seeks to go beyond the *status quo*, and to seek visionary scenarios that are not limited or constrained by the energy systems of today. Where possible, this work provides suggestions for how various barriers and obstacles to high shares of renewable energy can be overcome, and to address misunderstandings that currently exist related to power from solar photovoltaics (PV) in Finland, and for 100% renewable energy systems in general (Haukkala 2015; Diesendorf & Elliston 2018). It is hoped that many conclusions can be applied to other countries at high latitudes.

This work also seeks to advance the science of energy system modelling. Through scenario modelling of integrated sectors of the energy system (power, heat and mobility), more meaningful simulations can be performed. It is also hoped that a high level of transparency of assumptions will become more standard practice within the scientific field. Lastly, this work seeks to harness all available and feasible forms of flexibility that exist within energy systems, both technological and behavioural. Some of these forms of flexibility are already familiar (flexible generation from hydropower or stored biomass), some are rather new (electrified transport), and others do not currently exist but show great potential (Vehicle-to-Grid). Still others may need to be re-invented or expanded, such as demand response.

In addition, this work sets out a critical framework on which to measure the effectiveness of energy system scenarios under a broader range of sustainability criteria. To this end, a sustainability checklist is proposed that can be applied by future researchers as they design future energy system scenarios. Although the checklist is applied in an exemplary manner to several well-known global energy scenarios in Publication II, future modellers are left to make decisions on how and when to implement the checklist into their own work. Further, this work challenges them to show how greater sustainability can be achieved throughout the coming energy system transition, and what impacts (both positive and negative) there would be to applying the proposed sustainability guardrails.

Lastly, this work seeks to situate the coming energy transition into society. Discourse on energy matters must go beyond the techno-economic context, as energy transitions have implications for the whole of society. In this regard, this research comments on how energy transitions and societal change are related. Examining such concepts through a Futures Research perspective allows desirable futures to first be envisioned, and then ultimately pursued. A decentralised, peer-to-peer society is critically analysed and offered as a vision of the coming era of renewable energy.

1.10 **Structure of the dissertation summary**

The first part of this dissertation represents important background information needed in order to have a fuller appreciation of the challenges and issues that modern energy systems face. The context of Finland is also introduced. The second part of this dissertation furthers the description of energy systems, but focusses on future trends that are of high relevance to any analysis of energy systems. In general, although energy systems tend to be planned on a national basis, they are still affected greatly by global environmental, technological, social and economic trends. Chapter 3 briefly introduces the science of energy system modelling, and describes the main tool used for this dissertation, the EnergyPLAN simulation tool. In addition, short descriptions of the linguistic analysis and Futures Studies relevant to this dissertation are provided. Chapter 4 shows the key results obtained from the eight publications that comprise this dissertation. Chapter 5 discusses these results as part of the greater body of scientific literature, suggests policy implications for Finland, and considers limitations of the current research. Lastly, conclusions are drawn in Chapter 6. References and the original publications are also included at the end of this dissertation.

2 Future trends for energy systems

2.1 Low carbon, no carbon and recarbonisation

Important classifications must be made regarding various forms of energy conversion or outcomes of energy systems. In this work, a low carbon technology or system refers to one which has appreciable net GHG emissions. A good example of a low carbon technology may be a gas turbine that combusts fossil natural gas. A low carbon energy system may be one that aids in achieving the common target of 80% reduction of GHG emissions compared to 1990 levels set out in the Paris Agreement (United Nations Framework Convention on Climate Change 2015). A no carbon technology or system is one that has virtually zero or net zero emissions. Solar PV or nuclear power plants may have no direct emissions related to power generation, but could have some emissions associated with their entire lifecycles. For example, there could be emissions associated with manufacturing solar PV frames, or associated with steel and cement needed for nuclear power plant construction. A no carbon system could also be created through the use of carbon capture and storage (CCS), or through the creation of a comparable natural carbon sink, such as a growing forest. A recarbonised system is one that also shows net zero emissions. For example, upon combusting biomass in a power plant, the biogenic carbon emissions could be captured and utilised in the process of methanation, thereby creating a synthetic natural gas that could be used in a gas turbine. A recarbonised system would therefore employ carbon capture and utilisation (CCU). There would of course be GHG emissions from the gas turbine, but they would not be classified as anthropogenic emissions or accounted as net emissions due to the closed loop nature of biogenic GHGs.

An important point to make is that only no carbon and recarbonised energy systems can achieve the virtually zero or net-zero emissions needed to achieve the goals of the Paris Agreement (Schellnhuber et al. 2016; T. W. Brown et al. 2018). Low carbon results will be highly desirable over the short term, and as a bridge to a net zero emission society over the long term. However, virtually all anthropogenic carbon emissions will ultimately need to be eliminated, or a carbon sink will need to be created to offset any future emissions.

2.2 Constraints on energy systems

Current and future energy systems will be constrained by several factors. Each will have a role in guiding future system development, technological innovation and policymaking. Nine major constraints will be discussed in both the global and Finnish context.

- Energy demand: As global population and affluence grows, an exponential increase in energy demand is expected. Much of this demand is also assumed to be for electricity, which could almost double by 2040 globally from current levels (International Energy Agency 2017b). The electrification of many energy services, such as mobility, will contribute to this growth. In Finland, population growth is not expected to be as high as the global average (Statistics Finland

2009), and energy efficiency measures, particularly in the built environment, are expected to lead to only moderate growth of energy demand (Ministry of Economic Affairs and Employment of Finland 2017).

- Climate change: Worldwide efforts to mitigate climate change will have a major impact on future energy system design. Without mitigation, the costs of climate change are expected to be enormous in economic, social and environmental terms (UNFCCC 2014). Finland has ratified the Paris Agreement and has been amongst the leaders in climate action in the European Union. GHG emissions have reduced consistently since 2003 and are expected to continue declining in the years to come (see Figure 3).
- Diminishing energy fuels: Fossil fuel reserves have reached or exceeded peak levels on a global level. Prices have been unstable in recent years due to fluctuating oil production primarily. Other fossil fuel prices have generally followed the global price of crude oil. Prices for fossil fuels are expected to continue to rise, and the quality of those fuels, particularly coal, may decrease. Finland is dependent on imports of fossil fuels, with the exception of domestic supplies of peat. Despite domestically available uranium, Finland is dependent on imports of enriched uranium for nuclear power production (International Energy Agency 2013).
- Energy injustice: Access to energy, particularly electricity, is set to increase in the future. Large populations in India and Africa currently lack access to modern or reliable energy services, and growth in China will be significant in the decades to come (International Energy Agency 2017b). In Finland, access to energy is liberal (International Energy Agency 2017b), although more rural areas may experience slightly more interruptions in electrical supply, and many summer cottages are not part of the electricity grid. This may make interest in micro-grid and off-grid solutions more attractive in the future.
- Heavy metal and other emissions: The combustion of fossil fuels, particularly coal, can result in heavy metal and other emissions (SO_x, NO_x, particulate matter) that cause illness, lost productivity and death. Finland has resolved to phase out coal combustion in the energy system by 2030 or sooner (Ministry of Economic Affairs and Employment of Finland 2017). However, the use of domestically available peat remains an important area of discussion.
- Energy subsidies: Global energy subsidies are skewed heavily in favour of fossil fuels and nuclear power. The G20 nations have long commented that subsidies distort energy markets (G20 2016), yet have done little of substance to combat this problem. Renewable electricity generation could grow much faster globally if a more level-playing field were established.
- Managing system complexity: Current energy systems have long, diverse and global value chains upstream from energy conversion, including mining and extraction, refining, shipping, storage, and pretreatment. In the case of nuclear energy, there are also value chains for waste storage, shipping, disposal and plant decommissioning. Renewable energy technologies such as solar PV and wind

energy have far shorter value chains, and can promote more decentralized energy systems (Scheer 2002).

- Energy security: A lack of energy, or threat thereof, may be disruptive to many aspects of life. Related systems may not be able to operate optimally, sustainably, competitively, or at all. Therefore, energy security must be sought through the establishment of reliable domestic resources or conversion technologies. Alternatively, supply chains may need to be secured through relations with neighbours, and may involve military action, both defensive and offensive. An energy system resilient to external pressures or threats should be an important goal (Azzuni & Breyer 2018). In Finland, energy security means enabling a competitive industrial sector, avoiding fluctuating energy costs, maintaining a reasonable trade balance, and meeting the growing needs of society (Ministry of Economic Affairs and Employment of Finland 2017). At the moment, Finland is highly dependent on imports of fossil and nuclear fuels (Ministry of Economic Affairs and Employment of Finland 2017). Greater energy independence could be achieved with renewable electricity generation.
- Ecological footprint: Energy systems must comply with all planetary boundaries (Steffen et al. 2015; Rockström et al. 2009), and efforts should be made to achieve greater sustainability beyond the task of mitigating climate change (O'Brien et al. 2009). Focusing on just one environmental criteria, such as GHG emissions, may do little to improve problems such as loss of biodiversity, chemical and radioactive pollution, freshwater consumption, land use change, and atmospheric aerosol loading. Growing energy needs in Finland should be satisfied without increasing the ecological footprint (Rees 1992). As of 2014, Finland had an ecological footprint of 6.1 global hectares and a biocapacity of 12.86 global hectares, meaning that there is ecological reserve at a national level. However, if this same ecological footprint were consistent globally, 3.62 planets would be needed to be sustainable (Global Footprint Network 2018). Salonen et al. (2018) suggest that "it seems that radical behavioural changes are required".

2.3 Energy system megatrends

On a global level, energy systems are undergoing a transition. This transition is primarily driven by a need to mitigate climate change, but it is also occurring concurrently with technological innovation and social change. These megatrends are global in nature, but are still highly relevant to the Finnish context. Five major trends will be discussed in the subsections that follow.

2.3.1 Renewable energy

Electricity generation from renewable energy has increased rapidly in recent years. Global installed capacities of RE have increased from 1058 GW in 2008 to 2179 GW in

2017 (Figure 4). In Finland, installed capacities have increased from 5 GW to almost 8 GW over the same time period (Figure 5). Much of the newly installed capacity on a global level is wind energy and solar PV, while in Finland it is dominated by wind. Globally, installed capacity of wind energy has increased by a factor of 4.5, and solar PV by a factor of 26 since 2008. By contrast, these factors are 14 and 8, respectively, for Finland (International Renewable Energy Agency 2018). However, several new, large-scale solar PV projects in Finland have been initiated (NeroWatt 2017), and the potential to develop solar PV on individual rooftops is quite high. Finland has lagged behind the rest of world and Europe with regards to solar PV installations. Part of the reason for this has been doubt that solar PV can be a competitive option at high northern latitudes (Haukkala 2015). However, estimates of the long-term market potential of ground-mounted solar PV in Finland are as high as 24 GW_p (Kosonen et al. 2014) and the rooftop hosting capacity may be as high as 12 GW_p (Lassila et al. 2016). At the moment, no special subsidies or support exist for solar PV in Finland outside of tax deductions that can be made for a range of labour-related household expenses, which would include a part of the installation expenses for solar PV. In addition, solar PV systems owned by companies, municipalities and organisations are subject to the same subsidies as other investments in renewable and new energy technologies that aid in achieving Government targets (Ministry of Economic Affairs and Employment of Finland 2018). In contrast, wind power is supported by a premium feed-in tariff. However, despite its success in boosting development of wind power, it will soon be replaced by a tendering scheme (Ministry of Economic Affairs and Employment of Finland 2017).

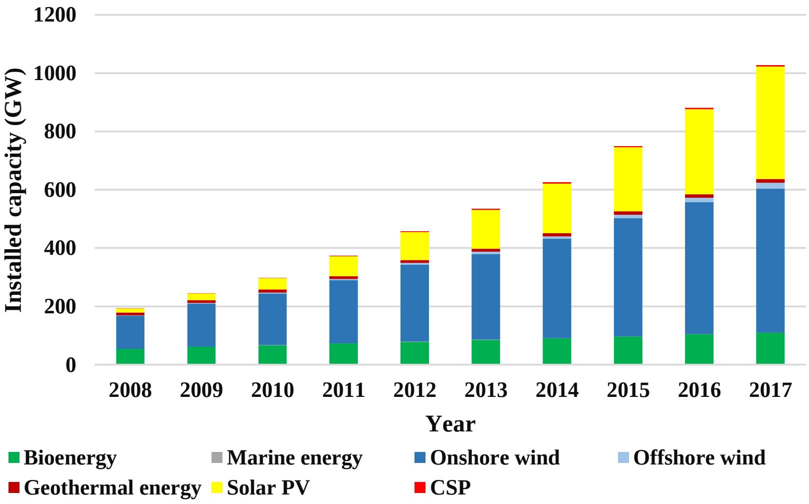

Figure 4. Installed global capacities of renewable electricity generation from 2008 to 2017. Capacities of hydropower increasing from 960 GW to 1270 GW have been excluded (International Renewable Energy Agency 2018).

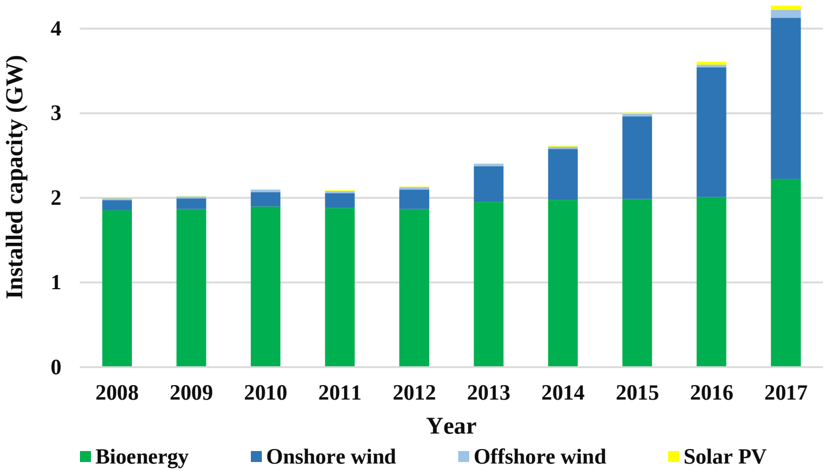

Figure 5. Installed Finnish capacities of renewable electricity generation from 2008 to 2017. Capacities of hydropower increasing from 3.1 GW to 3.3 GW have been excluded(International Renewable Energy Agency 2018).

2.3.2 Energy storage and system flexibility

As the share of renewable energy increases in energy systems, especially VRE, the need for storage over the short-term and long-term has been well documented. Several studies have shown that once the share of RE in power generation reaches approximately 50%, a need for electric energy storage becomes evident. Upon reaching a share of 80%, seasonal storage is needed (Bogdanov & Breyer 2015b; Weitemeyer et al. 2015). In the past, energy storage was dominated by the flexible dispatch of hydropower, the use of pumped hydro storage, and in some cases thermal energy storage. In addition, the dispatchable nature of some energy resources, such as fossil fuels and biomass, meant that the storage of energy carriers, such as electricity and heat, was not always necessary. Flexibility in energy systems came from how and when the energy resources were transformed to energy carriers, which was, more or less, on demand. Therefore, if future energy systems are to utilise high shares of VRE, flexibility must be harnessed elsewhere in order to maintain the balance between supply and demand on both a short-term (hours and days) and long-term (seasonal) basis.

Several forms of energy storage have emerged as potential candidates to provide such flexibility. On a global level, battery electric storage has emerged as a key technology in the transition towards sustainability (International Renewable Energy Agency 2017). Stationary battery applications have begun to grow rapidly. Further, wider deployment is expected, driven by lifetime extensions, performance improvements and cost reductions in Lithium-ion batteries, high-temperature sodium-sulphur, and flow batteries (International Renewable Energy Agency 2017). As battery factories grow in scale to supply the demands for electric vehicles, there is potential for batteries to have a major impact on the electricity and transport sectors (Fuchs et al. 2012). The Finnish city of Vaasa has launched an initiative to create a so-called battery Tesla Gigafactory, located near the most significant deposits of Lithium in Europe, and the world's largest cobalt refinery (EnergyVaasa 2017).

The concept of transforming power into other useful substances, in a generic process called Power-to-X (PtX), has attracted a great deal of attention in recent years. PtX is comprised of a number of potential storage options, such as Power-to-Gas (PtG) (Götz et al. 2016), Power-to-Heat (via heat pumps and thermal energy storage) and Power-to-Liquids (PtL). In addition, the PtX concept can result in other value-added products, such as Power-to-Water, Power-to-Hydrocarbons and Power-to-Chemicals (Caldera et al. 2016; Fasihi et al. 2017). The extent to which PtX may be of benefit to the Finnish energy system is a major theme in this research.

2.3.3 Electrified mobility

The potential to electrify various forms of mobility, especially light duty and passenger vehicles, is quite large. Electrification of other aspects of mobility is also possible, including motorcycles, trains, boats, busses and ferries. Further still, efforts are being made to electrify heavy-duty transport and even short-haul air travel. However, it is the trend towards battery electric vehicles (BEVs) that may prove to be the most profound in the years to come. The range of BEVs has expanded dramatically in recent years. In the category of full electric vehicles, battery size ranges from 16 kWh in the Mitsubishi i-MIEV (range of 160 km) (Mitsubishi Motors Corporation 2018) to 100 kWh in the Tesla Model S (range 613 km) (Tesla 2016). Since 2010, approximately 2 million electric cars have been sold, and the IEA projects this value could exceed 200 million by 2030 if electric vehicles had only a 30% market share (International Energy Agency 2017a).

The impacts of increased electrification of mobility are primarily twofold. First, there will be a significant increase in the global demand for electricity. However, much of this demand will be relatively flexible, and may occur mostly in evening hours, when electricity demand is typically low. So-called smart charging can also be performed in a manner that does not provide extra strain on power systems. Second, the potential battery storage capacity that could be utilised as part of global energy systems is massive. For example, if 200 million vehicles each had a 60 kWh battery on average, this would represent 12 TWh of storage capacity. This value is almost three times greater than the current total global electric storage capacity (mostly pumped hydro storage) of 4.67 TWh (International Renewable Energy Agency 2017). This example does not include capacity related to other forms of transport, which includes billions of motorcycles, tens of millions of busses, etc. The main point is that the trend towards the electrification of transport may offer significant flexibility to future energy systems in the forms of flexible demands and capacity for energy storage.

2.3.4 Energy efficiency

Decreasing energy intensity through efficiency is one of the major goals of the EU (European Commission 2018). By 2020, energy efficiency measures are set to achieve 20% savings. This target has been increased to 30% by 2030. This will primarily be achieved through efficiency measures in buildings and products, as well as the cogeneration of heat and power. Energy efficiency is also a key issue amongst the G20 members, which represent more than 80% of the world's economic output, primary energy consumption and GHG emissions. Lastly, one of the United Nation's Sustainable Development Goals aims to double the rate of energy efficiency improvements globally by 2030 (G20 2016).

At the same time, the concept of energy efficiency can be a slippery slope. While the G20 members report that between 1990 and 2013 energy efficiency improvements resulted in energy consumption savings of approximately 50 PWh and GHG emissions avoidance of 10.4 billion tonnes (G20 2016), total primary energy consumption increased by approximately 42 PWh and GHG emissions increased by 9.4 billion tonnes (International Partnership for Energy Efficiency Cooperation & Agence de l'Enviroanement et de la Maitrise de l'Energie 2015; OECD 2018). Population increase and economic growth account for much of these seemingly contradictory statistics.

Therefore, several other factors should be borne in mind when referring to energy efficiency, and overall energy consumption must be examined critically. Firstly, buildings may become more energy efficient in terms of energy use per square meter, but there may not be an actual efficiency gain. This can occur if living spaces become larger over time, or if the number of people per dwelling decreases. Secondly, switching to more efficient products, such as from internal combustion engine (ICE) vehicles to electric vehicles (EVs), may seem greatly more efficient from one perspective, but not another. Certainly, EVs consume about a third of the energy per passenger kilometre than ICE vehicles. However, increased access to mobility can result in more passenger kilometres per year. Likewise, choosing a more efficient mode of driving may not be considered an efficiency improvement if it displaces the decision to walk, ride a bike or take public transit. These phenomena represent a 'backfire hypothesis', called the energy efficiency rebound effect, whereby energy efficiency measures arguably result in greater overall energy consumption in certain circumstances (Gillingham et al. 2016). Thirdly, an efficient demand can sometimes be better suited temporally. Using a highly efficient appliance during times of peak consumption can be a much larger burden (and cost) to an energy system than one which is made during an off-peak time. For these reasons, a more effective metric of efficiency may be energy use *per capita*. Over the period of 1990 to 2013, this value has increased from 69.5 GJ/capita to 80.4 GJ/capita globally, and this energy use is by no means shared equally amongst all nations (The World Bank 2018).

2.3.5 Prosumerism

Consumers of energy that have the ability to be producers at the same time are referred to as prosumers. Such prosumers can be private individuals, business, or even industries. Prosumerism is arguably an old form of capitalism, and at the same time a new one (Ritzer & Jurgenson 2010; Ritzer 2014). In essence, it is defined by a lower cost abundance where scarcity previously dominated. The most recognizable forms of prosumerism are currently digital, such as Facebook or Wikipedia, but other forms exist. Mobility has adopted prosumerism through Uber, the service industry has adopted prosumerism through Airbnb, and rooftop solar PV arrays denote the homes, businesses and industries that have become energy prosumers. Future energy systems may see great abundance of lower cost energy as a result of peer-to-peer networks that develop to distribute this abundance. As such, at least some of the importance of centralised electricity generation may be replaced by distributed generation. This may have profound impacts on the amount of energy that is grid-based, and consequently affect energy markets. Indeed, the societal impacts of prosumerism and a peer-to-peer society are other areas of interest for this research (see Publication VII).

2.3.6 Societal engagement

The presence of energy prosumers indicates that there is at least some movement away from more traditional, centralised energy provision and towards more decentralisation. Soutar and Mitchell (2018) describe two narratives of social engagement in energy systems that illustrate at least the poles of what is more likely a continuum of energy system engagement. The first involves centralised energy systems with consumers who have little or no engagement with the energy they use or the resources used to create it, a so-called ‘consumer/deficit view’. To such consumers, energy is an abstract commodity that is not much contemplated outside of the energy services it provides, or the bills that are paid for it. There is no day-to-day handling of or concern for energy resources, and there is little thinking of either where it comes from or any responsibility for how it is produced or any pollution it creates. These worries are more the responsibility of others, who often lack accountability, transparency and responsiveness. In this regard, energy is seen as a public good provided by hierarchical infrastructures and top-down modes of governance (ibid.).

Alternative, the ‘energy citizenship view’ shows an increase adoption of affordable, low carbon energy technologies by a broader range of technology owners (communities, municipalities, businesses, households, etc.), who are distributed geographically and most often exploiting variable renewable energy resources. Balancing consumption and generation of energy becomes the responsibility of a larger number of actors, and flexibility in demand is needed in smaller networks. Importantly, the new engagement with energy involves a much higher awareness of where it comes from, how it is produced and distributed, and its local environmental impacts. There is also a noted shift in energy governance and responsibility from the central to the local, resulting in energy system democratisation (ibid.). Likewise, business opportunities can be created or expanded at a local level, supporting a more circular economy (Scheer 2002).

2.4 Nuclear energy

Finland has a long history with nuclear power, beginning in 1962 with the commissioning of a small (250 kW) research reactor at the University of Helsinki. Since then, four larger reactors were built between 1977 and 1980. Currently, after several refurbishments, the reactors total 2764 MW of electrical power (World Nuclear Association 2017), which generated 22 TWh of electricity in 2016, representing 18% of total energy consumption, 26% of electricity consumption, and 47% of domestic electricity generation (Statistics Finland 2018). The oldest operating reactor is expected to be shut down by 2027, and the newest by 2038.

A fifth nuclear reactor is currently under construction in Finland, a 1600 MW European Pressure Reactor (EPR), Olkiluoto 3. Construction for the initially estimated €3.2 billion project began in 2005 and was to be completed by 2010. However, time overruns have left the project still unfinished, and the budget has soared to estimates of €8.5 billion. Construction has been so delayed that signs of aging concrete were recently noticed at the project even though it has yet to be commissioned (Jokinen 2018). Several dates have been announced for the start of operations, but all have been pushed back.

Currently, preparatory work has begun at the site of a proposed Hanhikivi 1 nuclear power plant, although the project currently lacks a construction license. This project is expected to be of 1200 MW capacity, and is owned by a consortium including several power and industrial companies. However, several members of the consortium have expressed interest in withdrawing from the project, or have already withdrawn, siting that the project is not in their best interests, or those of taxpayers (Kiviranta 2015; Paakkanen 2017). It is unclear at this time if the project will ever be realised.

2.5 Carbon capture and storage

Carbon capture and storage (CCS) has been proposed as an option to establish and maintain sinks of carbon to ultimately reduce levels of atmospheric CO_2. While there is appeal to this idea, CCS remains unproven and uncertain as a long-term solution. It has also been called “a Faustian Bargain par excellence” (Spreng et al. 2007), one that may only extend the era of fossil fuels and associated GHG emissions. In addition, CCS requires a long-term commitment to vigilant monitoring and management, one which may extend well into the future and represent an intergenerational ethical dilemma. Moreover, the degree of this burden and the risk of GHG leakage back to the atmosphere increases as stored levels of CO_2 increase. Therefore, greater reliance on CCS could mean greater risk and intergenerational burden.

There are several reasons why fossil fuel based CCS is incompatible with the need to create net zero emissions in energy systems. Firstly, emissions occur upstream from fossil fuel use in energy plants, as the extraction, refining and transport of fossil fuels result in emissions. Secondly, CCS results in lower power plant efficiency, meaning that more fuel will be necessary to create the same amount of power, resulting in greater emissions. Thirdly, only between 50 and 90% of emissions can be captured from power plant flue gas streams, meaning that some other sink would still need to be established to maintain net zero emissions (Leeson et al. 2017; Bui et al. 2017). Fourth, there are currently great economic challenges associated with CCS (Buck et al. 2016), as shown by the economic failure of a world-leading CCS coal plant in the U.S. (Zegart 2017). Finally, leakage of the carbon captured throughout the transport and deposition phases of CCS, and the permanent storage of CO_2 has yet to be demonstrated. The result of CCS will be positive emissions, possibly substantial, unless another carbon sink or offset is established. Figure 6 shows the options available for CCS and related technologies.

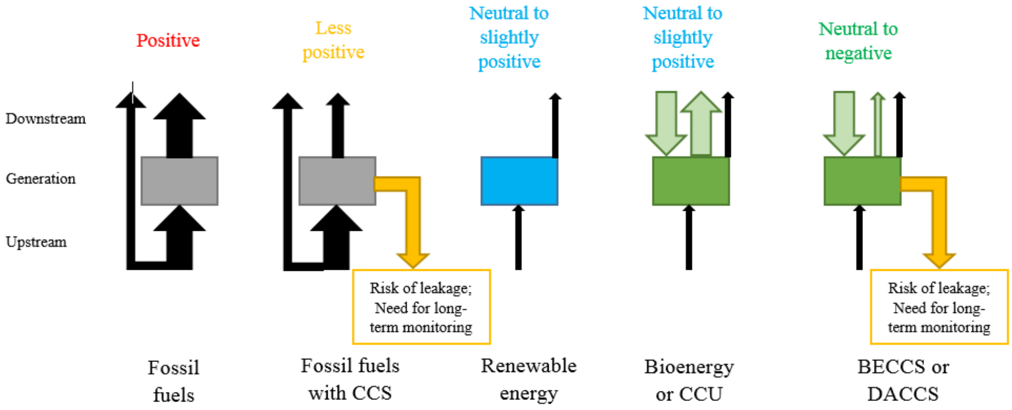

Figure 6. The carbon balance for various technologies. A more detailed discussion of the sustainability of CCU follows in Section 2.6. Adapted from (IEAGHG 2011). CCS-Carbon capture and storage; CCU-Carbon capture and utilisation; BECCS-Bioenergy carbon capture and storage; DACCS-Direct air carbon capture and storage

2.6 Carbon capture and utilisation

There are three possible alternatives to CCS that may offer more robust solutions. The first is bioenergy with CCS (BECCS), which involves the capture and storage of biogenic carbon emissions, such as those from the combustion of sustainably sourced bioenergy. As emissions from such combustion are offset by growing biological material, overall emissions are neutral, or even negative. Second, direct air capture CCS, or DACCS, has very few upstream emissions due to the fact that carbon is captured from the atmosphere. These emissions can be reduced or eliminated by utilising sustainable forms of the heat and electricity needed for DACCS.

By contrast, carbon capture and utilisation (CCU) does not involve the long-term storage of carbon, but instead seeks to utilise the captured CO_2 to create hydrocarbons needed in various processes. CCU is often performed in conjunction with water electrolysis, which extracts H_2 and O_2 from water. The end product of this process is often methane (CH_4) or some longer chain hydrocarbon that produces a synthetic fuel or industrial raw material (Fasihi et al. 2017). Importantly, it is only BECCS, DACCS and bioenergy or DAC-based CCU that offer the level of carbon neutrality commensurate with the targets set in the Paris Agreement. CCU may also be a temporary mitigation strategy for unavoidable CO_2 emissions, such as those from waste incineration or cement mills. At the same time, all negative emissions schemes have been dubbed as questionable, “late-regret magic bullets”, which may not provide the best opportunity to meet the Paris Agreement targets (Schellnhuber et al. 2016).

Some CCU schemes can also be questioned. In particular, combining CCU with fossil fuels cannot be seen as a sustainable solution, as it does nothing to reduce the positive emissions associated with fossil fuels shown in Figure 6 (left), and may give the illusion that emissions are being reduced significantly, when they are not. While CCU, viewed in isolation, is a neutral to slightly positive process, it does nothing to change the nature of the emissions being captured, nor does it improve the sustainability of the overall upstream processes. Captured and utilised fossil emissions will remain positive fossil emissions even after CCU. Likewise, if sustainability issues are present upstream from the use of certain types of bioenergy, those issues do not disappear by adding a CCU scheme. For example, not all forms of bioenergy are equal with regards to overall sustainability. Energy crops can be associated with large demands for land, inefficiency related to other forms of renewable energy, high cost, water demands, and competition with agriculture for arable land (Williamson et al. 2016). In contrast, biomass residues come with “fewer trade-offs than dedicated bioenergy crops” (Rogelj et al. 2018). The important point to make is that CCU does nothing to eliminate upstream sustainability issues if they are present.

2.7 Cost trends in global energy systems

A comprehensive analysis of the levelised cost of electricity (LCOE) in the G20 was recently performed (Ram, Child, et al. 2017), which showed the increasing competitiveness of renewable energy, particularly solar PV and wind energy, to fossil fuels and nuclear energy. Furthermore, it is projected that the costs of wind and solar PV will fall even further, complemented by drops in the cost of battery technology. The authors suggest that global power systems will undergo a fundamental transition as a result of this well-established momentum, and a new age of sustainable living will be fostered.

According to the United Nations Environment Programme and Bloomberg New Energy Finance, the levelised cost of solar PV dropped 72% worldwide over the period of 2009-2017, onshore wind power dropped 27% over the same period, and offshore wind power dropped 44% since 2012 (McCrone et al. 2018). These falling costs have resulted in the LCOE of solar and wind being amongst the lowest in the world. This is evidenced by several auction bids in the last year that are the lowest costs seen so far: 30 USD/MWh for onshore wind in Morocco, 55 USD/MWh for offshore wind in Denmark, and 29 USD/MWh for solar in Chile (McCrone et al. 2017). Recently, Saudi Arabia received a bid to produce solar PV electricity for 18 USD/MWh by Electricite de France SA (Dipaola 2017), another record low.

Cost reductions are also seen for storage technologies. In particular, the cost of Lithium-ion batteries has fallen by 73% for transport applications between the period of 2010-2016 (International Renewable Energy Agency 2017). For stationary applications, the International Renewable Energy Agency suggests that Li-ion battery costs could decline as much as 64% further by 2030, to 145 USD/kWh. Causes for the continued decline include establishing of economies of scale, increased calendar lifetime, increased cycle lifetime, and increased efficiency. Other estimates suggest that the cost could drop even more drastically, to approximately 100 €/kWh (approximately 135 USD/kWh) for battery packs by 2025 (UBS 2014). Other battery technologies are also expected to see cost reductions in the range of 50-66% by 2030 (International Renewable Energy Agency 2017). Cost reductions in other types of electricity storage (e.g. flywheels and compressed air energy storage) are also expected (International Renewable Energy Agency 2017). Overall, cost reductions in electricity storage are expected to have an important role in enabling the transition towards higher shares of VRE.

3 Methods of studying energy systems

The following sections introduce the various methods used in this research. The first method involved utilising aspects of Critical Discourse Analysis (CDA) to study how meaning is negotiated in words and expressions. The ultimate goal was to determine what meaning was being intended or communicated through the use of the expressions ‘energy system transition’ and ‘energy system transformation’. The second method involved the use of an energy system modelling tool, EnergyPLAN, to simulate a variety of scenarios for the Finnish energy system. The third method was to use Futures Studies to reflect upon possible energy futures, primarily from a social perspective. Each method will be described in turn.

3.1 The meaning of words and expressions

It seems obvious that a change towards greater sustainability in global energy systems is both desired and currently underway. And in some cases, such as the German concept of *Energiewende* (Krause et al. 1980), the concept of change is both named and rather comprehensively understood in terms of its scope, direction, degree and level of urgency. However, in English language scientific literature, a sometimes confusing and rather ambiguous use of terminology has resulted in a vague and often contradictory presentation of the concept of change in energy systems. In particular, two expressions have risen to the fore: transition and transformation. And while some authors go to great lengths to define each word explicitly, others use the terms rather carelessly, and even synonymously in the same sentence.

Key issues related to the use of competing terms involve how this linguistic confusion manifests itself within the scientific literature and throughout popular culture. Specifically, are fundamentally different concepts being either presented or possibly understood by the use of different terms to denote change? In addition, do the terms frame the concept of change in different manners to the extent that they present various levels of problem recognition, variable urgency or speed of change needed, different obstacles to change or competing actions and actors needed to achieve change?

The underlying theoretical approach inspiring Publication I was Critical Discourse Analysis, discussed comprehensively by Fairclough and Wodak (1997). In essence, linguistic, semiotic and interdiscursive features can influence and be influenced by society to the extent that values, attitudes and behaviours can be framed or shaped. Linguistic features, in particular, come to be part of a discourse that represents a shared way of understanding the world. And different discourses can shape how different alternatives of change are either accepted, resisted, complied with, or imposed (van Dijk 1993).

It was postulated that, upon the brink of so much fundamental change in global energy systems, confusion over what to call the change might lead to resistance, or at least deflect attention away from the desired outcomes of change, such as mitigating climate change or increasing sustainability. For this reason a comprehensive analysis of definitions and uses of the expressions ‘energy system transition’ and ‘energy system transformation’ was undertaken with the goals of representing more completely what the concepts represent, and advocating more consistent usage in scientific literature and popular culture. Several questions and sub-questions arising from the field of CDA were used to explore various aspects of the meaning of these key expressions (see Table 3, Publication I).

3.2 Overview of energy system modelling

A comprehensive review of modelling tools used to simulate future energy scenarios featuring the integration of renewable energy was performed by Connolly et al (2010). While it was evident that no single tool stood out as being ideal, a full discussion of the functionality of each tool was presented. In the end, the discussion aided in the finding of a suitable tool for this research given criteria that were deemed necessary to be fulfilled. Specifically, a model with hourly resolution for an entire year was deemed a minimum standard due to the variable nature of some forms of renewable energy generation, and the need to maintain the balance between supply and demand. Energy system dynamics are often measured in milliseconds, but data is not usually available for modelling at this resolution, and computing time would represent an unmanageable burden. Sub-hourly modelling may be preferred (Troy et al. 2012), but is not practically realistic at this time. In addition, Brown et al. (2018) argue that hourly modelling is sufficient to capture the largest variations in variable supply from wind and solar, and the dimensions of flexibility needed in the system. Time-steps of greater than one hour, on the contrary, may not capture the full dynamics of the system, and could result in modelling outcomes that show higher levels of installed capacities of variable renewable energy, and lower levels of storage. Further, that year had to be a unique, real weather year, and not a series of representative time slices. Instead, the tool should allow a better representation of week to week, and month to month energy system performance. These criteria were essential in enabling the analysis of how all the elements of an energy system combined to satisfy real hourly demands. The hour is also the basic unit of time in which market and consumer costs of energy can vary (e.g. €/kWh or €/MWh). Next, a tool was sought that was able to model the power, heat and mobility sectors in order to uncover any potential benefits of sector integration. Further, a tool was needed to represent the complexities of the Finnish national energy system, one that involves large amounts of trade of energy carriers with other nations. At the same time, the tool should have a flexible geographic scope to allow simulation of larger or smaller regions. In addition, the simulation tool should have the ability to show how a wide range of energy system costs could be represented and optimized. In the end, the EnergyPLAN tool (Lund 2015; Lund et al. 2017) was selected from the others to represent the Finnish energy system in this research and will be described in more detail in the following section (3.3).

A growing body of research on energy system modelling supports the claim that power grids can remain stable with electricity provided by 100% or near-100% renewable energy (Jacobson 2017; Sgouridis et al. 2016; Breyer et al. 2017; Teske et al. 2015). Such research has been accomplished with a variety of modelling tools, and wide-ranging techno-economic assumptions. Rather consistently, results demonstrate that 100% RE energy systems may be, at best, least cost solutions (Child et al. 2017), and at worst, not significantly greater in cost than current energy systems (e.g. Mathiesen et al. 2011). These results are primarily achieved through modelling of high shares of low cost wind and solar PV power generation combined with a range of energy storage solutions and flexibility measures. Harnessing the flexibility available in energy systems is a major theme in energy system modelling of the future. Therefore, the modelling tools employed must have the functionality to demonstrate how storage solutions, grid exchange, flexible generation and flexible consumption can reliably interact over long periods of time, over a variety of geographic areas, under real weather conditions, and at a sufficient time resolution (e.g. hourly).

Despite the growing body of literature that shows the feasibility of 100% renewable energy systems, debate is lively. Perhaps the most recent debate that captures the essence of arguments and counterarguments occurred between Heard et al. (Heard et al. 2017) and Brown et al. (Brown et al. 2018). The main criticism of 100% RE studies presented by Heard et al. (Heard et al. 2017) was that the body of literature (24 studies were reviewed) failed to show consistency with mainstream energy-demand forecasts; simulation of supply to meet demand reliably at hourly and sub-hourly timescales, with resilience to extreme climate events; identification of necessary transmission and distribution requirements; and maintenance of the provisions of ancillary services. In these regards, the 100% RE studies "substantially underestimated the challenge and delayed the identification and implementation of effective and comprehensive decarbonization pathways" (ibid.). Brown et al. (Brown et al. 2018) counter that the above criteria, while important, are not critical to demonstrate either feasibility or viability of the studies, and that each of the issues can be addressed at low economic cost. Each of the above criteria are systematically demonstrated in the Brown et al. study, which also includes further criteria and issues related to feasibility. Each criterion and issue is systematically regarded, and further examples are provided to show that the claims of Heard et al. have been "exaggerated". In the end, they reaffirm that the main conclusions of the reviewed studies on 100% RE are valid. This is echoed in more recent work by Diesendorf and Elliston (Diesendorf & Elliston 2018), who assert the feasibility of 100% renewable energy systems on the grounds that studies have clearly demonstrated the reliability, security and affordability of such systems as well as the technical and economic viability of a multidecadal transition timescale.

3.3 EnergyPLAN

A full description of the EnergyPLAN model can be found at the tool's website (Lund 2015). EnergyPLAN is a user-friendly, free computer model that was designed to aid in the representation of regional, national or multi-national energy systems. Since its creation at Aalborg University in Denmark in 1999, it has undergone continuous improvement, and had been successfully used to simulate energy systems with high shares of renewable energy in a growing number of scientific publications, including Finland (Zakeri et al. 2014; Zakeri et al. 2015; Rinne & Syri 2015). In addition, training was available for the tool online, and its developers were gracious in extending additional personal guidance and feedback throughout the research process. A forum for questions also supports continued learning of how the tool can be used most effectively. Importantly, the EnergyPLAN tool was built on a solid theoretical framework (Lund et al. 2014).

Main inputs into EnergyPLAN include demands for electricity, cooling, district heating, individual heating, fuel for industry, and fuel for transport. Hourly profiles of these demands are also needed as inputs. In addition, renewable electricity generation capacities and hourly profiles are important inputs. EnergyPLAN accepts inputs for onshore wind, offshore wind, concentrating solar thermal, solar PV, geothermal, hydropower (dam and run-of-river), wave and tidal power. In addition to installed capacities, users input hourly generation profiles for the appropriate resources and technologies. Capacities and efficiencies also have inputs related to various condensing power plants, boilers, combined heat and power plants, heat storage, liquid and gas storage, electricity storage, and compressed air energy storage. Next, transport inputs concern the number of various types of vehicles, such as petrol/diesel vehicles, gas vehicles, electric vehicles, V2G electric vehicles, hydrogen vehicles, and biofuel vehicles, as well as their fuel use. Next, several regulation strategies are available to assist with assigning various technical operation limitations (e.g. minimum power plant operating capacity), strategies for handling excess electricity, interconnection capacities, and characteristics of external electricity markets (including hourly prices). Lastly, several aspects of costs are assigned as inputs, including fuel types and costs, CO_2 emission factors and costs, capital expenditures, fixed operational expenditures, variable operational expenditures, and interest rate.

Processing of an EnergyPLAN scenario proceeds as an optimization of the operation of the energy system presented by the inputs. This differs in nature to several other tools, which seek to optimize long-term investments in an energy system. In order to determine optimal energy system set-up, different scenarios can be run and outputs compared. The outputs of EnergyPLAN include annual, monthly and hourly values of various forms of electricity generation, import/export, excess electricity generation, breakdown of expenditures, fuel consumption, CO_2 emissions, and shares of renewable energy. Simulations tend to last only seconds, so several scenario variations can be tested in short periods of time. This allows the user to become a driver of optimization without huge demands on time. At the same time, it remains unclear whether a found solution is an overall optimized one (Lund et al. 2017). Several graphics of outputs aid in this process, and outputs can also easily be copied to excel files for additional processing. This allowed in-depth comparison of scenarios, as found in Publications III and VI, or more detailed examinations of individual scenarios, such as in Publications IV, V and VII.

The main limitations of the EnergyPLAN faced during this work are detailed in Publications III-VII, and discussed further in section 5.3.

3.4 Limitations of energy system modelling

The goal of energy system modelling is not to predetermine a static pathway towards the future, nor to predict a specific future. Energy system modelling is limited to presenting potential representations of or pathways towards future scenarios, which are based on a myriad of technical and economic assumptions. The goal of modern energy system modelling should be to reduce uncertainty about the future, specifically a future with much higher shares of renewable energy (Connolly & Mathiesen 2014). However, assumptions and outcomes of energy systems models come with their own inherent uncertainties. Many technical assumptions, including efficiencies, availabilities, and resource qualities, are made for the future. Some of the main assumptions used in this work are summarized in Table 1, but are described in more detail in each Publication along with references. In addition, future costs of resources, technologies and services are assumed. In this research, all assumptions are rigorously derived, supported by scientific literature at every possible opportunity, and fully documented. Thirdly, one must accept that future inventions and innovations can occur, and that these can become unforeseen disruptions which can alter the fundamental trajectory of change in energy systems. Fourthly, energy system modelling often depicts outcomes that represent significant long-term benefits to society, even those that are inter-generational, and can therefore be biased against short-term interests of individual stakeholders. So, the task of modelling future energy systems can never be to eliminate uncertainty. Instead, it should only be to reduce the most plausible, visible or potentially disruptive uncertainties that society may face. For these important reasons, results of energy system modelling should aim to enable and expand public discourse on energy-related issues, and not to direct it. As well, the public discourse should include an evaluation of the assumptions used in energy system modelling as well as any bias that could be present. In turn, all this essential discourse will enable and direct any change that actually occurs.

Table 1. Main capital expenditure (Capex), lifetime and efficiency assumptions related to key technologies for the current situation up to 2020, 2030 (Åland study only) and 2050. In cases where two values are present, the latter refers to the Åland study. Blank values for 2030 represent technologies that were not used in the study. Abbreviations: OCGT-open cycle gas turbine, CCGT-combined cycle gas turbine, CHP- combined heat and power, PtG-power-to-gas, SOEC-solid oxide electrolyser cell, EV-electric vehicle

Technology	Parameter	To 2020	2030	2050
Solar PV - ground mounted	Capex (€/kW$_e$)	900	550	300
	Lifetime (years)	30	35	40
Solar PV - rooftop	Capex (€/kW$_e$)	1200	700	400
	Lifetime (years)	30	35	40
Wind onshore	Capex (€/kW$_e$)	1100	1000	900
	Lifetime (years)	20	25	30
Wind offshore	Capex (€/kW$_e$)	2500	2100	1800
	Lifetime (years)	20	25	30
Hydropower - Run of river	Capex (€/kW$_e$)	2750		3060
	Lifetime (years)	50		50
OCGT	Capex (€/kW$_e$)	600		600
	Lifetime (years)	30		30
	Efficiency	40 %		40 %
CCGT	Capex (€/kW$_e$)	820		820
	Lifetime (years)	30		30
	Efficiency	60 %		60 %
Biomass CHP	Capex (€/kW$_e$)	1700	1200	1600
	Lifetime (years)	30	25	30
	Efficiency	40 %	40 %	40 %
Nuclear power plant	Capex (€/kW$_e$)	5500		6500
	Lifetime (years)	40		40
	Efficiency	33 %		37 %
CO_2 Hydrogenation plant (PtG)	Capex (€/kW$_{gas}$)	1750/1500	600	870
	Lifetime (years)	30/20	15	30
	Efficiency	63 %		70 %
SOEC Electrolyser	Capex (€/kW$_e$)	590		480
	Lifetime (years)	20		30
	Efficiency	73 %		73 %
Lithium ion stationary battery	Capex (€/kWh$_e$)	300		75
	Lifetime (years)	10		20
	Efficiency (round-trip)	95 %		95 %
Lithium ion EV battery	Capex (€/kWh$_e$)	200	100	100
	Lifetime (years)	8	10	12
	Efficiency (round-trip)	95 %	95 %	95 %

3.5 Futures studies

Futures studies involve an interdisciplinary investigation into strategic foresight. From several perspectives, one can consider the possibility, plausibility or desirability of different kinds of futures. Through the exploration of alternative futures, one is able to better understand the volatility, uncertainty, complexity and ambiguity (VUCA) of changes that lie ahead, thereby, taking a step towards increasing human control over future events (Bell 2009). It has been argued that expanding visions of energy futures can aid in deepening and broadening energy research. In Publication I an investigation was made into the possibility of how naming a future change can affect acceptability of that change. In Publication VII, it is argued that how one imagines a future change can affect its desirability. To date, much of the research on energy visions of the future have been techno-economic in nature, and relatively less work has been done to develop a vision of the coming era of renewable energy from a societal perspective. The focus, thus far, has been on the futures of energy systems and not on the futures of societies specifically, although some studies have taken some socio-cultural aspects into account (Miller et al. 2015; Schmid et al. 2017; Weimer-Jehle et al. 2016). Far from being a Utopian fantasy or “wild crystal ball gazing”, futures studies offers an innovative and anticipatory opportunity to discuss the social implications of a changing energy system (Bell 2009).

A Futures Studies approach is needed to anticipate discontinuities between current and future states. Anticipating these discontinuities can aid in mitigating potential disruptions and embracing potential empowerments on a societal level. After all, it will be societies that ultimately determine the techno-economic future, and not the other way around. Without question, the social and techno-economic realms cannot be viewed in isolation. Historical societal change can easily be linked to changes in energy systems (Rifkin 2011). It seemed only fitting that this research include an analysis and vision of the potential precursors and effects of a new age of renewable energy. This, too, is provided as a stimulant for broader public discourse.

4 Results

Summaries of main aims, methods, and results from each publication are presented in turn in the following sub-sections.

4.1 Publication I: the concept of change in energy systems

Aims

This work sought to accomplish two main tasks. First, it was deemed necessary to determine if the terms ‘transition’ and ‘transformation’ had fundamentally different meanings in scientific literature, either in definition or by usage. Second, there was an assessment of how the terms were used to determine if the concept of change was framed in such a way as to highlight differences of problem recognition, degree or speed of changed necessary, actions and actors needed to achieve change, and obstacles to overcome. Upon achieving these two tasks, a more concrete definition or manner of usage was proposed.

Methods

In total, 41 publications were analysed that used the terms ‘energy system transition’, ‘energy system transformation’, or both. These publications were found using the ScienceDirect search engine, and classified according to one of three categories: transition, transformation, or transition/transformation. A series of key questions were then applied to the title, abstract, or introduction of the publications to determine the general intention of meaning of the key phrases. These questions probed how change is defined, how change is described as proceeding, the barriers to change, the agents of change, and the outcome of change. Several aspects of meaning were investigated, especially those involving positive or negative connotations. The frequency of specific word usage in the text was measured, and the three main categories were compared.

Results

A quantifiable, systematic difference in meaning between the terms ‘transition’ and ‘transformation’ was not found in this study, although articles that use the terms ‘transition’ showed a tendency to highlight social agents of change more prominently, and change was often described as occurring over longer periods of time. However, some evidence was found to support the idea that the concept of change is being framed differently in different article types. In ‘transition’ articles, framing of the concept led to a greater sense that a social problem exists which requires social actors to achieve social goals. In the end, a recommendation for usage was determined for the terms that involved limiting the use of the term ‘transformation’ to instances where the physical or technical aspects of change are being described. In contrast, the term ‘transition’ could be used when a higher order of change is highlighted, specifically one that involves the social nature or consequences of change.

4.2 Publication II: towards sustainability in energy scenarios

Aims

This study was a fundamental examination of how influential energy system scenarios have represented sustainability. A primary motivation of this work was concern that future energy scenario modelling was focussed too narrowly on the concept of climate change mitigation, despite the great importance of this issue. Therefore, the first aim was to consider the concept of sustainability in energy systems in a manner that adheres to a broader set of guardrails, respecting all relevant planetary boundaries and sustainability principles. Secondly, a sustainability hierarchy was proposed for the purpose of scrutinizing future global energy scenarios more comprehensively as well as the transition towards sustainability proposed in each. A third aim was to investigate whether several influential global energy scenarios had adequately adhered to the proposed hierarchy, and to suggest ways that the guardrails could be operationalised during the creation of energy system scenarios. This included the development of a sustainability checklist that could be applied by future energy system modellers to their own work.

Methods

After an extensive literature review of the concept of sustainability and of then available global energy scenarios of influence, eight studies, some with multiple scenarios, were chosen to represent global scenario modelling work. Each represented a global energy system scenario for 2050 and was deemed influential to a notable degree. Moreover, each showed clear pathways towards specific goals for the future. Scenarios were first examined qualitatively for adherence to the proposed hierarchy of sustainability, and then quantitatively for energy generation and storage technologies utilised in 2050.

A transparency checklist was then created to determine the presence or absence of specific information (general, data presentation, assumptions, modelling properties). The judgement of all authors determined if such information was presented, and if the presentation was sufficient.

Lastly, a sustainability checklist was created for the sustainability guardrails introduced. How three scenarios adhered to the guardrails in relation to social, environmental and economic criteria was then determined through the use of several Yes/No questions developed. For the transparency and sustainability checklists, all items were judged as being explicitly stated, not fully disclosed, or not available / cannot be determined.

Results

Global energy scenarios show too great an emphasis on CO_2 emission mitigation, often at the expense of the other planetary boundaries. Often neglected are land use change, stress on biochemical flows, ocean and climate systems, and biodiversity. In addition, certain ethical choices are often neglected or left unjustified in scenarios, such as the access to preserved ecosystems by current and future generations, negative impacts related to energy extraction on human lives, and preventing resource use conflict. At the same time, some social and economic aspects are coming to the fore in modelling frameworks, such as universal access to energy services, limiting air pollution, and increased energy efficiency through electrification. None of the global energy transition scenarios investigated adequately described the important role of flexibility measures in future energy systems that feature high shares of renewable energy, such as grids, storage, supply side management, demand response, and sector coupling. The concept of resilience in socio-economic systems was also inadequately incorporated in modelling. Importantly, fully renewable energy system scenarios appeared to fulfil a wider range of environmental, ethical, and socio-economic sustainability objectives.

The sustainability hierarchy proposed in this work can aid in showing how a broader range of sustainability criteria are represented in energy scenarios. This can aid modellers as they construct scenarios, and can also help policy- and lawmakers more accurately judge the quality of future energy scenarios beyond the current focus on CO_2 mitigation, and to possibly expose any possible vested interests in the scenario itself. Ultimately, through more informed discourse, more resilient energy systems can be created that serve as beneficial long-term social contracts.

4.3 Publication III: a recarbonised Finnish energy system

Aims

The purpose of this work was to envision and analyse several recarbonised energy system scenarios for Finland in 2050. In addition to the consideration of other sustainability criteria, several scenarios were devised that not only led to the essentially zero GHG emissions, but did so through the replacement of some fossil-based carbon emissions with those that are derived from synthetic or biogenic sources. At the same time, all scenarios had to meet a list of fundamental requirements of the Finnish energy system. The study aimed to, firstly, examine the potential components of an integrated (electricity, heating/cooling and transport) energy system in Finland in 2050. Secondly, the cost impacts of varying levels of nuclear power and forest-based biomass were determined. Thirdly, scenarios with high shares of variable renewable energy were explored, with particular note of the roles of Power-to-Gas, Power-to-Liquid and energy storage technologies. Fourthly, there was an aim to develop the energy system modelling of Finland by exploring scenarios that had not previously been considered, and by offering complete transparency of all modelling assumptions. Lastly, the aim was to stimulate discourse on energy-related issues in Finland that would advance the transition towards long-term sustainability.

Methods

The EnergyPLAN modelling tool was used to build eight test scenarios for Finland in 2050. These were classified into two main groups: Basic and Low-biomass scenarios. Within each group, four scenarios were designed with differing levels of nuclear power: 100% RE, Low nuclear (1.6 GW), Medium nuclear (2.8 GW), and New nuclear (4.3 GW). In addition, three reference scenarios were constructed for comparative purposes. One was for 2012 and based on known energy system outcomes. A second was for 2020 and based on known government emissions reduction and energy efficiency targets. A third was a Business As Usual (BAU) Scenario was provided for 2050 and based on scenario parameters used for other national studies. The 2012 scenario outputs from EnergyPLAN were compared with actual data for Finland, and the modelling results verified that the tool could adequately represent the Finnish energy system. However, the limitations of the EnergyPLAN tool were noted in depth. Lastly, detailed projections of the costs of energy system components were compiled to enhance transparency of reporting and allow for wider consideration.

Results

A 100% renewable energy system for Finland was determined to be the most cost competitive option for Finland in 2050 based on the assumptions used in this research. Further, Finland could achieve a high level of energy independence while still achieving the overall goals of the energy system to provide reliable and affordable energy services. Based on current cost trends, increasing shares of nuclear power in the energy system would lead to higher overall energy system costs. In addition, effective utilisation of bioenergy resources in Finland lead to lower overall system costs through the provision of a dispatchable energy resource that results in the need for lower amounts of energy storage, particularly long-term seasonal storage. At the same time, all scenarios showed some need for the development of PtG technology to provide seasonal storage despite a mild seasonal complement of solar PV and wind power generation being noticeable. The 100% RE Basic scenario has the lowest overall annual cost at 24.1 b€/a, followed by others that range in cost up to 26.4 b€/a. These costs can be compared to those for the energy system modelled for 2012 (18.0 b€/a) and a Business As Usual scenario for 2050 (25.4 b€/a). Electricity generation of approximately 160-200 TWh was seen in all scenarios except the BAU (105 TWh), which still depended on higher levels of fossil fuels to satisfy energy demands, particularly in the transport and industry sectors.

In each of the test scenarios, higher annualised investment and fixed operational costs and lower fuel and emissions costs are seen when compared to the reference scenarios. This indicates possible domestic investment and job creation opportunities through higher shares of renewable energy. Also, the 100% RE scenarios were deemed to be less susceptible to risks associated with nuclear power and fossil fuels of environmental disaster, inter-generational ethical dilemmas and stranded investments. An exception was noted that natural gas may be needed as a key component of an energy system transition, and that gas-based storage, energy conversion and transmission infrastructure may continue to remain key elements of the energy system even after the change away from fossil-based natural gas to biomethane. The study concludes that future discourse and research involving the Finnish energy system should include the vision of a 100% renewable energy system for the nation.

4.4 Publication IV: flexible generation and energy storage solutions

Aims

This study was a continuation of Publication III, with a closer examination of the least cost 100% renewable energy scenario for Finland in 2050. Hourly data for the scenario was analysed to determine the roles of energy storage solutions (ESS) in greater depth. This included the roles of gas storage, Power-to-Gas, Thermal Energy Storage, stationary batteries, and Vehicle-to-Grid connections. Specific key research questions included how much wind and solar PV power were used directly, and the annual energy demands covered by the various forms of ESS.

Methods

To evaluate the relative contributions of various energy storage technologies, total energy consumption was determined based on end user annual demands for electric and thermal energy, which were both inputs to the EnergyPLAN scenario (100% RE Basic) described in Publication III. These were 105 TWh of electricity and 65.3 TWh of heating. For some forms of ESS, hourly outputs from the EnergyPLAN results were readily available. For others, detailed hourly calculations were derived from known outputs of stored gas. These calculations enabled the determination of the amounts of electric and heat energy that ultimately came from stored grid gas, for example, from combined heat and power plants.

For each hour of the year, the ratio of variable renewable electricity (solar PV, onshore wind, offshore wind) to total electricity generation was determined, and multiplied by the amount of total electricity consumption to determined hourly direct consumption. In addition, this hourly ratio was multiplied by the total amount of power going to electric storage (stationary batteries, V2G batteries and PtG electrolysers) in each hour to determine the amount of VRE going to storage. Hourly results were visualised, and annual totals were tabulated and analysed.

Results

VRE contributed approximately 60% to final energy consumption in the scenario, and accounts for about 70% of total electricity generation. Annually, 47% of VRE was used directly, with about 51% going to storage and the remainder (about 3%) being curtailed. Electric storage totalled 21% of end-user consumption, and the majority of this (87%)

came from V2G batteries, which raised the question of whether stationary batteries would be necessary if higher participation in V2G services could be achieved.

On a seasonal level, complementary generation of energy from solar PV and wind power aided in reducing the intermittent nature of each in the given scenario based on weather year data from 2005. At the same time, PtG technology bridged the gap between demand and supply on a daily, weekly and seasonal basis. PtG technology was also seen to provide base loads of electricity, heating, cooling and mobility when needed. Storage of gas from PtG, biomass gasification and biogas generation accounted for 26% of annual gas usage. The role of thermal energy storage, although relatively plentiful in Finland at about 20 GWh, was utilised rather minimally, and accounted for 4% of end-user heat demand. It was concluded that storage solutions will be an important part of a future Finnish energy system that features high shares of VRE, and that the precise mix of storage solutions for a given region or nation must make careful consideration of the many aspects of flexibility available throughout the energy system, including generation, storage and demand.

4.5 Publication V: solar PV in northern latitudes

Aims

It was postulated that among the barriers to high shares of renewable energy in Finland, doubt and lack of experience were most significant, at least in terms of new variable renewable energy resources such as solar PV. Therefore, a main aim of this work was to demonstrate how such an energy system could deliver all the reliability and security needed in a highly industrialised, northern society. The roles of various energy storage solutions were highlighted with regards to how they enabled high shares of solar PV, a resource with strong seasonality in Finland. This work expanded upon the analysis presented in Publications III and IV. Another main aim was to examine a comprehensive range of technological, economic, institutional, political and behavioural barriers to high shares of solar PV in Finland, and then suggest possible ways to overcome such barriers. This included some general suggestions in policy terms as to how a 100% renewable energy system could be achieved in Finland by 2050.

Methods

In the first part of this work, hourly results from a 100% renewable energy scenario for Finland in 2050 were visualised and analysed from data derived from a previous EnergyPLAN analysis of the Finnish energy system (Publications III and IV). A detailed representation of energy supply, consumption and storage was compiled for three representative weeks of the year: February 1-7, a time of peak energy consumption and relatively low generation of solar PV; June 20-26, a time of relatively low energy consumption but of very high solar PV electricity generation; December 20-26, a time of essentially no solar PV generation and an extended period with little wind power. The interactions of generation, storage and consumption of electricity, heat and gas (methane) were visualised and interpreted in order to fully illustrate how such an energy system could work. Storage solutions included stationary batteries, V2G batteries, thermal energy storage for the district heating system, and grid gas storage. Possible seasonal complementarity of electricity generation technologies were also investigated by the presentation and examination of several hourly profiles of annual values.

In the second part of this work, previous research on the barriers to successful deployment of solar PV in Finland (Haukkala 2015) were revisited and updated. These barriers were classified as either technological, economic, institutional/political, or behavioural after a new survey of 31 representatives of the Finnish Local Renewable Energy Association and active citizens in an energy transition campaign was performed. Potential methods of overcoming these barriers would then postulated by the authors.

Results

Results demonstrate how high shares of solar PV in Finland can be supported by energy storage solutions and other flexibility measures, such as flexible demand and smart charging of vehicles. Further support also arises from a seasonal complementarity between solar PV and wind power, and from the use of flexible bioenergy-based energy conversion in combined heat and power plants. Batteries have a key role in providing short-term electric storage, and the role of V2G batteries was much greater than that of stationary batteries. Synthetic gas from the PtG process and dispatchable bioenergy in the forms of solid, liquid and gaseous fuels provided storage on a longer-term basis. Synthetic gas and biomethane were seen as key energy carriers for seasonal storage.

As the future energy system simulated was such a great departure from the current Finnish energy system, it was important to determine what obstacles or barriers may inhibit its development. However, none of the barriers identified appeared to be unmanageable, and plausible solutions were readily found. General policy suggestions were made in this regard, with caution that policies must achieve a wide range of societal, economic and environmental goals at the same time.

4.6 Publication VI: a sustainable energy system for Åland

Aims

In popular culture, islands are often romanticized as places where local creativity and resources provide novel solutions and charm. They are often seen as having high levels of independence, self-sufficiency and isolation from mainland or continental areas. However, nothing could be further from that vision upon examination of many current island energy systems. Most islands, island nations and regions of archipelago are highly dependent on imported energy carriers such as electricity and fossil fuels, a dependence that may have great impacts on trade balances and local economies. The aim of this publication was to determine the extent to which the autonomous region of Åland can contribute to climate action, enhance its local economy, and develop energy independence through the use of local renewable energy resources. This publication was supported and inspired by a local Åland Smart Energy Platform, the goal of which was to facilitate planning and decision making regarding the future energy system of Åland. The aim was to investigate whether a 100% renewable energy system could be achieved in Åland by 2030. Further, the aim was to compare the costs of several fully functional, reliable and sustainable energy system scenarios for Åland. Next, the roles of Power-to-Gas, Vehicle-to-Grid and other energy storage solutions were examined for each scenario. Lastly, the optimal roles of domestic production of energy carriers and imports were analysed.

Methods

The EnergyPLAN modelling tool was used to construct six test scenarios of the Åland energy system (power, heat and mobility). Various combinations of domestic generation of renewable energy, energy storage solutions, electrified transport and energy carrier trade defined each scenario. In one scenario, electrified transport was extended beyond land vehicles to include the electrification, and subsequent battery use, of marine transport vessels. These test scenarios were compared to three reference scenarios. The first was a scenario for 2014 based on known generation and consumption data for the region. The second was a transition scenario for 2020, which featured high levels of sustainable imports and the introduction of electrified transport. The third was a business as usual scenario that also featured high levels of energy trade with neighbouring regions and moderate electrification of the transport sector. Scenarios were compared in terms of overall costs to determine a least cost option for Åland. In addition, job creation estimates were made for each scenario.

Results

Results show that a reliable, fully sustainable energy system is feasible for Åland by 2030. It was shown that domestic investment in electricity generation from wind power and solar PV could promote sustainable growth, increase local employment, eliminate the need for imported fossil fuels, and replace reliance on energy imports. Each of the test scenarios were able to demonstrate full sustainability through scenario design, and each offered a different vision of how sustainability could be created and maintained for Åland. Annualised costs of each 2030 scenario ranged between 225 and 247 M€/a, a difference of about 10%. At the same time, analysis revealed that the nature of energy system costs were quite different in each scenario. Scenarios with higher amounts of domestic energy conversion naturally had higher capital investment expenditures, but higher overall job creation. Other scenarios that featured higher levels of energy trade had higher fuel and import costs, but lower job creation. As test scenarios and the 2030 BAU scenario (229 M€/a) were so similar in cost, other factors, such as job creation or the social desirability of the scenario, should be used as a basis for further discourse on the future of the Åland energy system by a wide range of local stakeholders.

An important observation was made related to the representation of costs in this study, one that should affect how energy system costs are represented in the future. One of the major capital expenditures seen in this study was the cost of vehicles. However, when vehicle costs were excluded from cost calculations, the ranking of scenarios from lowest to highest annualised costs changed. It was noted that the transition towards the electrification of transport will come at great expense globally. But a question was raised concerning the extent to which this should be considered an energy system cost. On one hand, it seems logical to do so. On another, since we do not normally associate the cost of other energy end-use devices, such as telephones or coffee makers, with the energy system, why should cars or boats be any different? Although it was beyond the scope of this publication to answer such a question, other issues were raised for future consideration. These include the extent to which the costs and benefits of energy services related to batteries and V2G services can or should be included in the cost of the energy system.

The role of energy storage solutions, particularly V2G connections, was notable as a means of increasing overall energy system flexibility and supporting high shares of variable renewable electricity generation. By expanding V2G participation into other forms of transport, such as boats, it was possible to show less need for other storage solutions and reduced offshore wind power capacity. This resulted in lower overall cost. In one scenario, expanded use of V2G resulted in no need for stationary battery capacity at all, and greatly reduced need for seasonal energy storage in the form of PtG.

Results also show that high levels of sustainable energy trade with neighbouring regions can also be part of a sustainable energy solution for Åland. This could involve the trade of electricity through current interconnections with Sweden and mainland Finland, or through the trade of sustainably produced biofuels, which may represent a larger relative expense if they were produced domestically on Åland due its small size and limited bioenergy resources. Among the least cost scenarios for Åland was one that had high amounts of strategic and sustainable trade of electricity and biofuels.

Several unique scenarios were created for the Åland energy system in 2030 that each achieves sustainability in its own manner. The option that the people of Åland choose for themselves through informed discourse will ultimately be the most optimal.

4.7 Publication VII: towards a peer-to-peer society

Aims

The purpose of this research was to more adequately account for the fact that energy systems have implications for society, and to examine the energy system transition from socio-cultural and futures-oriented perspectives in order to supplement the techno-economic focus of the research introduced so far. This work sought to describe the synergy between social change and energy system transitions, and to outline a plausible vision of a new era of renewable energy from a socio-cultural perspective.

Methods

An extensive literature review was conducted to establish the relationship between changes in energy systems and changes in society. Furthermore, connections between energy technology and communications technology were noted. Insights were gathered from a wide range of literature from different fields of study before a sociotechnical, imaginary vision of an energy future was envisioned. The vision is then passed through a more critical notion of postnormality to ensure that it is purposeful and meaningful, and does not result in too much complexity, chaos or contradiction in society.

Results

At the core of the vision developed in this research for 2050 is an emancipatory, peer-to-peer society which is empowered by more decentralised renewable energy. Such societies involve individuals and groups that are self-organised, and often act outside of traditional organisations. At the same time, a more decentralised energy system does not imply a complete lack of establishment or order. Energy systems will always require some kind of public authorities who maintain the functionality and reliability of the system as a whole. Four main assumptions guided the vision: a growing number of energy prosumers will comprise a more distributed energy system, there will be falling average marginal cost of energy, energy will be plentiful, and a sustainable circular economy will be established to ensure material constraints are not violated.

This research finds that a transition towards sustainability is best understood and advanced as the sum of several changes: economic, technological, political, institutional, and socio-cultural. A vision that encompasses each of these elements is more holistic in nature than more common techno-economic energy system scenarios, and enables discussion on the plausibility and desirability of different alternatives. The outcome of this research is that it may serve as a possible guide for future energy system planning from a broader perspective, one that considers a wider range of causes and effects of large-scale change.

5 Discussion

5.1 General discussion of presented results

The Finnish energy system is already in a transition towards greater sustainability, as shown by the currently high level of low carbon power production (80%) (Finnish Energy 2018) and national policies that support further decarbonisation (Ministry of Economic Affairs and Employment of Finland 2017). The changes that have occurred and that will continue to occur in the Finnish energy system go beyond techno-economic issues, and will continue to influence and be influenced by the society as a whole. Such societal effects will be seen within the borders of Finland, throughout the European Union, and around the globe as the main driver of change at the moment, the mitigation of climate change, is a global effort to deal with a global problem. This research has been an effort to situate Finland within the global transition towards sustainability in energy systems. At its core, this dissertation represents a vision and initial feasibility assessment of the components of a sustainable energy system for Finland by 2050. It brings legitimacy to the idea that a 100% renewable energy system is not only possible, but may be a highly competitive option for Finland. This vision has already had an impact on the discourse around the future of energy in Finland (Ministry of Employment and the Economy of Finland 2016), and it is greatly hoped that it will continue to stimulate this evolving societal discussion.

There are several aspects of this vision that merit further discussion and reflection. The first is whether a 100% renewable energy system can be considered a viable option for Finland at all. Through hourly resolved scenario modelling of the Finnish energy system, it appears that a 100% renewable energy system can be achieved for Finland in 2050, and this system can provide the reliability, security, economic competitiveness and sustainability desired by a highly industrial, advanced northern society. The energy resources, conversion technologies and storage solutions needed already exist to ensure a fully functional energy system. This claim is confirmed by several other studies that demonstrate the technical plausibility of 100% renewable energy systems using the EnergyPLAN tool for Europe as a whole, Denmark, Ireland, Macedonia, Mexico, Kenya, Tanzania, China, Hungary, Italy, Latvia, New Zealand, Norway, Serbia, Sweden, and Turkey (Lund 2015). At the same time, modelling limitations already discussed must still be kept in mind, and appropriate caution should always be exercised when comparing conclusions of other national studies. The claim is also reinforced by several global studies indicating the plausibility of 100% RE (Jacobson 2017). A current estimate is that more than 77 peer reviewed articles and almost 50 further reports, conference papers and dissertations feature scenarios for 100% renewable energy, and that much of this research has been conducted in the last decade. Further, the results of this research are in line with other studies of the Finnish energy system, which show that high shares of renewable energy would be possible for Finland (Rinne & Syri 2015; Lund et al. 2015; Salpakari et al. 2016; Pursiheimo et al. 2017; Pilpola & Lund 2018; Mikkola & Lund 2016).

A second main issue concerns the economic competitiveness of a 100% renewable energy system for Finland. A growing body of research is indicating that 100% renewable energy systems can be either lower in cost (Bogdanov & Breyer 2016; Barbosa et al. 2017; Gulagi et al. 2017; Aghahosseini et al. 2016; Bogdanov & Breyer 2015a; Barasa et al. 2016; Ram et al. 2017a), or only marginally higher in cost (Connolly & Mathiesen 2014; Lund & Mathiesen 2009; Mathiesen et al. 2015) than those which do not feature such high shares of RE. At the same time, economic competitiveness of a scenario should be judged by a wider range of criteria, including job creation. This study is in line with several others that propose a positive link between renewable electricity generation and job creation (Vakkilainen et al. 2015; Connolly & Mathiesen 2014; Lund & Mathiesen 2009; Mathiesen et al. 2011; Ferroukhi et al. 2015). Others also suggest similar positive employment effects for renewable energy and storage (Ram et al. 2017a; Ram et al. 2017b). The economic risk inherent in various scenarios should also be considered. Divestment from fossil fuels and nuclear power is already underway to some extent (Baron & Fischer 2015). And, budget and time overruns for nuclear power plants seen in recent years have resulted in higher levels of investor scepticism (Schneider & Froggatt 2014; Koplow 2011; Pearce 2017; Moody’s Investor Service 2008; Sovacool et al. 2014; Gilbert et al. 2017). This may make investment capital more difficult and expensive to raise. The 100% renewable scenarios presented in this research can be viewed as less exposed to such risks.

A third main issue concerns the viability of alternatives to a 100% renewable energy system for Finland. Results of this dissertation have shown that nuclear power and fossil fuel-based carbon capture and storage are not sustainable alternatives for the Finnish energy system. Beyond the economics and contribution to climate change mitigation, there are other sustainability criteria that need to be considered for the future. These include, but are not limited to, exposure to the risk of catastrophe on environmental and personal grounds. A comprehensive discussion of these risks is included in Publication IV, and further developed in a recent report (Ram et al. 2017a). A recent study of the Finnish energy system suggests that while all low-carbon transition options for Finland appear to expose the nation to notable risks, worst-case energy policy risks were associated with over-reliance on nuclear power or bioenergy (Pilpola & Lund 2018). Further, such risks could be mitigated through greater deployment of variable renewable energy, PtX flexibility options, and energy efficiency measures.

High shares of variable renewable energy must be supported by energy storage solutions and other flexibility measures within the energy system. It is argued that such solutions and measures will be necessary once shares of variable renewable energy reach 50% of power demand, and that seasonal storage will be needed upon reaching 80% of power demand (Weitemeyer et al. 2015). However, the results of this dissertation show that such solutions and measures will be context dependent, and that a mix of strategies must be considered that are appropriate for each context. For example, the strategies for the Åland Islands were shown to be quite different than for Finland as a whole. Harnessing the full flexibility that is available in energy systems is a commonly proposed theme in scientific literature concerning the Finnish energy system, especially when the discussion surrounds scenarios with high shares of variable renewable energy (Pilpola & Lund 2018; Lund et al. 2015; Salpakari et al. 2016; Mikkola & Lund 2016; Kiviluoma 2013; Rinne & Syri 2015; Zakeri et al. 2014).

This dissertation shows that V2G participation has the potential to add significant flexibility to future energy systems. In addition, results indicate that this flexibility can be increased by higher V2G participation. However, it has also been observed that higher penetration of V2G may only bring marginal benefits to the Finnish energy system due to limited demands for power system reserves and system flexibility (Kiviluoma 2013). In essence, the greater the number of participants, the lower the individual benefit when the combined value of that flexibility is seen as static. Indeed, the full complexity of V2G participation has yet to be revealed, and there may be notable technical challenges on the horizon, especially in cold environments such as Finland (Lindgren & Lund 2016; Salpakari et al. 2017). It is an emerging concept that is not well understood in practice beyond the potential it represents. There has also been little social discussion on the desirability of V2G participation. It seems reasonable to conclude that some may be eager to have a grid-connected vehicle while others would be very resistant. And there has been no concrete solution yet proposed on how to aggregate and coordinate the large number of vehicles and their owners needed for such large-scale V2G participation. At the same time, it does seem reasonable that such a solution will arise given the potential benefit and value of such flexibility.Results show that PtG technology may contribute to the seasonal balancing requirements of storage on a national level. The observations made in this study are in line with several others that show that PtG technology can bridge the gap between supply and demand in the context of high shares of variable RE (Palzer & Henning 2014; Henning & Palzer 2014; Agora Energiewende 2014; Götz et al. 2016). Furthermore, these technologies may be available to provide base loads of energy for the power, heating and mobility sector when necessary. Further still, PtX technologies (Gas, Liquids, Chemicals) show the promise of profitability in niche applications already in Finland (Breyer et al. 2015), and the role of synthetic hydrocarbon trade may expand internationally beyond the energy sector (Fasihi et al. 2017; Agora Energiewende 2014; Agora Verkehrswende et al. 2018). Research on the Finnish energy system also indicate the potential benefits of PtX solutions to add flexibility to future energy systems (Pilpola & Lund 2018; Lund et al. 2015).

Flexible generation from biomass and gas-based combined heat and power plants should be expected to retain a strong position in the Finnish energy system through the provision of seasonal balancing of energy conversion, and as transport fuels for those aspects of the mobility sector that may not be electrified. Each of the scenarios investigated in this dissertation featured high shares of bioenergy, some of them at much higher levels than are currently seen. There seems little doubt that bioenergy solutions will continue to be explored in Finland to supply power, heat and mobility demands of the future. Bioenergy can provide most of the flexibility offered by dispatchable solid, liquid and gaseous fossil fuels. However, some forms of bioenergy are prone to quality degradation over time, and there is no authoritative inventory of exactly how much sustainable bioenergy can be provided in Finland. For this reason, bioenergy should be considered an essential but limited energy resource for the future. As well, over-reliance on bioenergy could expose the nation to notable risk (Pilpola & Lund 2018). Further, there seems little reason to suggest that investments in gas-based technologies will be stranded in the future. A change that would be anticipated in the future is that fossil natural gas is replaced by biomethane or synthetic natural gas. Gas-based distribution, conversion and storage technologies are mostly unaffected by such a fuel switching. Another possible effect may be a change in the full load hours of gas-based thermal plants.

A more decentralised energy system may be anticipated for the future, and prospects of peer-to-peer exchange of energy should be anticipated. This aspect of the vision proposed represents perhaps the greatest departure from the current energy system, and is not one that is easily related to existing knowledge. On the contrary, peer-to-peer exchange of energy is not possible in Finland, and is not supported by laws that govern the transmission or sale of energy. Energy is a highly regulated commodity that is governed by taxation laws, and exchange at a local level would imply utilisation of privately owned and operated distribution grids, especially for electricity. It is unknown what effects peer-to-peer exchange would have on energy markets, but it seems reasonable to claim that it would be disruptive. At the same time, large-scale decentralisation of large technical systems is not unprecedented. Automobiles are widespread globally, yet they are essentially decentralised forms of energy service providers, in this case mobility. Drivers routinely make their own decisions about energy procurement, energy storage and can exercise their own demand flexibility. Furthermore, current society has demonstrated a willingness to embrace more decentralised, peer-to-peer relationships involving the transfer of news and information. The vision presented in this research seems no more Utopian than what has already been demonstrated in reality. There are barriers to the realisation of the peer-to-peer vision suggested, without question. However, overcoming such barriers may not be as unprecedented as they may seem from the current perspective.

Next, a strong role of energy prosumers can be anticipated in the future Finnish energy system transition towards sustainability. Already in Finland, the majority of solar PV ownership (if not all) can be described as prosumeristic in nature. The largest solar PV plants in Finland are each operated by food companies (Atria – Nurmon Aurinko Oy, and three rooftop plants owned by Ruokakesko Oy) and two large plants run by Helen Oy offer the opportunity for their retail customers to rent panels and produce their own energy (NeroWatt 2017). This prosumer behaviour will be motivated not only by possible personal desires to participate in climate action, but also by the fact that solar PV electricity is already available in many market segments of Finland below the retail price of electricity (Ahola 2017).

Lastly, this dissertation has contributed to the development of energy scenario modelling for Finland and in a larger context. First, Publication II proposes a sustainability hierarchy that can be regarded through the application of checklists for energy system modellers and other stakeholders. These can provide a means to measure how well a broader range of sustainability criteria are adhered to in energy scenarios, thereby enabling modellers to create more sustainable scenarios, and providing other stakeholders a means to judge the quality of energy scenarios. Second, modelling was performed for the integrated Finnish energy system, including the power, heating/cooling and mobility sectors in an hourly resolution using real weather data for an entire year. This allowed a more comprehensive view of how the components of an energy system with high shares of renewable energy would operate in a complementary manner. This also enabled observations of possible seasonal complements between various forms of generation and storage. Third, this work represents a very high level of transparency of the many assumptions used in energy system modelling work. It is hoped that this level of transparency will become more standard practice in the scientific community, and in reports by governmental and non-governmental agencies. Fourth, this work has contributed novelty to the science of energy system modelling by expanding the concept of V2G beyond road vehicles and into watercraft. The electrification of many mobility services in the future may bring still more opportunities for V2G expansion: commercial vehicles such as forklifts, agricultural vehicles, forestry vehicles, etc. These, too, could be incorporated into future modelling work. Finally, this work has acknowledged the many uncertainties and limitations that are inherent with modelling future energy systems, and has attempted to address alternative theories in a meaningful way.

5.2 Policy implications for Finland

Publication V goes into some detail about the kinds of policies that could support a transition towards higher shares of renewable energy in Finland. At the same time, it must be acknowledged that specific policy recommendations for Finland are difficult to make based on the information presented in this dissertation. For this reason, comments will be rather general in nature.

The transition towards sustainability of the Finnish energy system needs political support. It also needs innovation, not only technological, but also innovative policy strategies, smart measures and efficient governance. In order to reach such goals, Finland may need to revise energy transition strategies, measures and governance to include financial incentives for the transition. Thanks to past measures and instruments to promote RE, the costs for RE have been substantially reduced due to technological learning, market diffusion, and improved economies of scale. To increase the share of RE in all sectors, concrete support schemes, financial incentives and market designs are necessary for a full transition. A first step is to define concrete short and long-term goals for change in the energy system. At this point, Finland has already achieved its 2020 goal of achieving at least a 37% RE share of final energy consumption (Eurostat 2017), and is actively creating new goals for the more distant future. According to the Ministry of Economic Affairs and Employment (2017), Finland has the long-term goal of becoming a carbon-neutral society. Further, renewable energy will increase to 50% of final energy consumption by 2030 while increasing energy self-sufficiency, efficiency, use of waste streams, bioenergy, and decentralised energy conversion.

Feed-in tariffs for renewable energy conversion, particularly wind power, are currently being phased out in favour of technology-neutral, competitive tendering processes and investment subsidies. However, it has been argued that tendering schemes may increase uncertainties for investors, reduce competition, favour large utilities and increase financial costs. At the same time, it has been noted that feed-in tariffs have the highest policy effectiveness compared to other instruments (Ragwitz et al. 2012; Kemfert 2017). Indeed, it has been acknowledged that the feed-in tariff system in Finland for wind power "has promoted the development of more cost-effective solutions and provided a strong incentive for project development" (Ministry of Economic Affairs and Employment of Finland 2017). In light of this acknowledgement, the decision to change the support scheme for wind power seems questionable and may slow down a transition towards greater sustainability. Ideally, there should be no support schemes in the long-term that distort energy market dynamics or obstruct such a transition. In the case of nuclear power, support is sometimes more difficult to quantify. However, it should be noted that shifting risks, burdens and costs from the nuclear industry to society as a whole is one way to distort market choices that may otherwise favour more sustainable options (Koplow 2011).

Energy policy in Finland must encourage innovation and development on several fronts. First, distributed energy conversion must be more actively promoted. In this regard, Finland must remove entry barriers for small-scale distributed energy conversion. This can be accomplished by resolving metering issues, easing permitting procedures and simplifying grid connections (Ruggiero et al. 2015). In addition, to promote a peer-to-peer society, a revision of energy-related taxation must occur in Finland. Current legislation and taxation does not support peer-to-peer transfer of energy in any form.

Second, policy must encourage the development of energy storage. An important form of energy storage for the future has been identified in this dissertation, V2G connections, that offers significant potential flexibility to future energy systems. However, this potential cannot be realised without a vibrant electric vehicle industry. This will naturally entail the development of electric vehicle infrastructure in Finland. A near-term policy for Finland could be to join a growing list of countries around the world which will phase out vehicles that use fossil fuels: China, France, the UK, India, and Norway. Alternatively, Finland could establish specific targets for electric vehicle sales, such as in Austria, Denmark, Japan, the Netherlands, Portugal, Korea, Spain and several states of the US (Petroff 2017).

Moreover, energy storage solutions should support longer-term, seasonal balancing. The results of this dissertation suggest that this can be accomplished by PtG technologies and the concept of carbon capture and utilisation (CCU) to some extent. This observation differs from the current policy of the Ministry of Economic Affairs and Employment of Finland, which includes reliance on the development of carbon capture and storage technology. At the same time, the Ministry has noted that CCS technology "has not progressed according to earlier estimates" (Parliamentary Committee on Energy and Climate Issues 2014). Section 2.5 of this dissertation discusses the risks associated with CCS and the relatively lower risks associated with BECCS and CCU in certain circumstances. For these reasons, Ministry policy that suggests that emission goals can only be reached if CCS technological development proceeds (among others) should be reconsidered. Both CCS and CCU should not be considered blanket terms for increased emission mitigation or low risk. Instead, the specifics of a particular scheme must be analysed in detail, and all seem to have notable levels of risk. The least risk seems to be associated with CCU schemes for unavoidable carbon emissions (e.g. from waste incineration or cement making), emissions from sustainably sourced bioenergy, or direct air carbon capture. The extent to which PtG would optimally provide seasonal balancing will depend on levels of reliance on other forms of seasonal balancing (e.g. dispatchable bioenergy-based generation and strategic use of imported/exported energy).

Lastly, it should not be the sole responsibility of the Finnish Government to set policy on energy related matters in Finland. In this regard, private citizens, companies and industries have a great deal to offer the energy system transition to come. Each of these groups can adopt their own policies that promote realistic actions that further the transition towards sustainability. Achieving a prosumer society can be accomplished through individual actions that are the result of sustainable choices. Renewable energy can be generated on the rooftops and on the premises of privately-owned buildings. Electrified mobility and participation in V2G services should be considered. Flexibility can be derived from displacing some demands for energy to times that more closely match the generation from variable renewable energy resources. And energy efficiency can be achieved throughout society through innovation and modernisation. Perhaps most importantly, a deeper, more personal relationship with energy can be fostered. Such an intimacy is not without precedent. Mushrooms or berries from the forest, a fish from a nearby lake, or vegetables grown in one’s own garden are much more personal than those bought from a store. Energy is at the core of many aspects of life in Finland, yet it is rarely personalised. Two tenets can change that: the belief that one can be a smart, efficient, and flexible consumer of sustainable energy, and the belief that one can be a prosumer of sustainable energy.

5.3 Limitations of the current research

The main limitation of this study is that while a vision of possible energy system in 2050 is described in some detail, it does not fully describe the transition between the current state of the Finnish energy system and that end point. Further study is needed that more fully accounts for the technological assets that currently exist in the energy system so that stranded investments can be avoided. The EnergyPLAN modelling tool that was employed in this research is not an investment optimisation model, nor does it provide a transitional pathway over time. Other modelling tools still need to be employed which may validate or challenge the results found here.

As with all energy system modelling, the workings of the future energy system presented in this work have been greatly simplified, and do not reflect the very diverse nature of the components of real energy systems. For example, the EnergyPLAN tool aggregates system components into one homogeneous technology, such as a single power plant that combusts multiple fuels. However, in real life there is a diversity of power plants that range in size, age, fuel, cost and efficiency. These plants also have individual strategies to maximise profitability, and this may be at odds with what may be optimal for the energy system as a whole. It must be borne in mind that energy system modelling is not an attempt to recreate reality, but to simulate a potential energy scenario.

A key design feature of the EnergyPLAN modelling tool places a limitation on the extent to which V2G participation can offer flexibility to the future energy system. Written in its code is an instruction that V2G capacity cannot exceed the stated power plant capacity in the energy system. There were several observations made for the Finland and Åland studies of times when power plants were operating when the V2G connections were not being fully exploited. There was energy in the batteries and the V2G power limitations were not exceeded. This meant that the V2G batteries had more flexibility to offer, but an artificial constraint was placed on them. Such a constraint is unrealistic, and rather unlikely in a more decentralised, peer-to-peer future. This work had sought to harness all the potential flexibility available from the energy system, but the modelling tool constrained this goal to some extent.

The cost assumptions used in this study have been meticulously derived from available scientific literature, but may prove to be either too conservative or too optimistic over time. Since many of the results are based on some level of cost optimisation, it must be acknowledged that different outcomes could be derived with different cost assumptions. This not only relates to the cost of technologies, but could arise from assumptions about the costs of various commodities, fuels or emissions, and from the assumed cost of capital. The main difficulty in performing a proper sensitivity analysis on assumptions is an uncertainty on where to begin and where to end. Energy systems are sensitive to dozens of cost parameters, so the focus in this dissertation was on deriving a set of cost assumptions that were based on scientific literature and consistent with the scenario that was being described.

6 Conclusions

This research takes its place among others that show future energy systems with high shares of renewable energy are economically competitive, reliable and feasible. Further, main findings show that a transition towards greater sustainability of the Finnish energy system can occur, and that a desirable energy future is possible in an era of renewable energy.

The transition of the Finnish energy system was analysed from linguistic, social and techno-economic perspectives. This involved the creation of several alternative scenarios and visions of energy futures that are very different from the current situation. It is hoped that these visions continue to stimulate further evolution of discourse around energy-related issues in Finland in scientific and general contexts. Primarily, it has been shown that a future Finnish energy system with high shares of variable renewable energy can be achieved, and that this kind of system can provide all the reliability and security needed for a highly industrialised society. Further, it has been shown that the general public may take a strong role in the transition to come through participation in distributed generation of sustainable electricity, V2G services, demand response, and increased efficiency. The feasibility of high shares of solar PV at such high northern latitudes has also been shown.

Throughout this research, sustainability in the Finnish energy system has been highly regarded through the application of a broader criteria of sustainability and respect for planetary boundaries. In particular, this research goes well beyond the goal of mitigating climate change, and considers further issues involved in creating a fully sustainable energy system for the nation. The rather contentious issues of nuclear power in Finland is discussed, and a conclusion is drawn that it should not be pursued on the grounds that it may not ensure the long-term sustainability of the energy system and could represent an unreasonable economic burden.

Analysis of the several alternative energy system scenarios suggests that there are no unmanageable economic, technological, operational, institutional or social issues to prevent development of higher shares of renewable energy (up to 100%) in the Finnish energy system. The only key barrier that currently remains appears to be a lack of political and social will. However, this is rather fitting in a democracy, as a wide range of stakeholder voices must be heard on such an important matter as the future of the Finnish energy system.

The importance of energy storage solutions and flexibility measures for sustainable energy systems with high shares of renewable energy appears clear. Electrical storage has been shown to provide the bulk of short-term storage, while the use of bioenergy and synthetic methane can provide longer-term, seasonal storage. Further research into the potential benefits of Power-to-Gas and Power-to-X for non-energy sectors seems warranted. In addition, future work should include examining the Finnish energy system in a greater Nordic or European context. This would necessarily include the large potential flexibility offered by high shares of hydropower in the Nordpool region, particularly Norway. Strengthening transnational interconnections within the region and beyond could be another viable alternative to more sophisticated flexibility measures, albeit one that impacts energy independence. Potential trade-offs between energy affordability, reliability, security and independence should also be considered.

Lastly, this dissertation situates the coming energy transition into a societal context. A socio-cultural vision is offered that may be desirable for some, but not for others. In this regard, it is hoped that debate will continue on the types of energy futures that may be desirable and how to achieve them. Energy systems are large-scale techno-economic systems that must also be viewed as long-term social contracts.

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Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems

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Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems

Michael Child*, Christian Breyer

Lappeenranta University of Technology, Skinnarilankatu 34, 53850, Lappeenranta, Finland

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ABSTRACT

It seems generally accepted that change will occur in global energy systems. There also appears to be consensus on the kinds of changes that may possible for the future, even though there may be disagreement over the exact mix of technologies and policies needed to increase sustainability or mitigate climate change. The terms transition and transformation have both been used to denote the type of change needed in large socio-technical systems. However, the terms have been used both in contradiction of each other and synonymously by different authors. A comprehensive review of both theory and usage in scientific publications was conducted to determine if the terms have been used to denote fundamentally different concepts and if the concept of change is framed differently by usage so as to affect understanding. Despite two camps being readily identifiable, it was concluded that the terms generally refer to the same fundamental concept. At the same time, framing of the concept can be viewed as somewhat different, resulting in a potential for confusion on the part of the reader that may detract from achieving the outcome of change. It is suggested that change to physical forms and systems be denoted as transformations, and that changes to large socio-technical systems be denoted as transitions when the focus is on a higher order of change that highlights the ways that society motivates, facilitates, and benefits from change.

1. Introduction

Global energy systems constantly evolve in response to a myriad of drivers. At the moment, and likely well into the future, the key drivers appear to be mitigating climate change, strengthening energy security, ensuring economic competitiveness, providing social justice, reducing energy poverty, and stimulating technological innovation. With such strong forces of change, and the possibility of yet unforeseen disruptive technological advances or other game changers, it seems obvious that energy systems of the future may be very different from those today. However, the nature, speed and degree of change remains elusive, at least in its description and denotation. At the heart of the matter appears to be whether the change should be referred to as a transition, or a transformation. The expressions *energy system transition* and *energy system transformation* are commonly used to denote the change, but there appears to be some confusion over the actual meanings of these expressions.

A cursory view of popular definitions of the words denoting change in energy systems is shown in Table 1. From these definitions, it appears that the word *transition* infers slightly more focus on the process or period of change, whereas *transformation* infers more focus on the magnitude, significance, or result of the change. This difference is seen in the following abstract, which uses both expressions (underlined).

> ***The paper highlights the energy dilemma in China's modernization process. It explores the technological and policy options for the transition to a sustainable energy system in China with Tsinghua University's Low Carbon Energy Model (LCEM). China has already taken intensive efforts to promote research, development, demonstration and commercialization of sustainable energy technologies over the past five year. The policy actions cover binding energy conservation and environmental pollution control targets, economic incentives for sustainable energy, and public R & D supports. In order to achieve the sustainable energy system transformation eventually, however, China needs to take further actions such as strengthening R & D of radically innovative sustainable energy technologies and systems such as poly-generation, enhancing the domestic manufacturing capacity of sustainable energy technologies and systems, creating stronger economic incentives for research, development, demonstration and commercialization of sustainable energy technologies, and playing a leading role in interna-***

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* Corresponding author.
E-mail address: Michael.Child@lut.fi (M. Child).

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Table 1
Definitions from common online dictionaries.

Dictionary	Transition	Transformation
Oxford University Press	***the process or a period of changing from one state or condition to another***	***a marked change in form, nature, or appearance***
Cambridge University Press	***a change from one form or type to another, or the process by which this happens***	***a complete change in the appearance or character of something or someone, especially so that thing or person is improved***
Merriam-Webster (2015)	***a change from one state or condition to another***	***a complete or major change in someone's or something's appearance, form, etc.***
Wiktionary	***the process of change from one form, state, style or place to another***	***a marked change in appearance or character, especially one for the better***

tional technology collaborations (Chai and Zhang, 2010).

Here the word *transition* is used close to the word *process*. By contrast, *transformation* is used later in the paragraph to denote what China ultimately strives *to achieve* after the process is over. However, definitions of words are only part of the analysis. Further insights should be gained from both the frequency of use and the communicative intention of the people using such expressions. The frequency of each expression was examined by seeing the number of hits they would receive from common academic and general search engines (Table 2).

It appears that in both academic and general usage, *energy system transformation* appears somewhat more frequently as a phrase, even when describing the same concept of change. This begs the question of what may be the underlying illocutionary force, or intention of producing one versus the other in speech or in writing. For example, a simple expression such as *I am cold* can have different illocutionary forces depending on the context. It could be a simple statement of fact, an answer to a question, or a directive to close a window. Similarly, two expressions such as *I am cold* and *Please close the window* could have the exact same illocutionary force (a request to close a window) yet quite different morphological forms.

Fairclough and Wodak (1997) discuss how linguistic factors (in addition to semiotic and interdiscursive features) can influence and be influenced by society. Words, grammar, organizational structures, etc. can shape societal values, attitudes and behaviours by framing issues and problems in a certain respect so as to highlight various levels of problem recognition, the degree of change needed, underlying actions needed and obstacles along the path of change. These linguistic factors represent a discourse, or “a shared way of apprehending the world”. Further, different discourses can shape the acceptability of various alternatives of change, such as promoting one alternative over another. In extreme cases, not promoting one or more alternatives can be the result of hegemonic power in society. This is typical of systems that either do not tolerate or do not need change, especially radical change. Importantly, Fairclough and Wodak (1997) argue that words or expressions that are used to convey concepts, representations or future realities should not always be taken at face value as they “are themselves elements of discourses which are associated with particular strategies for change”.

Table 2
Frequency of use of expressions. The search was performed in June, 2015.

Expression	SCOPUS	ScienceDirect	Google Scholar	Google
Energy system transition	34	98	306	6920
Energy system transformation	27	108	915	10200

In particular, Fairclough and Wodak (1997) commented on the use of the words transition and transformation in the context of the climate change agenda. In this work, a transition was defined as “passage from a well-known defined point of departure to a unitary and well-defined destination”. In terms of efforts related to social change, using the word transition was “difficult to reconcile with the complexity and diversity of the processes which are actually taking place”. Fairclough and Wodak (1997) then cite other authors (Stark and Bruszt, 1998) who prefer *transformation* in such cases.

Insights into the concept of change can also be gathered from the field of Natural Science, particularly from the seminal writings of Stephen J. Gould (Eldredge and Gould, 1972; Gould, 1977), who argued that evolutionary change in species did not happen through slow, gradual change (phyletic gradualism), but by discontinuous breaks and jumps followed by long periods of stability (punctuated equilibria). Accordingly, phyletic gradualism was described as process of slow, steady, directional transformation from one morphological form to another. On the other hand, punctuated equilibria were characterized as long periods of stability in the fossil record broken sharply by rapid, divergent, discontinuous, and abrupt transitions (Gould, 1977).

In the field of Futures Research, the word *transformation* has been reserved for a change in human society that is quite unique. As one of the “four generic futures” that govern future scenario development (the others are continued growth, collapse, and discipline), a transformation occurs through the power of new or innovative niche technology that anticipates “a change from its present form into a new ‘posthuman’ form, on an entirely artificial Earth”, thereby creating a so-called “dream society” (Dator, 2009). In this sense, transformational scenarios are not only much less likely, but often viewed as being highly radical in their nature. They are inherently different from, and perhaps opposite to, business as usual. As such, the end state appears fundamentally different from the starting state.

From the field of economics, seminal work by Polanyi (1944) outlined the rise of the current market economy, which he dubbed *The Great Transformation*. Polanyi describes how the evolution of modern nation states forced changes in both social structures and human nature which in turn created favourable conditions for capitalism. Implied in this account is that relationships among societal actors and the norms they follow underwent major reorganization to produce a new social order and way of life. In this case, social-based regulatory systems were replaced by self-regulating markets. In this new world order, nothing new or innovative was created, as market-based economic activities were already in place for commodities that were either rare or traded over long distances, nor was anything destroyed outright – social-based regulation still exists in some areas. The change involved a redirection of the system whereby the new system evolved out of the old.

Recent work related to sustainable development and mitigation of climate change shows confusion in naming what is happening to modern energy systems. On the one hand, there are those who claim a Great Transition is needed (Boulding, 1964; Daily and Walker, 2000; Jorgenson, 1986; Lieberthal and Lieberthal, 2003; Raskin et al., 2002). Common within each is how *transition* is defined. In general, it is seen as a paradigm shift that "would challenge both the viability and desirability of conventional values, economic structures and social arrangements" (Lieberthal and Lieberthal, 2003). There also appears to be mention of some kind of evolution to a higher or better state of being. Change is seen as structural and not at all incremental, representing a discontinuity in historical trajectory that may appear either idealistic or improbable from current perspectives. In fact, these recent works describe change in a very similar way to Polanyi (1944) albeit with a different outcome. In this case, the self-regulating markets would be constrained by social, cultural or environmental goals. However, the magnitude and mechanisms of change appear similar.

In the context of the dynamics of change in socio-technical systems, researchers have defined three separate typologies of change processes involving a multi-level perspective (Geels, 2002, 2007, Geels and Kemp, 2007). The macro elements of a socio-technical system (or landscape) involve the exogenous environment that encompasses the system. These elements are rather rigid by nature and represent strong tendencies of a system, such as cultural icons, forms of government, environmental values, geographic arrangements of cities, or large-scale infrastructures (e.g. electricity systems, railroads, highway systems, or telephone networks). However, such elements are susceptible to occasional change due to significant events such as major shifts in public opinion, challenges of previously held assumptions of how the world works, scientific discovery, or influence from outside the system (e.g. war, pestilence, poverty, drought, disaster, embargo, etc.). The meso elements comprise the socio-technical regime, and include dominant technologies, actors and social groups (engineers, corporations, scientists, consumers, policy-makers, special-interest groups, etc.), and the rules that guide perceptions and activities. These rules can be formal (standards, laws, targets, regulations, etc.), normative (beliefs, behavioural norms, identities, roles, etc.), or cognitive (guiding principles, corporate values, rules of thumb, agendas, etc.) (Geels, 2007). The meso social agents and norms "maintain and refine the elements" of the technical system (Geels, 2007). The micro level is comprised of an abundance of relatively independent niche actors, technological innovations, radical novelties, or fringe activities (ibid.). This micro level is often enabled or subsidized by the mainstream regime actors as pilot or demonstration projects, but can often be the result of independent invention or development.

The three change processes identified were reproduction, transition, and transformation (Geels, 2002). Reproduction involves incremental, cumulative, almost invisible changes to the socio-technical regime without any fundamental change in the overall socio-technical landscape. In this case, significant innovation is rare or has little impact. The system in question is in a state of dynamic stability. It may also be possible that a lack of change is the result of strong vested interests that exercise hegemonic power, such as monopolies.

A transformation occurs when "changes at the landscape level create pressure on the regime, leading to re-orientation of the direction of innovative activities" (Geels and Kemp, 2007). The changes in the socio-technical landscape involve challenges of "previously held assumptions and place new issues on the problem agenda". In such a change dynamic, incumbent actors survive through negotiation, struggle or shifting alliances, usually after rejecting the need for transformation for as long as possible. Often, transformation is initiated by the identification of a previously unknown or unaccounted negative externality which causes the initial challenge to the *status quo*. The result is "a new system may grow out of the old one, through cumulative adjustments in a new direction". As an example, the authors offer the transformation of waste management activities in the Netherlands from one that was based on uncontrolled landfilling to one that involves recycling, incineration, reuse and controlled landfilling (Geels and Kemp, 2007). In other work, Geels argues that transformation is the most likely process of change in Large Technical Systems that tend to have relatively high momentum "as result of stabilizing connections between technology and society" (Geels, 2007), such as energy systems.

Lastly, a transition occurs when new, innovative changes break through into the mainstream socio-technical landscape so as to change both the trajectory of the landscape and lead to the creative destruction of some or all of the actors within the socio-technical regime. In this case, developments in the landscape cause a need for a reaction by the regime actors, who are subsequently unable to respond well enough. Thereby, a window of opportunity is open for one or more innovations that are ultimately accepted by a new social order. The example given by the authors is of the transition from transportation by horse and carriage to a system based on cars. In this case, the system does not find a new direction, but a completely new system trajectory is established (Geels and Kemp, 2007). A more modern example may be the transition from fixed-line to mobile telephone systems.

In a similar vein, Roggema et al. (2012) define the same three terms. Firstly, incremental change is defined as "a slow process, which modifies the landscape only slightly". Second, a transition is "a gradual, continuous process of societal change, changing the character of society (or a complex part) structurally" in response to a crisis or chaos that shifts a system from one form to another (weaker to stronger) and establishes a new state of stability. Thirdly, a transformation is "the capacity to transform the stability landscape itself in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable". In this regard, transformation is seen as "disconnected processes of growth".

Later, Geels and Schot (2007), Verbong and Geels (2010), and Geels (2012) redefined and reclassified the terms they used based on the timing and nature of different multi-level interactions. As such, a transition was redefined as a change "from one sociotechnical regime to another". Moreover, different transition pathways were identified: transformation, reconfiguration, technological substitution, and de-alignment/re-alignment. So, a transformation became a typology of transition rather than a separate change process. No change was made to the earlier definition of transformation, but a transition became a higher order, more general change process. The process of reproduction remained as a non-change process that reflected "gradual adjustment and reorientation of existing regimes".

In German, there is a single named concept – *Energiewende* – that has a universally understood meaning which has served as a rallying cry for change in energy systems. The concept was introduced by the Öko-Institut (Krause et al., 1980), an ecologically oriented research institute, which applied the ground-breaking work of Lovins (1977) on the final energy target of a fully renewable energy based system to the German context. Although precise translations can be debated, *Wende* denotes several dimensions, such as a change, turning point, switch-over, rebound, reversal, tacking, and even revolution, finally suggesting a new direction or trajectory. However, the term is commonly used for the kind of peaceful revolution that has resulted in such dramatic socio-political change as the destruction of the Berlin Wall and the reunification of the country. Whether one is an opponent or proponent of the changes, methods or goals proposed, there is at least a broad understanding of what the concept means, which allows for easier discourse around the concept. The German word, *Energiewende*, began appearing in leading English language media in April, 2011, and several translations have been offered (Hockenos, 2012). Such a concept is needed in English to reflect the magnitude and importance of change, but exactly which it should be, *transition* or *transformation*, is currently unclear.

Schmid et al. (2017) found that there may indeed be conflicting visions related to representations of a 'desirable' future energy system and the means by which to realize it. Further, they suggest that different mental models, worldviews, narratives, or storylines can frame competing concepts of a future energy system by "simplifying complex situations into chains of events and contain elements such as a protagonist and a challenge". Essentially, an internal representation of a concept provides an individual or group with a shared way "to interpret the environment, to reason and to make decisions". Their findings conclude that open acknowledgement of worldviews that underlie different visions of change "is the elephant in the room of energy policy debates". Such acknowledgement may be one method of overcoming future political stalemate, and conflict between challenger actors and energy system incumbents. One such worldview is a focus on the technologies and economic elements that comprise future energy systems. The other is a complementary framework that conceptualizes change in energy systems also as a collection of broader social endeavors.

Chappin and Ligtvoet (2014) examined the use of *transition* and *transformation*, finding that the choice of one term or another was determined mainly by networks and clusters of "directly and indirectly cooperating authors" who "repeatedly write together and cite each other's work". The research indicated that the larger cluster around the usage of *transition* was more likely related to existing networks, (e.g. the Sustainability Transition Research Network), geography (i.e., around the Netherlands), or co-authors than the product of two distinct schools of thought related to the dynamics of change. At the same time, there was a suggestion that, in the context of energy systems, *transition* authors tend to highlight societal contributions and impacts, while *transformation* authors tend to take "a more descriptive stance". However, the study cautions that this difference "does not necessarily imply less impact". Chappin and Ligtvoet (2014) also caution that their bibliometric analysis should be enriched by more systematic and detailed explorations of the terms. To this end, the study clearly indicated what different terms were being used by different groups, and the influence of clusters of existing networks, but took little accounting of what various authors intended to mean. Nor did this study examine the specific context of change in energy systems. Only by doing so can one determine if fundamentally different discourses exist that frame the concept of change needed in energy systems.

Therefore, the purpose of this work is to review how each word is being used in relation to changes to energy systems in scientific literature and to attempt to devise a recommendation for future use. To do this, a systematic review of the usage of each word in recent journal publications was performed in addition to consideration of how the authors intended the word to be understood (either directly or indirectly). Accordingly, two main questions guided this work. Firstly, do the words *transition* and *transformation* represent fundamentally different concepts in the scientific literature? And secondly, are the expressions used in such a way as to frame the concept of change in a different way, so as to highlight various levels of problem recognition, the degree of change needed, underlying actions needed and obstacles along the path of change? The answers to these questions are then followed by general conclusions on findings and recommendations for future use of the terms.

2. Methodology

In the first part of this analysis, scientific publications were chosen that dealt with the topics of energy system transitions and energy system transformations. Journal articles were selected during the first week of June, 2015 in the following manner. Using ScienceDirect, an advanced search was performed for scientific publications that contained both the expressions "energy system transition" and "energy system transformation" within all search fields. Articles were rejected if one of the search expressions was found only in the references. The final list included 12 publications. Next, an advanced search was made using just the expression "energy system transition" within the abstract, title or keywords. If the publication was found in the previous category, it was not included. One publication was not available for free to the Lappeenranta University of Technology library and was rejected. Articles were also rejected if the expression only occurred in the references section of the publication and not specifically used in the text. The final total for this category was 16 publications. Using the same criteria for the expression "energy system transformation", 13 publications were selected. All publications used in this study are listed in Table 4.

Next, a series of questions was devised that explore various aspects of meaning related to the words *transition* and *transformation*. These questions were mostly based on characteristics gleaned from the Introduction above. Table 3 introduces each question and the sub-questions used to determine answers. Each question was answered after the careful reading of the scientific publications. Furthermore, answers to questions were based on explicit use of words or expressions in the Title or Abstract of each article. It was assumed that language use in these sections of the publications would be representative of the text as a whole. Moreover, these sections were deemed sufficient linguistic context to acquire the general intention of meaning or description necessary for further analysis. In two cases when an Abstract was not available (Huberty and Zysman, 2010; van Vuuren et al., 2012), the first paragraph of the introduction was used. The keywords for each article were also compiled to determine if the intended topics of the articles differed in nature. Results were then compiled, tabulated and analyzed. In many cases, answers to key questions were not easily discerned. This explains the lack of reporting for some individual articles in Tables A1–A3. Results were then analyzed in terms of a variety of semantic features that may be present, especially any that elicit positive or negative connotations.

Table 3
Key questions and sub-questions applied to each article.

Key question	Sub-questions
What words are used to define or describe change?	What is the speed or time frame? How forced or natural is the change? Is it described as radical or fundamental? How serious is the problem?
How will change proceed?	Is it continuous or discontinuous? Is it gradual or punctuated? How desirable or undesirable is it? What specific words are used to denote change? What degree of effort is necessary? What is the consequence of inaction?
What are the barriers to change?	How are barriers denoted? What is the source of barriers?
Who or what are the agents or facilitators of change?	What people, policies or institutions are involved in enabling change? What spheres of life do the agents come from (social, environmental, economic, or technological)? What is the motivation of change?
What is the outcome of change?	Is there a well-defined goal or target? Is the outcome restricted over time or space? Are there mention of alternative outcomes?

Table 4
List of publications used in this review.

Transition articles	Transition/transformation articles	Transformation articles
Lachman, 2014	Demski et al., 2015	Huberty and Zysman, 2010
Miller et al., 2015	Chai and Zhang, 2010	Jacobsson and Lauber, 2006
Schubert et al., 2015	Muench et al., 2014	Ydersbond, 2014
Diaz-Rainey and Tzavara, 2012	Eom et al., 2015	Marcucci and Fragkos, 2015
Peter Andreasen and Sovacool, 2014	Butler et al., 2015	Chowdhury et al., 2014
Parag and Janda, 2014	Bertram et al., 2015	Bădileanu, 2014
Zhang et al., 2010	Pfenninger and Keirstead, 2015	Sano et al., 2015
Momirlan and Veziroglu, 2005	Winskel et al., 2014	Gambhir et al., 2013
Morlet and Keirstead, 2013	Nilsson et al., 2011	Delina, 2012
Hall and Foxon, 2014	Eyre and Baruah, 2015	Capros et al., 2014
Rutter and Keirstead, 2012	Yuan et al., 2012	van Vuuren et al., 2012
McDowall, 2012	Späth and Rohracher, 2010	Pregger et al., 2013
Hong et al., 2013a		Stenzel and Frenzel, 2008
Hong et al., 2013b		
Foxon et al., 2013		
Hugh et al., 2007		

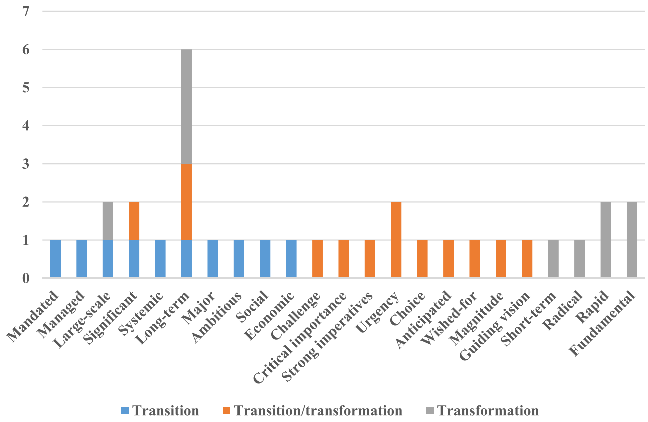

Fig. 1. Frequency of selected words used to describe change in different article types.

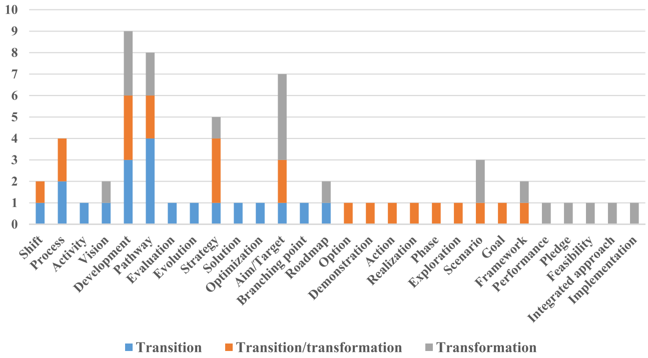

Fig. 2. Frequency of selected words used to describe how change proceeds in different article types.

3. Results

Table A1 (Appendix A) shows the results related to the general representation of change. A smaller collection of selected words used to define or describe change and their frequency are shown as a summary in Fig. 1. In each of the article types, change appears to be denoted as a large-scale and long-term process. However, transformation and transition/transformation articles may also focus on the short term and highlight a faster speed at which change should take place. In addition, transformation articles show a tendency to highlight the fundamental or systematic nature

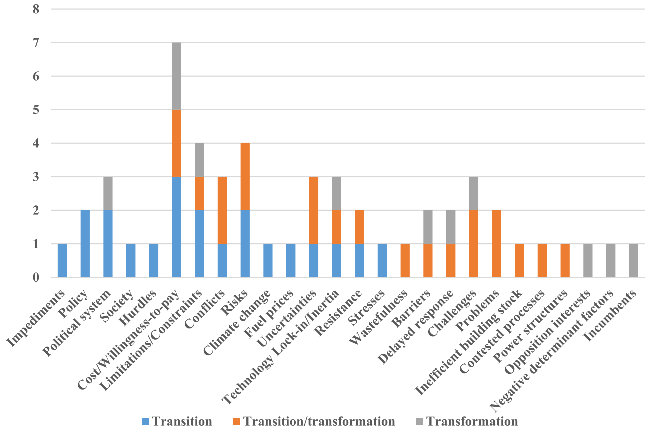

Fig. 3. Frequency of selected words used to describe barriers to change in different article types.

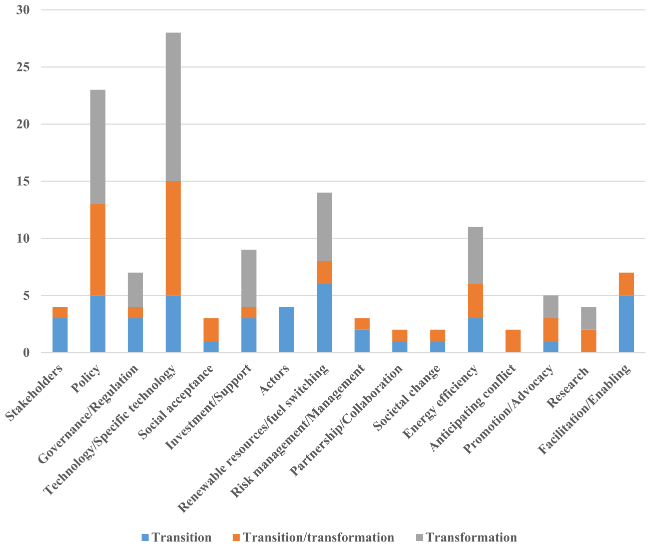

Fig. 4. Frequency of selected words used to denote agents of change in different article types.

of change. Alternatively, transition and transition/transformation articles tend to show the social or emotional aspects of change by highlighting the significance, urgency, anticipation or ambitiousness of change. At the same time, there are exceptions to this general trend with transition articles, with one article referring to change as something that is mandated and managed. One could, however, infer an orderly social, economic or political control of change from the use of such terms.

Table A2 (Appendix A) show the results related to the key question of how change is described as proceeding. A smaller collection of selected words used to describe change how change will proceed and their frequency are shown as a summary in Fig. 2. In very many cases, change is described as a result of developments or processes which proceed along pathways toward targets. Quite often, there appears mention of roadmaps, frameworks or strategies. In this regard, change appears to be orderly and the result of intentional, premeditated actions that are the result of informed choices or options. As such, there appears to be no significant difference between the different article types.

Table A3 (Appendix A) shows results related to the denotation of barriers in different article types. A smaller collection of selected words used to denote barriers and their frequency are shown as a summary in Fig. 3. In general, word choice in transformation articles appear to be more moderate, reflecting a neutral impression of the barrier. There is reluctance, opposition interests, challenges, limitations or effects. By extension, one could infer that the barrier itself is more manageable, is easier to overcome, or can somehow be avoided. In contrast, transition and transition/transformation articles again show rather negative emotional connotations by utilizing words such as conflict, risk, cost, resistance, power, or stress. In only one case (Capros et al., 2014) did a

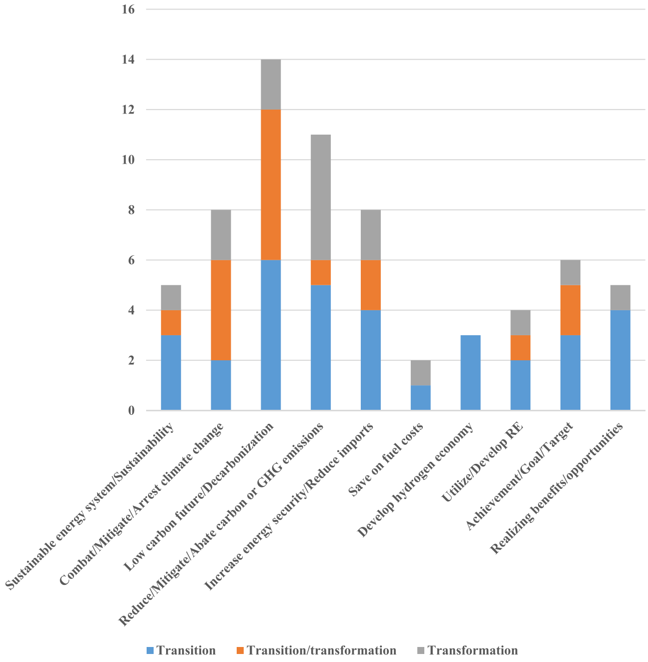

Fig. 5. Frequency of selected words used to denote the outcome of change in different article types.

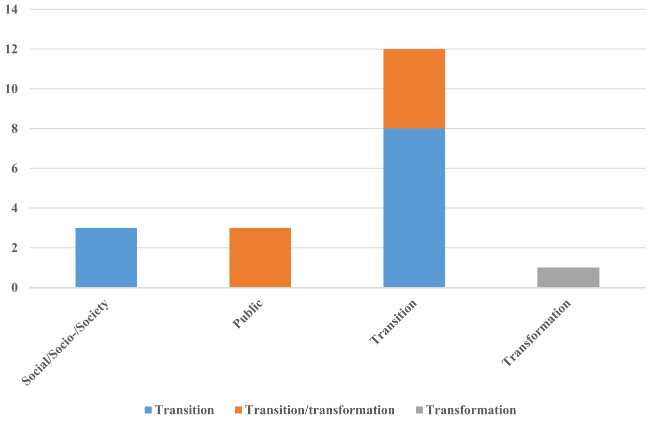

Fig. 6. Frequency of selected words used as keywords in different article types.

transformation article show strong emotional connotations, with the expression “significant adverse effects”.

Table A4 (Appendix A) shows results related to the agents of change. A smaller collection of selected words used to denote agents of change and their frequency are shown as a summary in Fig. 4. In most cases, such agents are denoted as technologies (both specific and general), policies, measures, efforts or incentives. In many cases, energy efficiency is named directly as a facilitator of change. In a great majority of instances, governance and institutional support are highlighted. In only one way do the different article types appear to differ to some extent. Transition article may show a tendency to also denote agents in human terms, such as actors, stakeholders, and partners. This slightly increased humanization appears to go hand in hand with the trend to show the social aspects of change as seen in the previous Tables A1 and A2.

Table A5 (Appendix A) shows results related to the outcome of change. A smaller collection of selected words used to denote the outcomes of change and their frequency are shown as a summary in Fig. 5. While some articles show very concise outcomes related to the diffusion of specific technologies or achievements in specific regions or countries, in general outcomes are rather consistent for each of the article types. These outcomes tend to involve creating a sustainable energy system, mitigating climate change, reducing or eliminating carbon emissions, and increasing the utilization of renewable energy. To some extent, however, transition articles show a wider range of outcomes, many of which fall into the social realm, such as reduction of import dependencies, a cleaner planet, enhanced energy security, lower fuel prices and meeting energy demands. This is combined with greater mention of general outcomes, such as goals, targets, benefits and opportunities.

Table A6 (Appendix A) shows results related to key words used. A smaller collection of selected words used as keywords and their frequency are shown as a summary in Fig. 6. In general, there is a wide range of terms used as key words, suggesting that authors are making some attempts at individuality. As expected, energy systems are often specifically mentioned as key words, as are agents of change and outcomes. Technology is often named, as are institutions and policies. However, to a degree in transition articles, there is also mention of words or phrases related to social life. This also happens to a lesser degree in transition/transformation articles. This is seen in such key words as socio-technical systems, socio-energy system, society, social acceptance, willingness-to-pay, green consumerism, critical stakeholder analysis, actors, public policy, public acceptability, and public perception. There is no such mention of public or social terms in the key words of transformation articles.

In summary, there appears to be a slight difference in how the different article types use language to denote change in energy systems. In transition articles, and to some extent transition/transformation articles, there appears to be more focus on the social elements of change and the outcomes of change from a social perspective. At the same time, there are still great consistencies with how change is represented independent of the article type, as each involves denotations of the technologies, resources, policies and pathways of change as well as consistency in representing the outcomes of change.

4. Discussion

It appears relatively easy to describe global energy systems as historically being in a state of reproduction. Like most large technical systems, energy systems are rather resistant to change due to “webs of interdependent relationships…and patterns of culture, norms and ideology” (Geels, 2007). Innovation has been rather incremental and has involved some new technologies, increases in efficiencies, lower costs, or conservation measures. However, the landscape has been dominated by nuclear and fossil fuels. Currently, the landscape has been effected by new scientific evidence concerning climate change and worries of nuclear disaster in a post-Fukushima world that have led to changes in the regime (needs for mitigation). Almost by definition (Geels, 2002), this has involved some period of denial by the regime that a problem actually existed or that there was a need for mitigation. A change is occurring whereby former niche actors and technologies (solar photovoltaics and wind power, in particular) are becoming a greater part of the mainstream technological regime. If current trends continue, a new system can grow out of the old, as major actors within the regime have, for the most part, been the ones to enable the niche technologies. According to definitions supplied by Geels and colleagues (Geels, 2002, 2007; Geels and Kemp, 2007), this change should be denoted as a transformation.

However, this technological transformation is only part of a wider process of change that involves a wider range of social, economic and environmental stakeholders and entities. In addition, new niche innovations could emerge that are not only unrelated to the current regime and landscape, but that could change both dramatically. The door must still be open for other transition pathways as outlined by Geels and Schot (2007). This may be especially true if the current regime became incapable of solving the problem of climate change. For example, the impacts of climate change could be so great at some time in the future so as to go beyond a tipping point and to lead to fuel shortages, some kind of natural disaster (melting ice sheets, changes in ocean currents, etc.) or other cataclysm (increased war, poverty, drought, energy injustice, terrorism, nuclear accident, etc.) which could force a transition to a system that has a completely different trajectory and could be made up of technologies that have yet to be invented. Alternatively, some new technology or energy source could enter the landscape (however improbably from our current perspective) that fundamentally alters the course of life (e.g. cold fusion, new super capacitors, warp drive).

There appears to be only slight evidence to suggest that *transition* and *transformation* authors are writing about fundamentally different concepts. Firstly, no evidence has been found that there is any intentional promotion of different alternatives, and different usages of these terms should not be seen as exercising either tolerance of or resistance to change. Secondly, there appears to be no significant difference in the representation of the complexity of change, the starting or end points of change, or the means by which change occurs. In this regard, the agents and outcomes of change show remarkable similarity throughout article types even though transition articles tend to denote a wider range of social agents. However, there does appear to be differences related to the representation of the speed or continuity of change. While there is general agreement that changes to energy system occur over the long-term, some articles advocate specific changes that may need to occur quickly over the short-term. Moreover, some transformation articles show more focus on the rapid speed of change necessary.

Furthermore, it appears that the concept of change is being framed differently in the transition and transformation article types, and this framing may affect reader understanding of the notion of change to some extent. This difference primarily is seen by the extent to which transition and transformation articles frame the concept as social. Firstly, the problem that motivates the need for change is represented differently. Transition articles tend to highlight a social problem that needs social actors to achieve social goals. Secondly, the underlying actions needed to achieve change are denoted in different ways. While there is high similarity between article types in denoting technologies, energy efficiency, government policies and institutions as agents of change, transition articles additionally highlight human agents to some extent. Thirdly, the obstacles to achieving change are not the same between the article types. Transition articles show a trend of highlighting emotional barriers, and perhaps give the impression that overcoming barriers will be demanding physically and emotionally. In contrast, transformation articles tend to use neutral terms or highlight the manageability of the barriers. Lastly, there are some differences in the way the degree of change necessary is represented in transition and transformation articles. In a few cases, transformation articles denote the nature of change as being radical and some suggest a “fundamental” difference between starting and end points. However, as stated previously, it remains unclear whether this difference in the framing of the concept will affect overall acceptance of or resistance to change. Instead, it appears that the transition articles just go further than the transformation articles in portraying the social aspects of problems, actions and outcomes.

Therefore, it appears that transition articles have more comprehensively described a new direction that pertains to both the socio-technical landscape and the socio-political-technical regime that maintains it. There appears to be little doubt that change to this complex, large socio-technical system is occurring. However, societal drivers seem to be more in the forefront of transition articles. A key element of a transition may be that some aspect of the old system remains relevant enough that the new system retains some aspect of fundamental similarity to the old. This relevance can be quantified by structure, style, aesthetics, or even as how influential the old system was on the new in terms of actors, rules or artefacts. It seems reasonable to assume that societies can experience a transition and remain relevant, but much less reasonable that they can undergo a fundamental transformation (literally a change of form) the same way a purely technical system can. Technologies can easily become irrelevant, societies cannot.

Interestingly, a provocative description of the difference between *transition* and *transformation* is offered from the realm of gender reassignment. One writer (Walsh) makes a concise and strict distinction between the two terms that has some relevance.

> ***While transition represents the physical manifestations that come with a change in gender expression, hormone replacement therapy, and sexual reassignment surgery, transformation is the*** **process of acknowledging and coming to terms with one's true gender in order to find emotional, spiritual, and relationship wholeness.**

What has been discovered in this study, however, would seem to suggest the exact opposite. Specifically, current scientific journal articles more often denote transformations as the physical manifestations of change while transition articles highlight a higher order of change from a multi-level perspective, one that includes the ways that society motivates, facilitates, and benefits from change. It would follow then that society is the ultimate enabler in a transition, while physical morphologies are more the focus of change in a transformation. It also follows that a transformation can be an integral part of a transition. If the logic is followed that a society can make a transition to a new way of life, then some aspect of society, especially a biological or technical entity, can be transformed as an element of that transition.

This interpretation allows the notions of *transition* and *transformation* to have quantifiably separate meanings while also allowing the notion of transformation to be an element of transition or to be completely independent. It also allows for several other usages of the words from the variety of disciplines discussed in the introduction to be maintained. Moreover, synonymous use of the terms can be permissible as the transformation of some entity can in theory be used as a synecdoche for the transition of some higher order entity. In essence, the part represents the whole. This is similar to how the expression, *I bought some new wheels*, can function as a synecdoche for the expression, *I bought a new car*.

There may also be caution in using the word transformation, and shortening the expression to *energy transformation* as is typically done with *energy transition*. This is because the expression *energy transformation* already has an established meaning that may cause confusion. Energy comes in several forms, such as mechanical, chemical, gravitational, electrical, or thermal. When one form is converted into another it is denoted as an energy transformation in the field of engineering (among others). The gravitational potential energy of water behind a dam is transformed into mechanical energy when the water is allowed to fall through a turbine. In turn, the mechanical energy of the turbine is transformed into electrical energy by means of a generator. Therefore, some care must be taken to ensure that the expressions are not confused in scientific writing.

For these reasons, it would be recommended to limit the use of the term *transformation* to the description of the physical manifestations of change, indeed, to something that actually has a physical form. Alternatively, when describing change from a higher order perspective, one that includes the complexities of societal motivation, facilitation, cost and benefit, the term *transition* would be preferable. Given that large technical systems, such as energy systems, are intricately intertwined with many facets of social life, and that change cannot occur in one sphere without the other, it would therefore be recommended that the term *energy system transition* be used more consistently in the scientific literature as well as in a wider range of media.

5. Conclusion and policy implications

In the end, there currently seems to be an overlapping of the semantic representations and usage of the terms *transition* and *transformation*. In some cases, it also appears that the words are being used interchangeably. In other cases, authors go through great pains to carefully define one term or both. In other cases still, the definition and usage of one author appears to be in complete contradiction with that of another. The consequences of this linguistic confusion may have rather serious consequences in the context of change that is expected to occur in global energy systems in the years to come. First, for authors of scientific manuscripts as well as their editors, this issue can represent an unnecessary (however interesting) burden. Second, confusion on the part of readers may result in a subconscious resistance to the overall message. Misnaming of a concept, especially such an important one, can lead to a diversion of attention away from the importance of the change itself. In the context of creating a more sustainable society and mitigating the very real effects of climate change, such a diversion seems risky. What is most important is that scientific writers and editors have some level of mutual understanding of how these terms can be used and make their choices clear and unambiguous.

Acknowledgements

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Appendix A

See Tables A1–A6.

Table A1
Answer to first key question by source and article type. What words are used to define or describe change?

Transition articles		Transition/Transformation articles		Transformation articles	
(Lachman, 2014)	Mandated Managed	(Muench et al., 2014)	Significant Challenge	(Huberty and Zysman, 2010)	Large-scale
(Miller et al., 2015)	Large-scale Significant	(Eom et al., 2015)	Long-term Critical importance Rapid shift	(Jacobsson and Lauber, 2006)	Rapid
(Parag and Janda, 2014)	Systemic	(Butler et al., 2015)	Strong imperatives	(Marcucci and Fragkos, 2015)	Short and long-term
(Zhang et al., 2010)	Long-term	(Bertram et al., 2015)	Long-term Urgency	(Momirlan and Veziroglu, 2005)	Radical Rapid
(Rutter and Keirstead, 2012)	Major	(Pfenninger and Keirstead, 2015)	Choice between renewable, nuclear, or fossil fuels	(Gambhir et al., 2013)	Fundamental
(Hong et al., 2013a)	Ambitious	(Nilsson et al., 2011)	Anticipated Wished-for	(Capros et al., 2014)	Systematic
(Hong et al., 2013b)	Social and economic	(Yuan et al., 2012)	Urgency Magnitude	(van Vuuren et al., 2012)	Fundamental Long-term
		(Späth and Rohracher, 2010)	Guiding vision	(Pregger et al., 2013)	Long-term

Table A2
Answer to second key question by source and article type. How will change proceed?

Transition articles		Transition/Transformation articles		Transformation articles	
(Miller et al., 2015)	Social, economic and political shifts	(Chai and Zhang, 2010)	Options Development Demonstration Binding targets Policy actions	(Jacobsson and Lauber, 2006)	Regulatory framework
(Schubert et al., 2015)	Process	(Eom et al., 2015)	Pathways	(Ydersbond, 2014)	Target Paths
(Peter Andreasen and Sovacool, 2014)	Activity Vision	(Butler et al., 2015)	Processes Realised	(Marcucci and Fragkos, 2015)	Strategies Scenario Targets
(Parag and Janda, 2014)	Process	(Bertram et al., 2015)	Targets	(Bădileanu, 2014)	Performance
(Zhang et al., 2010)	Development	(Pfenninger and Keirstead, 2015)	Options	(Sano et al., 2015)	Pledges Mitigation options
(Morlet and Keirstead, 2013)	Lowest cost technology pathways Evaluations	(Späth and Rohracher, 2010)	Shifts Development Strategizing Discursive strategies	(Gambhir et al., 2013)	Development
(McDowall, 2012)	Optimization Evolution Pathways Development	(Nilsson et al., 2011)	Explored Developments Scenarios Paths Processes	(Pregger et al., 2013)	Targets Scenario Implementation Development Roadmap
(Rutter and Keirstead, 2012)	Strategic Solutions	(Eyre and Baruah, 2015)	Shift Diversified strategy Ambitious goals	(van Vuuren et al., 2012)	Pathways Vision Integrated approach
(Hall and Foxon, 2014)	Evolution	(Yuan et al., 2012)	Pathways Framework	(Capros et al., 2014)	Targets Feasibility
(Hong et al., 2013a)	Aims	(Winskel et al., 2014)	Phases	(Stenzel and Frenzel, 2008)	Development
(Hong et al., 2013b)	Pathway				
(Foxon et al., 2013)	Pathways Branching points Development				
(Hugh et al., 2007)	Roadmap				

Table A3
Answer to third key question by source and article type. What are the barriers to change?

Transition articles		Transition/Transformation articles		Transformation articles	
(Diaz-Rainey and Tzavara, 2012)	Political system Willingness-to-pay Limitations	(Demski et al., 2015)	Wastefulness Conflict	(Jacobsson and Lauber, 2006)	Reluctant government Opposition interests
(Hall and Foxon, 2014)	Cost	(Muench et al., 2014)	Barriers	(Chowdhury et al., 2014)	Institutional barriers
(Schubert et al., 2015)	Political system (possible) Societal limitations Hurdles	(Eom et al., 2015)	Delayed response will result in need for faster transition Challenges Risk	(Bădileanu, 2014)	Negative determinant factors
(Lachman, 2014)	Impediments	(Butler et al., 2015)	Uncertainty	(Delina, 2012)	Challenges
(Peter Andreasen and Sovacool, 2014)	Conflicts	(Pfenninger and Keirstead, 2015)	Cost	(Stenzel and Frenzel, 2008)	Economic effects
(Zhang et al., 2010)	Risks Policy measures	(Winskel et al., 2014)	Erratic public funding Persistent problems	(Pregger et al., 2013)	Associated costs Technological limitation Delaying has significant adverse effects
(Miller et al., 2015)	Policy is too constrained	(Nilsson et al., 2011)	Constraints	(Capros et al., 2014)	Incumbents Resistance proactivity Inertia
(Rutter and Keirstead, 2012)	Constrained by climate change and rising fuel prices	(Eyre and Baruah, 2015)	Challenges Inefficient building stock High penetration of NG Problems Risks Uncertain		
(McDowall, 2012)	Uncertainties Breaking incumbent system 'lock-in' Resistance to change	(Späth and Rohracher, 2010)	Contested processes Conflict Power structures		
(Hong et al., 2013a)	Cost				
(Stenzel and Frenzel,	Stresses				

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Table A3 *(continued)*

Transition articles		Transition/Transformation articles		Transformation articles	
2008)	Risk				
(Ydersbond, 2014)	Political system Willingness-to-pay Limitations	(Lachman, 2014)	Wastefulness Conflict	(Miller et al., 2015)	Reluctant government Opposition interests
(Delina, 2012)	Cost	(Schubert et al., 2015)	Barriers	(Butler et al., 2015)	Institutional barriers
(Jacobsson and Lauber, 2006)	Political system (possible) Societal limitations Hurdles	(Diaz-Rainey and Tzavara, 2012)	Delayed response will result in need for faster transition Challenges Risk	(Bertram et al., 2015)	Negative determinant factors
(van Vuuren et al., 2012)	Impediments	(Peter Andreasen and Sovacool, 2014)	Uncertainty	(Nilsson et al., 2011)	Challenges
(Marcucci and Fragkos, 2015)	Conflicts	(Zhang et al., 2010)	Cost	(Hong et al., 2013a)	Economic effects
(Bădileanu, 2014)	Risks Policy measures	(Momirlan and Veziroglu, 2005)	Erratic public funding Persistent problems	(Späth and Rohracher, 2010)	Associated costs Technological limitation Delaying has significant adverse effects
(Demski et al., 2015)	Policy is too constrained	(Morlet and Keirstead, 2013)	Constraints	(Eyre and Baruah, 2015)	Incumbents Resistance proactivity Inertia
(Capros et al., 2014)	Constrained by climate change and rising fuel prices	(Hall and Foxon, 2014)	Challenges Inefficient building stock High penetration of NG Problems Risks Uncertain		
(Yuan et al., 2012)	Uncertainties Breaking incumbent system 'lock-in' Resistance to change	(McDowall, 2012)	Contested processes Conflict Power structures		
(Stenzel and Frenzel, 2008)	Cost				
(Hong et al., 2013b)	Stresses Risk				

Table A4
Answer to fourth key question by source and article type. What or who are the agents and facilitators of change?

Transition articles		Transition/Transformation articles		Transformation articles	
(Lachman, 2014)	Effort Stakeholders Policy	(Demski et al., 2015)	Public acceptance Public values Attitudes Efficiency Dialogue Robust decision-making Anticipating conflict	(Huberty and Zysman, 2010)	Technologies Research policy Transformation of economy Increase efficiency
(Miller et al., 2015)	Recommendations Rethinking Policy Governance	(Chai and Zhang, 2010)	Technology Policy Intensive efforts Promote research Economic incentives Public R & D support Further actions Radically innovative technologies International collaborations	(Jacobsson and Lauber, 2006)	New technologies Spread of technologies Advocacy Support policies Modest price
(Schubert et al., 2015)	Technology Social acceptance	(Muench et al., 2014)	Increase RE Technologies Policy Alignment of interests of market participants Regulations Information	(Ydersbond, 2014)	RE production Political and public policies RE technologies Cost-competitiveness World leaders
(Diaz-Rainey and Tzavara, 2012)	Investment	(Eom et al., 2015)	Optimal policies Ambitious mitigation strategies Low GHG emitting technology Deployment measures Facilitation	(Marcucci and Fragkos, 2015)	Drivers Natural resources Backstop technologies Policies

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Table A4 *(continued)*

Transition articles		Transition/Transformation articles		Transformation articles	
			CCS		
(Peter Andreasen and Sovacool, 2014)	Critical stakeholders Influential actors Technical development Hydrogen technology advancement Use of renewable resources	(Butler et al., 2015)	Public attitudes Acceptability Efforts Enact Policy	(Chowdhury et al., 2014)	Developing technologies Creating an initial market Policy Incentives Diffusion of PV technology Wider use of RE technology
(Parag and Janda, 2014)	Actors Strategies	(Winskel et al., 2014)	Strong policy imperatives Leading role of private business Energy innovation	(Bădileanu, 2014)	Positive determinant factors Electricity market Price
(Zhang et al., 2010)	Risk management	(Pfenninger and Keirstead, 2015)	Technological options Emission restrictions	(Sano et al., 2015)	Short-term emission fixes Technologies Fuel switching
(Momirlan and Veziroglu, 2005)	Hydrogen utilization	(Bertram et al., 2015)	Limit on emissions Policy signals Retire coal capacity Low-carbon technologies Energy efficiency Facilitation	(Gambhir et al., 2013)	Technology-specific solutions Measures Options Mix of technologies Increased electrification Energy efficiency
(Morlet and Keirstead, 2013)	Policy Governance	(Nilsson et al., 2011)	Tool Technical, economic and policy change Political and institutional factors	(Delina, 2012)	Improvement of technology Development of new technologies Coherent governance Institutional design Promote Policy Enabling conditions
(Hall and Foxon, 2014)	Investment Enabler Stakeholders Partners and investors	(Eyre and Baruah, 2015)	Systematic change in space heating systems Minimal policy intervention Heat pumps Energy efficiency Biomass	(Capros et al., 2014)	EU Roadmap 2050 Policy Accelerated energy efficiency Transport electrification Supply-side restructuring High RES CCS, Nuclear power
(Rutter and Keirstead, 2012)	Wider changes in technology and society Increased efficiency Driven by urbanisation and access to basic energy services	(Yuan et al., 2012)	Manage Technology options Policy Policy-makers Stakeholders	(van Vuuren et al., 2012)	Motivated by challenges and critical issues Energy efficiency Scale up of investments RD & D
(McDowall, 2012)	Alternate fuel Hydrogen Decision points Policy responses	(Späth and Rohracher, 2010)	Mobilizing social actors Co-ordination of dispersed agency Promotion Actor network Systematically exploiting resources Anticipation of conflict Modify durable power structures Orient strategic action	(Pregger et al., 2013)	Political consensus Policy targets Energy efficiency RE Policy measures Investments Strong market dynamics New generation technologies
(Hong et al., 2013a)	Plan Target Technologies Technical performance Efficiency Promoted Implemented Facilitation			(Stenzel and Frenzel, 2008)	Support Technological capabilities Political activities Shaping of regulatory environment Coordination of strategies Novel policy shaping
(Hong et al., 2013b)	Improving energy efficiency Utilizing renewable resources Policy				
(Foxon et al., 2013)	Triggers Governance Actors Risk mitigation strategies				
(Hugh et al., 2007)	Planning Facilitating Actors				

Table A5
Answer to fifth key question by source and article type. What is the outcome of change?

Transition articles		Transition/Transformation articles		Transformation articles	
(Lachman, 2014)	Sustainable energy system	(Chai and Zhang, 2010)	Sustainable energy system for China	(Huberty and Zysman, 2010)	Mitigate climate change
(Schubert et al., 2015)	Normative targets Goals Replace fossil fuels Reduce emissions Reduce import dependencies Phase out nuclear energy	(Demski et al., 2015)	Desirable futures Security Stability Social justice Fairness Autonomy and power Low carbon energy	(Jacobsson and Lauber, 2006)	Achievement Arrest climate change Low-carbon economy
(Diaz-Rainey and Tzavara, 2012)	Decarbonized energy system	(Pfenninger and Keirstead, 2015)	Energy security	(Ydersbond, 2014)	95% reduction of GHGs
(Peter Andreasen and Sovacool, 2014)	Hydrogen economy Mitigation of CO_2	(Eom et al., 2015)	Goal Limiting climate forcing to 450 ppm	(Marcucci and Fragkos, 2015)	Global GHG target of 450 ppm
(Parag and Janda, 2014)	Low carbon society	(Butler et al., 2015)	Low carbon energy sytem for UK	(Chowdhury et al., 2014)	Meet environmental and climate challenge
(Zhang et al., 2010)	Targets Sustainable energy supply	(Bertram et al., 2015)	< 2° increase Achieving stringent long-term climate targets	(Bădileanu, 2014)	Maintain current system of electricity supply
(Momirlan and Veziroglu, 2005)	Benefits Opportunities Cleaner planet Sustainable energy system	(Muench et al., 2014)	Solution Diversity of solutions Increase share of RE in national energy mixes	(Sano et al., 2015)	Global GHG reduction
(Morlet and Keirstead, 2013)	Carbon target Emission reductions Combat climate change	(Winskel et al., 2014)	Decarbonization of UK	(Gambhir et al., 2013)	Carbon abatement
(Hall and Foxon, 2014)	Benefit Energy security Decarbonization Public goods Economic opportunities	(Nilsson et al., 2011)	Low carbon Swedish energy system	(Delina, 2012)	Energy efficiency
(Rutter and Keirstead, 2012)	Access to basic services Mitigate climate change Save on fuel prices	(Eyre and Baruah, 2015)	Climate change mitigation Low carbon heating	(Capros et al., 2014)	EU decarbonization 80% GHG reduction
(McDowall, 2012)	Decarbonization Hydrogen transition	(Yuan et al., 2012)	Low carbon power sector of China	(van Vuuren et al., 2012)	Sustainability of global energy system
(Hong et al., 2013a)	Enhance energy security Mitigate emissions Develop RE industry	(Späth and Rohracher, 2010)	Save region from economic decay Greater sustainability	(Pregger et al., 2013)	Economic benefits Fuel cost savings Lower fuel imports
(Hong et al., 2013a)	Meet energy demand Mitigate emissions Utilize renewable resources			(Stenzel and Frenzel, 2008)	Diffusion of RE technologies
(Foxon et al., 2013)	UK low carbon electricity future by 2050				
(Hugh et al., 2007)	Hydrogen energy system				
(van Vuuren et al., 2012)	Sustainable energy system	(Oxford University Press)	Sustainable energy system for China	(Chappin and Ligtvoet, 2014)	Mitigate climate change
(Jacobsson and Lauber, 2006)	Normative targets Goals Replace fossil fuels Reduce emissions Reduce import dependencies Phase out nuclear energy	(Lachman, 2014)	Desirable futures Security Stability Social justice Fairness Autonomy and power Low carbon energy	(Miller et al., 2015)	Achievement Arrest climate change Low-carbon economy
(Ydersbond, 2014)	Decarbonized energy system	(Zhang et al., 2010)	Energy security	(Muench et al., 2014)	95% reduction of GHGs
(Marcucci and Fragkos, 2015)	Hydrogen economy Mitigation of CO_2	(Diaz-Rainey and Tzavara, 2012)	Goal Limiting climate forcing to 450 ppm	(Eom et al., 2015)	Global GHG target of 450 ppm
(Chowdhury et al., 2014)	Low carbon society	(Peter Andreasen and Sovacool, 2014)	Low carbon energy sytem for UK	(Butler et al., 2015)	Meet environmental and climate challenge
(Bădileanu, 2014)	Targets Sustainable energy supply	(Parag and Janda, 2014)	< 2° increase Achieving stringent long-term climate targets	(Bertram et al., 2015)	Maintain current system of electricity supply
(Sano et al., 2015)	Benefits Opportunities Cleaner planet Sustainable energy system	(Schubert et al., 2015)	Solution Diversity of solutions Increase share of RE in national energy mixes	(Pfenninger and Keirstead, 2015)	Global GHG reduction
(Gambhir et al., 2013)	Carbon target Emission reductions Combat climate change	(Momirlan and Veziroglu, 2005)	Decarbonization of UK	(Winskel et al., 2014)	Carbon abatement
(Delina, 2012)	Benefit Energy security Decarbonization Public goods	(Morlet and Keirstead, 2013)	Low carbon Swedish energy system	(Nilsson et al., 2011)	Energy efficiency

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Table A5 *(continued)*

Transition articles		Transition/Transformation articles		Transformation articles	
	Economic opportunities				
(Capros et al., 2014)	Access to basic services Mitigate climate change Save on fuel prices	(Hall and Foxon, 2014)	Climate change mitigation Low carbon heating	(Eyre and Baruah, 2015)	EU decarbonization 80% GHG reduction
(Yuan et al., 2012)	Decarbonization Hydrogen transition	(Rutter and Keirstead, 2012)	Low carbon power sector of China	(Huberty and Zysman, 2010)	Sustainability of global energy system
(Pregger et al., 2013)	Enhance energy security Mitigate emissions Develop RE industry	(McDowall, 2012)	Save region from economic decay Greater sustainability	(Späth and Rohracher, 2010)	Economic benefits Fuel cost savings Lower fuel imports
(Stenzel and Frenzel, 2008)	Meet energy demand Mitigate emissions Utilize renewable resources			(Hong et al., 2013a)	Diffusion of RE technologies
(Hong et al., 2013b)	UK low carbon electricity future by 2050				
(Foxon et al., 2013)	Hydrogen energy system				

Table A6
Key words by source and article type.

Transition articles		Transition/Transformation articles		Transformation articles	
(Lachman, 2014)	Energy system transition management Socio-technical systems Panama	(Demski et al., 2015)	Public acceptability Public perception Energy system transitions	(Jacobsson and Lauber, 2006)	Renewable energy Regulatory framework Market creation
(Miller et al., 2015)	Socio-energy system Governance Society Transition Design	(Chai and Zhang, 2010)	Energy technology Energy policy Sustainable development China	(Ydersbond, 2014)	Renewable energy Energy policy Transformation Comparative study Historical institutionalism Sweden, Norway
(Schubert et al., 2015)	Energy scenarios Social acceptance Political feasibility Institutions	(Muench et al., 2014)	Energy distribution Power system Barriers	(Marcucci and Fragkos, 2015)	Regional decomposition analysis Model inter-comparison Climate change mitigation pathways Backstop technologies
(Diaz-Rainey and Tzavara, 2012)	Innovation diffusion Willingness-to-pay Energy system transition Financing renewables Green consumerism Smart grids	(Eom et al., 2015)	Near-term climate policy Technology deployment Emission pathway Technology upscaling	(Chowdhury et al., 2014)	PV diffusion Energy policy Feed-in tariff Japan Germany
(Peter Andreasen and Sovacool, 2014)	Hydrogen fuel cells Critical stakeholder analysis Hydrogen policy	(Butler et al., 2015)	Public acceptability Uncertainty Energy policy Energy transitions	(Bădileanu, 2014)	Energy system Price liberalization Electricity market Energy welfare
(Parag and Janda, 2014)	Energy system transition Middle-out Agency and capacity Middle actors	(Bertram et al., 2015)	Climate change mitigation Energy systems modelling Energy efficiency Carbon dioxide emissions AMPERE Integrated assessment	(Sano et al., 2015)	Climate change mitigation Decomposition analysis Energy end-use sector Global energy system model
(Zhang et al., 2010)	Renewable energy Energy supply Market development Public policy China	(Pfenninger and Keirstead, 2015)	Energy system modelling Energy policy Renewable energy	(Gambhir et al., 2013)	China CO_2 emissions Low-carbon technology
(Momirlan and Veziroglu, 2005)	Hydrogen Environment Chemical properties Fuel CO_2 emissions Atomic hydrogen/carbon ratio Pollutants	(Winskel et al., 2014)	Energy Technology Innovation	(Delina, 2012)	Energy efficiency Governance Motivation Capacity Intervention Institutions
(Morlet and Keirstead, 2013)	Urban energy systems Governance Scenario analysis	(Nilsson et al., 2011)	Backcasting Systems Institutions Sweden Climate	(Capros et al., 2014)	EU decarbonization pathways Climate policy delays Energy roadmap EU energy policy Technological limitations

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Table A6 *(continued)*

Transition articles		Transition/Transformation articles		Transformation articles	
			Governance		
(Hall and Foxon, 2014)	Smart grids Political economy Co-evolution	(Eyre and Baruah, 2015)	Scenarios Heating Fuel switching Electrification Energy efficiency Heat pumps	(Pregger et al., 2013)	Energy scenario Renewable energy Economic effect
(Rutter and Keirstead, 2012)	Urban energy systems History Transitions	(Yuan et al., 2012)	Multi-level perspective Energy transition management China Power systems	(Stenzel and Frenzel, 2008)	Innovation diffusion Energy system transformation Corporate political activities
(McDowall, 2012)	Scenarios Energy system models Technological transition Hydrogen economy	(Späth and Rohracher, 2010)	Guiding visions Transition management Multi-level framework Regional governance Energy systems	(Stenzel and Frenzel, 2008)	Innovation diffusion Energy system transformation Corporate political activities
(Hong et al., 2013a)	China Renewable 12th five year plan				
(Hong et al., 2013b)	Renewable Jiangsu 2050				
(Foxon et al., 2013)	Branching points Transition pathway Path dependency				
(Hugh et al., 2007)	Hydrogen energy system Transitions Roadmap Actors Qualitative analysis				

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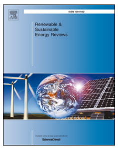

Sustainability guardrails for energy scenarios of the global energy transition

Michael Child*, Otto Koskinen, Lassi Linnanen, Christian Breyer

Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

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ABSTRACT

Sustainability guardrails in global energy scenarios were reviewed and further developed based on a literature review of global energy system transition scenarios. Environmental planetary boundaries mark out the safe operation space for human activities. The planetary boundary framework has yet to be fully incorporated into global energy scenario modeling, where the emphasis has been almost solely on CO_2 emission mitigation. Stress on biochemical flows, land use change, biodiversity, ocean and climate systems are often neglected. Concurrently, social and economic aspects, such as limiting air pollution, providing universal access to modern energy services and improving energy efficiency by electrification of energy services are emerging as new paradigms in energy scenario modeling frameworks. However, ethical choices, such as current and future generations' access to preserved ecosystems, aversion of energy resource risks, preventing resource use conflicts, and negative impacts on human lives from energy extraction and use are not usually discussed or justified in energy scenario modeling. All investigated global energy transition scenarios failed to adequately describing the critical roles of flexibility in future energy systems based on high shares of renewable energy, such as storage, grids, demand response, supply side management and sector coupling. Nor did they adequately incorporate the concept of resilience in socio-ecological systems.

1. Introduction

It has been recognized that human civilization is over-exploiting planetary resources faster than they are being renewed [1]. Nine planetary boundaries have been defined to assess the safe limits into which human activities should be confined in order to take into account assimilative capacities of the planet, related uncertainties, the complexity of the biosphere, and possible tipping points [2,3]. Currently, the biosphere's capacity to assimilate the impacts of human action is being exceeded, resulting in dangerous interference in the global climate system [4], an increased rate of biodiversity loss, and overstressed nitrogen and phosphorus cycles [2,3]. In addition, the planetary boundaries framework includes stratospheric ozone depletion, ocean acidification, chemical pollution, land-system change, freshwater use and aerosol loading [2]. Human activities are the largest drivers at the planetary scale, thus the current geological era has been proposed to be named the "Anthropocene" [5]. The growing awareness of the environmental state of the planet and concerns about the threats of climate change have led world leaders to agree on a shared, long-term goal of limiting global emissions of greenhouse gases to ensure a 2 °C compatible pathway within this century, and pursue efforts to limit global warming to 1.5 °C above pre-industrial levels [6]. A common, long-term, legally binding climate target is a start; however, a truly sustainable development of resource extraction and use for human needs would address the other planetary boundaries as well.

Motivations of influential global energy scenarios differ. Governments can assess implications of different energy and environmental policies, non-governmental organizations (NGOs) can draw attention to alternative polices, and companies can assess market risks and their investments [7]. Thus, an energy scenario can be handcrafted to drive certain interests. For this reason, transparency in the creation of energy scenarios is essential, since model assumptions greatly affect

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Abbreviations: 2DS, Two degree scenario; AFOLU, Agriculture, forestry and land use; BECCS, Bioenergy and carbon capture and storage; BEV, Battery electric vehicle; CAES, Compressed air energy storage; CCS, Carbon capture and storage; CCU, Carbon capture and utilisation; COP21, Twenty first annual Conference of Parties; CSP, Concentrating solar thermal power; DACCS, Direct air carbon capture and storage; EMF, Energy Modeling Forum; ETP, Energy Technology Perspectives; hi-Ren, High renewable energy; hi-Nuc, High nuclear energy; GEA, Global Energy Assessment; GHG, Greenhouse gas; IAM, Integrated assessment modeling; IEA, International Energy Agency; IIASA, International Institute for Applied Systems Analysis; IMF, International Monetary Fund; IPCC, Intergovernmental Panel on Climate Change; IRENA, International Renewable Energy Agency; LCOE, Levelised cost of electricity; NELD, Non-economic loss and damage; NGOs, Non-governmental organizations; OECD, Organization for Economic Co-operation and Development; PHS, Pumped hydro storage; ppm, Parts per million; PtX, Power-to-X; PV, Photovoltaic; R&D, Research and development; RE, Renewable energy; TES, Thermal energy storage; WBGU, German Advisory Council on Global Change; WEC, World Energy Council; WEO, World Energy Outlook; WRI, World Resource Institute; WWF, World Wildlife Fund; WWS, Wind, wave and solar; Subscripts, eq, Equivalent

* Corresponding author.

E-mail address: Michael.Child@lut.fi (M. Child).

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the modeling outcomes. For example, incorrect assumptions have often been made concerning the future costs of solar photovoltaics (PV), no doubt a key technology on global level. In one case, Luderer et al. claim capital costs for solar PV projects will be in the range of 800–1400 $/kWp (620–1080 €/kWp[1]) in 2050. In reality, utility-scale project costs in Europe, India and China have already reached those same price levels today [8,9], and PV experts expect costs in the range of 360–520 €/kWp [10] and 320–430 €/kWp [11] in 2050, depending on the deployment scenario. Transparency of assumptions thus becomes an important precursor to assessing the quality of a scenario.

It appears safe to assume that a global energy transition is underway, and that world leaders will need to provide plans and solid policy options for the future. To do this, realistic and valid information concerning key technologies that drive the transition must be presented. It appears clear that global installed capacity of solar PV will increase significantly and that the cost of this technology will fall accordingly. The same could be argued for wind power. Therefore, policymakers must be able to carefully consider the important nature of solar PV and wind power technology costs relative to future global, cumulative installed capacities. In addition, such weather dependent energy generation technologies must be seen in the context of greater temporal and spatial accuracy, something which is neglected in past IAM exercises. Such consideration can only arise from accurate and relevant energy system model frameworks that conform to a meaningful set of sustainability criteria. Several studies which do have high temporal and spatial resolution on a continental scale and realistic technological representation of weather dependent power generation imply that fully renewable energy mixes, mostly based on wind and solar PV, are technically and economically viable options [12–14]. First insights from global scale modeling with an hourly resolution for a full year imply that not only are fully renewable power systems technically possible, they are economically attractive as well, from the system point of view and all over the world [14–17].

The ongoing energy transition is not only technological, but also a combination of economic, political, institutional and socio-cultural changes; thus, it should be guided by ethics and sustainability [18], as well as with a resilience perspective [19]. Importantly, the mitigation of climate change must not only be seen as a challenge to be overcome, but as a real-life, real-time struggle to prevent damage to humans, many of whom are paying or will pay disproportionate costs related to climate change. These groups include people who may be most vulnerable to the impacts of climate change, such as future generations, minority groups, and people in economically disadvantaged countries. Determining energy mixes for energy scenarios requires ethical choices due to long reaching impacts of energy decision-making and profound impacts on economics, the environment and people's lives. Consequently, future energy scenarios take on the role of long-term social contracts, which must be based on principles of justice [20].

For these reasons, the first aim of this study is to highlight the need for consideration of planetary boundaries and other sustainability principles in global energy scenario frameworks. This consideration includes not only climate change constraints, but other limitations as well. Second, we propose a literature derived hierarchy and sustainability guardrails according to which future global energy scenarios (and the transition) could be scrutinized. Third, we investigate whether sustainability guardrails have been deployed before in global energy scenarios and discuss how the determined sustainability principles could be operationalized into the creation of energy scenarios. This includes what kind of indices can be used for tracking the sustainable development of the global energy system.

2. Sustainability guardrails for the global energy system

Generally, sustainable futures must acknowledge that certain levels of cost and damage are intolerable, no matter what short term gains can be achieved. To this one can add that certain rights are inalienable. In essence, higher normative requirements will always outweigh any gains that can be achieved through intolerable acts. Such is the motivation for opposing such things as slavery, inequality, child labour, hazardous work conditions, etc. And this same motivation can be extended into all three spheres of sustainability (social, environmental, economic). Specifically, the world can seek to exclude anything which is unacceptable by establishing clear boundaries of tolerance. Such boundaries have also been introduced as guardrails for sustainable energy policy [21]. The German Advisory Council on Global Change (WBGU) has applied the principle of setting normative guardrails in order to create a sustainable global energy scenario. WBGU's ecological guardrails consist of compliance with a climate protection window, protection of marine ecosystems (by limiting carbon sequestration), sustainable land use (by limiting bioenergy), protection of rivers and catchment areas (by limiting large hydro power) and prevention of air pollution. The socio-economic guardrails include keeping risks within a normal range (by limiting nuclear power), preventing disease caused by energy use, limiting the proportion of income expended on energy, providing access to modern energy services, meeting an individual minimum requirement for modern energy services, and establishing a minimum level of macroeconomic development. Similarly, according to a definition by the Brundtland Commission [22], we should ensure that future generations are able to meet their needs, and that the resource limitations for sustainable development are contemporary and bounded by the present state of technology, social organization around environmental resources, and the ability of the biosphere to absorb human activities.

Häyhä et al. [23] point out that although the planetary boundaries framework proposes quantitative global limits, decisions regarding resource use and emissions are made nationally and sub-nationally. Thus, the operationalization of planetary boundaries as biophysical, socio-economic, and ethical dimensions in national policymaking is of high priority. Keeping this in mind, the realization of multiple sustainability targets requires that they can be simplified to pass in real world politics, as is argued to be the case for the two degree target. Determining sustainability targets in an objective manner is no easy task given that some guardrails must never be breached. For this reason, Serdeczny et al. [24] propose a framework for categorising different aspects of non-economic loss and damage (NELD): human life, meaningful places, cultural artefacts, biodiversity, communal sites, intrinsic values, agency (the ability to engage with or change one's world), identity, production sites and ecosystem services. The identified methods for valuing NELD are economic evaluation, multi-criteria decision analysis, composite risk indices, and qualitative and semi-quantitative approaches.

Given that social and economic sustainability targets are context dependent and subjective choices, their valuation could be based on the United Nation's development goals [25], global question polls, and participatory workshops. For example, 10 000 citizens from 76 countries participated in a global survey [26], and the majority of respondents (56%) preferred subsidization for wind, solar, marine and geothermal energy resources in order to make large scale cuts in greenhouse gas emissions. A very high proportion (97%) of the participants thought that a global dialogue, such as the survey they answered, should be conducted in the future when dealing with similar issues.

It can be argued that sustainability principles are hierarchical (Fig. 1). In the concept of strong sustainability, it is emphasized that certain elements of natural capital[2] are irreplaceable [27], and thus the

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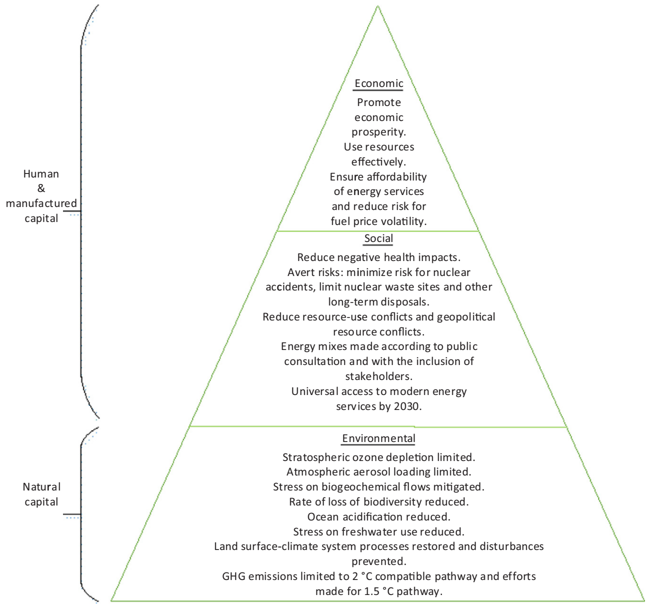
[1] A long-term exchange rate of 1.3 USD/EUR is applied in this study. Brackets signal conversion preceded by original number.

[2] Consists of resources for production, waste absorption from production, life-support



Economic

Promote economic prosperity.
Use resources effectively.
Ensure affordability of energy services and reduce risk for fuel price volatility.

Social

Reduce negative health impacts.
Avert risks: minimize risk for nuclear accidents, limit nuclear waste sites and other long-term disposals.
Reduce resource-use conflicts and geopolitical resource conflicts.
Energy mixes made according to public consultation and with the inclusion of stakeholders.
Universal access to modern energy services by 2030.

Environmental

Stratospheric ozone depletion limited.
Atmospheric aerosol loading limited.
Stress on biogeochemical flows mitigated.
Rate of loss of biodiversity reduced.
Ocean acidification reduced.
Stress on freshwater use reduced.
Land surface-climate system processes restored and disturbances prevented.
GHG emissions limited to 2 °C compatible pathway and efforts made for 1.5 °C pathway.

Fig. 1. Proposed hierarchical framework for assessing sustainability of global energy scenarios.

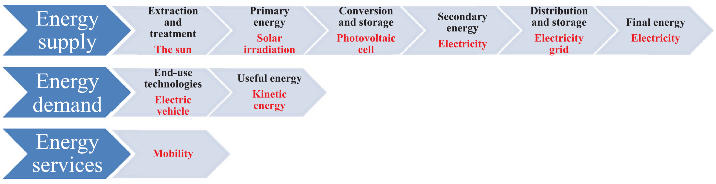


Fig. 2. Simplified representation of an energy system, with an example (in red) of the many stages a resource will pass through before becoming an energy service. Adapted from [29].

use of natural capital should not lead to irreversible destruction of this capital [28]. It follows that the human use of natural capital should be limited in such a way that it is not depleted. Given that there are ecological limits, or tipping points with points of no return, it can be thought that dimensions of sustainability have a hierarchy; and the environmental dimension serves as the basis for other sustainability dimensions. Thus, the planetary boundaries framework sets the foundation for sustainable energy systems.

Fig. 2 highlights how sustainability goals can be achieved throughout the complicated, multi-stage process that defines an energy system. Such a system begins with energy resources that go through technological conversion into useful forms of energy and possible storage. These forms of energy are then used to satisfy demands for energy services.

Difficulties in taking sustainability criteria into account when assessing energy scenarios arise from the fact that an energy system involves a multi-stage process of satisfying demands for energy services (Fig. 2). In addition, sustainability criteria can be applied to either one or more of these stages. In general, the energy system can be divided into a supply side and a demand side. On the supply side, there are upstream aspects to consider, such as the extraction and treatment of a resources so that a form of primary energy is produced. Downstream aspects include conversion, distribution and storage technologies that ultimately give rise to a form of final energy that can be supplied to end-users. On the demand side, end-users employ technologies to create a useful form of energy that provides a desired energy service. Sometimes this process is simple, such as a person moving in and out of the sun or shade to keep warm or cool. In most cases, however, the process can be quite complicated. A detailed representation of this process is found in [29].

2.1. Operationalising sustainability guardrails

Operationalising a sustainability criteria into energy scenario creation, therefore, involves judging how and where the criteria impacts the process. For example, using a resource efficiently not only implies examining efficiency of end-use technologies, but also includes potential improvements downstream and upstream in the supply chain. Further, one could question whether a demand itself is reasonable in relation to a different demand in another part of the world. Likewise, promoting

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(*footnote continued*)
functions and amenity services [27].

universal access to modern energy services may not merely involve such elements as improving the quality of resource distribution (e.g. electricity transmission grid extension), but a sustainable solution could be found from another aspect of the energy system (e.g. an off-grid solar PV system). For these reasons there may indeed be more than one potential pathway towards sustainability. In the case of the current energy transition, several potential solutions have risen to the fore: efficiency, renewable energy (primarily solar, wind and biomass), nuclear energy, carbon capture and storage, and energy subsidies. Therefore, the hierarchical nature of the sustainability criteria presented in Fig. 1 may aid in resolving differences in opinion or expose/eliminate vested interests in scenario design.

2.1.1. *Efficiency*

Efficiency can be achieved in several ways. A common suggestion is that electrification of energy services, where applicable, is a key for reducing primary energy use. For example, a battery electric vehicle (BEV) powered by wind or solar energy is about 3 and 4 times more efficient than diesel and petrol based vehicles, respectively, as measured by well-to-wheel fuel consumption in litres of gasoline equivalent per 100 km driven [30]. Further, electric heat pumps are about 4.5–5.5 times more efficient than direct heating from combustion, and modern cooking technologies are 2–3 times more efficient than traditional appliances [31]. Efficiency gains can also occur from changes to the built environment through adopting new standards for new buildings and increasing renovation rates of existing buildings.

However, energy scenarios may fall short of reaching fully sustainable targets for energy efficiency. The seventh UN Sustainable Development Goal sets out targets for energy, including those specific to efficiency. A recent UN report [32] observes that over the period of 1990–2010, global energy intensity (or the amount of energy needed produce a unit of GDP) fell 1.3% annually, from 10.2 to 7.9 MJ/USD_{2005}. Moreover, the UN target is to double the rate of energy efficiency improvement, to 2.6%/year by 2030. In a recent IEA analysis of the Nordic countries [33], achieving the 2 °C requirement would require a building renovation rate of about 2–3%/year, well beyond current rate of 0.5%/year achieved in the Nordic countries. In other words, striving for a 1.5 °C target would require even more stringent renovations rates. Such stringent targets may indeed aid in reaching one sustainability target (efficiency), but could result in other sustainability issues, such as a potentially unrealistic target being set without proper public consultation and inclusion of stakeholders, who would ultimately be the drivers of such renovations. In other words, the IEA scenario should have also included comment on how this important aspect of social sustainability was safeguarded. Without such comment, controversy could result. A scenario designed with adherence to a full range of sustainability guardrails could prevent such controversy.

2.1.2. *Renewable energy*

Next, expanded use of renewable energy, particularly solar, wind and biomass, has emerged as a candidate for reaching sustainability goals. According to the International Renewable Energy Agency (IRENA) REmap scenario, renewable energy can constitute 25% of used primary energy in 2030, and combined with efficiency measures in energy consumption, the renewable share in the same scenario can reach 30% of primary energy [31]. Further, some studies suggest that benefits from renewables can extend beyond what is usually perceived as the energy sector. Caldera et al. [34] demonstrate that renewables can alleviate water stress in a financially competitive and sustainable manner around the world. Similarly, the World Resource Institute (WRI) determined thermal generators can worsen water stress in areas that are already freshwater-constrained [35] due to such plants' own demands for water. As a result, solar PV and wind power were viewed as more suitable technologies for providing electricity in such areas, while the authors remind that improving energy efficiency is still the least-cost solution. This is in addition to the fact that solar PV and wind power result in lower GHG emissions.

Biomass as a source of renewable energy generation must be regarded carefully in future energy system scenario design by the application of acceptable sustainability criteria concerning use. Sustainable bioenergy does not cause negative impacts on natural ecosystems, soil fertility, water resources, livelihoods, people's access to food and biodiversity [36]. In 2010, the UN conference of parties agreed to bring the rate of loss of natural habitats close to zero, set a conservation target of 17% for terrestrial and inland water areas and 10% for marine and coastal areas, and aimed to restore 15% of degraded areas through conservation and preservation [37]. In the EU, it seems unlikely that the 2020 biodiversity targets will be met, thus more stringent actions are needed [38]. In the IPCC emission reduction pathways [4], in which CCS is not deployed, the emission estimations for agriculture, forestry and land use change (AFOLU) range from net zero to a possible carbon sink on the level of -15 $\text{GtCO}_{2\text{eq}}$/a in 2050. Given that in COP21, a pledge was made to pursue efforts to limit the temperature increase to 1.5 °C, the possibility of AFOLU sectors becoming a natural sink for carbon should be enhanced (and better investigated in energy scenarios). A median negative emission level of -5 $\text{GtCO}_{2\text{eq}}$/a by 2100 is required to limit warming to less than 1.5 °C within the 21st century with more than a 50% probability [39]. Even considering that building, industry, transport and electricity sectors are fully carbon-neutralized, the IPCC puts non-CO_2 emissions at 3–12 $\text{GtCO}_{2\text{eq}}$/a, highlighting the ambition and challenge of the 1.5 °C target. Avoiding large upfront carbon debt from biomass feedstocks converted to energy must therefore be of high priority. The implication for the creation of energy scenarios, considering strict sustainability criteria, is that the global bioenergy potential in 2050 has been identified at around 80–100 EJ/a of primary energy [21,29,36,40].

2.1.3. *Nuclear power*

The overall sustainability of nuclear power was recently discussed in the context of the Finnish energy system [41]. Several sustainability issues related to nuclear power were also discussed that were global in nature. First, there are environmental concerns regarding decommissioning of nuclear power plants and the disposal of nuclear waste. In many parts of the world, such as Finland, sites of nuclear plants are not expected to be recovered back to their original state, and become permanently affected by previous operations. This, along with the long lifetime of nuclear waste, represents an inter-generational ethical dilemma of whether current society has the right to impact the environment over such a long time scale. Second, Leuraud et al. [42] showed a link between protracted low-dose radiation exposure and an increased risk of leukaemia in nuclear power plant workers. Third, Sovacool et al. estimate that a collective 686 global nuclear safety incidents from 1950 to 2014, including large-scale events such as those witnessed in Fukushima and Chernobyl, have resulted in approximately USD 265 billion in property damage and 182,794 deaths. These larger-scale events also have irreparable impacts on ecosystems due to genetic mutations in flora and fauna [43], and also spread impacts over greater distances [44,45]. Moreover, it is estimated that disasters similar in magnitude to Fukushima have a 50% probability of occurrence every 60–150 years [46]. In addition, while the frequency of such events appears to be decreasing, their overall severity has increased. These serious risks to environment and health can be seen in addition to global risks associated with nuclear weapons proliferation and the potential of terrorist attacks on nuclear facilities.

It may be argued that there is an unfairness to nuclear power as a global solution for climate change mitigation due to the fact that it is not a conversion technology that promotes equity among nations. Importantly, smaller and less developed nations may find the high initial capital costs prohibitive. In addition, some nations that may aspire to have nuclear power development may have the technology denied to them due to international sanctions. In the recent case of Iran, nuclear power development was obstructed for a decade by UN sanctions, despite the country's consistent pledges that such development was for peaceful purposes. In the decade of dispute, international tensions were often high, and military posturing was prevalent, which lead to destabilisation throughout the Middle East. Furthermore, some countries may feel unsolicited pressure from neighbouring countries that opt to accept the risks associated with nuclear power. An uneven playing field may develop between international industries that either do or do not have access to highly subisdised nuclear power. More importantly, fallout from nuclear disasters does not honour national borders, leading to further possibilities of dispute. Such unfairness is not seen with renewable energy resources such as the sun and wind. While the quantity of these resources is certainly not uniform globally, there are very few regions on the planet where at least one of these resources is not plentiful. In addition, the conversion technologies are freely shared internationally. Indeed, the growth of global installed capacities of solar PV and wind turbines has lead to significant cost reduction that will continue well into the future, to the mutual benefit of all.

2.1.4. Carbon capture and storage

CCS technology is advocated as a techno-economic mandatory element of a 2 °C scenario in several studies [4,47,48]. However, this claim is questionable given the outdated cost assumptions for renewable energy in the mentioned references, in particular solar PV and supporting battery technology. CCS could be used in reducing industrial sector emissions and eradicating emissions from bioenergy combustion [49]. At the same time, the energy system should be electrified as far as possible to reduce environmental, economic and social burdens. The remaining energy services which cannot be provided through electrification, services for providing seasonal storage, or processes which require a hydrocarbon feedstock, could be substituted with renewable based synthetic hydrocarbons [50] in a carbon capture and utilisation (CCU) process. When the atmosphere is the source of carbon, no large scale CO_2 storage capacities are needed, making the Power-to-X (PtX) concept climate neutral, and removing fuel extraction impacts on the environment. In the end, the entailed uncertainties surrounding fossil CCS in the remaining carbon budget in limiting global warming are large. However, risks are much smaller in a pathway which includes a phase out of fossil fuels starting immediately together with the scale-up of renewable power, compared to a pathway with the continued burning of fossil fuels and advocated large scale CCS deployment scale-up within this century. Indeed, so-called 'negative emissions' schemes have recently been challenged [51] as a method of respecting the 2 °C guardrail. Instead, bioenergy with CCS (BECCS) and direct air CCS (DACCS) have been advocated with the important proviso that sustainable sequestration schemes can be deployed. For example, Kriegler et al. point out there is a need for about 10 Gt of CO_{2eq} removal in the 2050 s to achieve the 1.5–2 °C pathways, and BECCS would be a suitable method [52].

There are several more reasons to question the sustainability of CCS. Importantly, costs of carbon capture and storage (CCS) technologies are high compared to alternatives [53]. One of the flagship US CCS plants is years behind schedule, billions of dollars over-budget, and may never turn a profit [54]. Next, the main restrictions for CCS are that the technology is not currently applied beyond a demonstration level in the power sector, potential storage capacities are limited both globally and regionally, relatively small leakage rates can compromise the climate stabilization function, there are remaining emissions from fossil fuel extraction, and there are no ancillary benefits [29]. Finally, recent research findings [55] raise hopes that where substantial quantities of water and porous basaltic rocks are available, CO_2 (for example released from geothermal sites in Iceland) could be safely stored in basaltic rocks. However, considering the remaining constraints of the technology, wide range deployment of fossil CCS in the power sector is not part of a sustainable energy system.

2.1.5. Direct and indirect subsidies

It is difficult to compare the economics of energy technologies on a vis-á-vis basis as subsidies cloud the issue. According to IEA definitions, fossil-fuel and renewable energy subsidies were 493 and 135 bUSD (380 and 104 b€) in 2014, respectively [56]. These same subsidies for fossil fuels result in premature deaths through local air pollution, exacerbate congestion of vehicles and increase atmospheric greenhouse gas concentrations [57]. Taking this into account, the International Monetary Fund (IMF) reports that the subsidies for coal alone cost 3.9% of global GDP, while total fossil fuel subsidies amounted to 6.5% of global GDP, or 5302 bUSD (4078 b€), in 2015 [57]. In addition, it is often neglected that as major economies rely on imported energy, part of their military expenditures can be accounted for in securing overseas supplies of energy, adding to the energy bill of fossil fuels. An estimate puts the annual military costs for the US securing Persian Gulf oil supplies at 219 bUSD for 1976–2007 [58]. Delucchi and Murphy [59] estimate the opportunity cost and conclude that, were there no oil in the Persian Gulf, then US combined wartime and peacetime defense expenditures might have been reduced by 27–73 $bUSD_{2004}$ per year, of which 6–25 $bUSD_{2004}$ is attributable to motor vehicle use.

The subsidies for nuclear power are even more elusive to pinpoint in the publicly available literature. In IEA statistics, cumulative public energy R&D spending on nuclear constitutes 48%, or 211b€ (274 bUSD), and renewables 11%, or 50 b€ (66 bUSD), of the total 443 b€ (576 bUSD) R&D spending in OECD countries over the time period 1974 – 2014 [60]. According to a FS-UNEP study [61], global energy R &D expenditure on renewables totaled 9.1 bUSD (7 b€) in 2015, with corporate funding amounting to 4.7 bUSD (3.6 b€). Solar energy alone attracted 4.5 bUSD (3.5 b€), of which 2.6 bUSD (2 b€) was corporate investments. The private sector has been responsible for the majority of cumulative R&D investments in solar PV over the recent decades, and the sum of this contribution is only 2% of historic, mostly public, R&D money spent on nuclear energy [62]. Despite this fact, solar PV has been able to achieve a lower LCOE than nuclear power. Further, no nuclear power plant could be built if owners had to pay for the full cost of liability insurance [63]. However, this indirect subsidy is difficult to comparably quantify, since there is no payment unless a catastrophe occurs. Neglecting the NELD of a nuclear meltdown, this could be compared to a loan guarantee given for accruing a PV manufacturing facility, which would have to be paid only if the fabricator failed to repay its lenders. However, given that PV systems show accelerating diffusion and have demonstrated a very stable learning rate, the guarantee given to a PV manufacturer instead of to a nuclear power plant shows much less risks and better long-term profitability for a government [62,63]. In most European countries, operators need to cover only 700 M€ (910 bUSD) of damages (with the government covering an equal share), and in the US, the Price-Anderson Nuclear Industries Indemnity Act covers up to 13 bUSD (10 b€) for a single accident [64]. However, after the Fukushima accident, the Court of Audit has reevaluated the risks of nuclear reactors in France. Consequently, the future liabilities for new reactors could add 15 €/MWh (19.5 USD/MWh) to the levelised cost of electricity if operator liability is capped around 100 b€ (130 bUSD) [64].

Even excluding the liability costs, nuclear technology does not compare well financially with alternative energy sources (and especially poorly considering future prospects), with the LCOE of Hinkley Point C estimated at 113 €/MWh [53]. The opportunity cost of nuclear power is raised by a risk of a terrorist attack, and the subsequent immediate deaths and carbon emissions due to burning of buildings and infrastructure. The opportunity cost of nuclear power is further increased by the longer commissioning delays experienced by nuclear technology compared to alternative technologies [65]. Thus, the main restrictions on nuclear power are unresolved problems of long-term waste disposal, the risk of catastrophic accidents and associated liabilities, possible proliferation of weapons-grade fissile material and the failure of the technology to provide significant generation capacity regardless of highest levels of governmental support [29]. Finally, institutions have proposed global nuclear phase-out scenarios in their sustainable energy studies [21,29,36,49,66], advocating for a major risk aversion and consideration of future generations, who would otherwise have to bear the responsibility of keeping an increased number of waste sites sealed off from the biosphere.

Now that important issues related to energy systems have been discussed in the context of a wider set of sustainability criteria, it is important to re-examine how influential energy scenario frameworks conform to or deviate from this proposed sustainability hierarchy. In essence, these scenarios were assessed on how a full range of sustainability considerations were taken into account. Upon such an examination, recommendations can be made regarding how such a hierarchy can be operationalised more completely in the future.

3. Methods

In total, eight studies, some with multiple scenarios, were selected as representative of global scenario modeling work based on their geographic scope. A wider range of studies was considered in related work [67], but the number was reduced to those that had a common representation of a global energy system scenario for 2050. A further criteria related to study selection included a perceived relevance and influence of the studies. In addition, each showed a specific goal being reached as well as a clear pathway towards it from the present time. The complete list of studies is:

- Royal Dutch Shell: Mountains & Oceans scenarios [68]
  Two scenarios provide storylines describing the pace of change, policy agenda and resource landscapes. The Mountains scenario presents a more centralized energy system based on fossil and nuclear fuels, with more advanced use of CCS. Alternatively, the more decentralized Oceans scenario has solar PV in the fore, with delayed employment of CCS. Thereby, it leads to higher emissions. The analysis extends to 2100.
- IEA: 2DS-hiRen variant [69] and WEO 450 [56]
  The IEA scenarios present unsustainable energy projections to trigger policy changes [56]. The IEA argues that the power sector should be accounted in any strategy which addresses economic growth, energy security, climate change and local air pollution [56]. Judging by the WEO contents, these are also modeling objectives in the scenario creation. Energy Technology Perspectives (ETP) provides the most advanced analysis of energy technologies in the IEA's modeling ecosystem. In the most recent studies, such as ETP 2015, an hourly resolved power sector is modeled. The main intervention scenario is the “2DS”, a pathway compatible with limiting emission to keep the average global temperature increase to 2 °C. Three variant scenarios (no CCS, hiRen, hiNuc) were included in the 2010 and 2012 versions of the report. Each has been excluded from the latest editions of ETP as equal options.
  The IEA's flagship report, World Energy Outlook (WEO), includes a “450 scenario” (referring to CO_2 concentration of 450 ppm in the atmosphere), which describes a pathway consistent with the 2 °C target. The WEO modeling tool is less accurate in representing energy technologies than ETP modeling tools, and WEO is more conservative with respect to renewables. Overall, the IEA reports show pathways in which fossil fuels and nuclear power retain a strong role in future energy systems. For example, only 20% less fossil fuels are used in 2050 compared to 2009 in the 2DS (2012) scenario. For this reason, even IEA's intervention scenarios can be seen as reinforcing a status quo. Energy subsidies for renewables are described detail, and energy subsidy reform for fossil fuels is discussed [56].
- World Energy Council: Jazz & Symphony scenarios [70]
  The Jazz scenario is one in which incumbent fossil fuel industries dominate and corporations play strong roles in the global context. In opposition, Symphony shows a pathway whereby certain renewable energies are promoted and main actors are governments. Jazz is similar to Shell's Mountains scenario in that unconventional gas is highly utilized. By contrast, unconventional fuels are more expensive in the Symphony scenario, and stronger climate policies are established. WEC assumes that a “P2G breakthrough” can occur after 2035 in the Jazz scenario. This breakthrough occurs earlier in the Symphony scenario, enabling the integration of renewables into the energy system.
- IIASA: Gea efficiency, GEA Efficiency, Mix and Supply scenarios [29]
  The Global Energy Assessment (GEA) began as an attempt in 2005 by the founding Chair of the IPCC to realistically address climate change challenges. In doing so, a comprehensive, science-based analysis was needed to assess the global energy system [29]. In total, 60 possible transformation pathways were investigated, of which 41 satisfied Global Energy Assessment (GEA) goals. The main goals were: providing energy services to about 9 billion people in 2050 while maintaining an average growth of 2% global GDP, addressing this issues of access to modern energy services and clean cooking, enhancing energy security (reducing energy trade balances), containing the mean global temperature increase to less than 2 °C, reducing ambient air pollution (and thus adversary health impacts), and mitigating anthropogenic environmental pressure. Including both industrialized and developing nations, approximately 31% less energy per capita is used in the Efficiency scenario in 2050 compared to 2005. In contrast, the Supply scenario shows about 3% more energy per capita being used. The study acknowledges the unresolved challenges related to nuclear power and CCS. As such, the two technologies are not depicted as necessities to reach the set goals. The integrated assessment models employed provide a comprehensive macroeconomic view of the energy sector and its key uncertainties. At the same time, there is a less accurate representation of energy technologies.
- WBGU: Exemplary path [21]
  IPCC scenarios provide the basis of WBGU analyses. The 450 ppm target provides the basis of the Exemplary scenario, which is also built on the assumption of high economic and energy demand growth. In such a manner, investigating how sustainability goals could be reached without deep changes in consumption patterns was possible. Several sustainability guardrails outline the IPCC scenario: securing access to modern energy services, preventing air pollution, protecting land and marine ecosystems, using bioenergy is within special sustainability limits, and phasing out nuclear power. In the 2040 s CCS is introduced but phased out by 2100, and energy production is about 50% renewable by 2050.
- WWF: The Ecofys Energy Scenario [49]
- This scenarios shows a pathway in which 95% of final energy is provided by renewables by 2050. The transition is achieved by widespread electrification of demand sectors, use of renewable energy fuels particularly for transport and industry, rapid deployment of technologies, and aggressive end-use energy savings. About 31% efficiency gain is achieved in the Ecofys Energy Scenario compared to the baseline scenario in 2050, and includes both end-use efficiency improvements and electrification. Reduction of final energy demand is about 20% over the period 2010–2050. Bioenergy utilisation (about 180 EJ/yr in terms of primary energy) greatly surpasses what is regarded as sustainable by the WBGU and Greenpeace.
- Greenpeace: energy [r]evolution & Advanced energy [r]evolution [36]
- Greenpeace has several broad goals for its scenarios, including: phasing out of subsidies for fossil fuels and nuclear energy, internalising the social and environmental costs of energy, advocating stricter efficiency standards, setting out legally binding RE targets, reforming of electricity markets to favor renewable power generation, establishing cross-sectoral RE support schemes to exploit

synergies between the power, heating/cooling and transport sectors, providing stable returns and risk minimization for investors in RE, and increasing R&D budgets for RE and energy efficiency [36]. The Greenpeace scenarios achieve a widely or fully decarbonised energy system by 2050 while also regarding environmental policy targets. Greenpeace considers the implications of a fully renewable and sustainable energy system on supply and demand sides, investments, emissions and employment. The study includes a reference pathway from IEA, an energy [r]evolution scenario from 2012 whereby 83% of final energy is provided by renewables, and an Advanced energy [r]evolution scenario for 100% renewables by 2050. The Advanced scenario is characterized by higher mobility sector electrification, and renewable hydrogen is converted into synthetic hydrocarbons to replace remaining fossil fuels. About 3% average annual growth of global GDP is assumed over the period of 2012 – 2050, and the population is assumed to be 9.5 billion in 2050. Significant efficiency gains are achieved due to both fuel switching and improvements in end-use efficiencies. In the Advanced scenario about 47% less energy is used in 2050 compared to the reference scenario (in terms of both primary and final energy demand). In addition, final energy demand is reduced about 13% over the period of 2012–2050.

- Jacobson et al.: WWS [14,71]
- Roadmaps for 139 countries which show how the electricity, mobility, heating/cooling, industry and agriculture/forestry/fishing sectors can be powered mainly by wind, water and solar resources. Efficiency gains in total energy demand due to fuel switching and electrification are around 32% compared to a reference scenario, with an additional 7% reduction due to improvements in end-use efficiency. These gains match with assumed demand growth, which results in about the same amount of primary energy being used in 2050 compared to 2012. Other noted benefits of the WWS vision include reduced air pollution, mitigated global warming, positive net creation of jobs, stabilization of energy prices, reduced energy poverty and reduced risk of international conflicts over energy resources. To begin, only the US was modeled with high spatial and temporal resolution and with energy technologies accurately represented, whereas calculations for the rest of the world were based on average annual capacity factors.

A fuller description of each model can also be found from [67]. Each scenario was examined qualitatively with respect to how they adhered to the proposed hierarchy of sustainability established earlier. In addition, scenarios were examined quantitatively in terms of the energy generation and storage technologies that were employed in 2050.

A transparency checklist was created that analyzed the presence or absence of specific types of information (general, data presentation, assumptions, modeling properties). Personal judgement was used to determine if such information was presented, and if such presentation was adequate. Judgements were discussed and agreed upon by all authors of this work. Specific categories of transparency are presented with results in Table 3.

A sustainability checklist was created related to the exemplary sustainability guardrails previously discussed. To this end, several Yes/No questions were developed to determine how three scenarios adhered to such guardrails in relation to social, environmental and economic criteria. The full list of questions is presented with results in Table 4. For both the transparency and sustainability checklists, each item was personally judged by the authors as being i) explicity stated, ii) not fully disclosed, or iii) not available / cannot be determined.

4. Results

The energy generation and storage technologies included in the reviewed scenarios are set out in Table 1 and Table 2, respectively. The credibility of energy scenarios is assessed in Table 3. Results pertaining to the sustainability checklist are presented in Table 4. A full analysis and description of the scenarios can be found in [67]. Three scenario studies are selected for sustainability assessment, and the exemplary sustainability guardrails in Table 4 could be used as a checklist in the creation of an energy scenario. Table 1 shows the major differences between scenarios regarding conversion technologies utilized. In general, each scenario employs solar and wind energy although the table does not show the precise deployment of all different technologies (solar PV vs CSP, onshore vs. offshore wind). The table also shows the consistent use of hydro and geothermal power generation. At the same time, there are several notable differences. The WWS scenario is the only one which does not use bioenergy (biomass and waste) as a source of power. Furthermore, five scenarios do not employ nulcear power. Three of these same scenarios also do not show the use of fossil fuels or CCS technology. Of note is that all scenarios but one [21] which show nuclear capacity also show the need for CCS.

Table 2 shows the major differences between scenarios regarding storage technologies utilized. PtG storage technology is employed in all but the IEA 450 scenario. Battery technology is employed in all scenarios, but the importance of V2G connections is mixed (4 out of 9 scenarios). There is a tendency to employ both CAES (5 out of 9 scenarios) and PHS (6 out of 9 scenarios), and almost ubiquitous use of TES (8 out of 9 scenarios). In general, scenarios that name the widest ranges of storage technologies tend to add other storage options, such as flywheels and different types of capacitors. Importantly, no single scenario has quantified the demand for storage capacities on a global level [72].

Table 3 shows the results related to a transparency check on the studied scenarios. What is most evident is that the scenarios under review did not equally report what is seen as critical background information. Such information is generally used to ensure replicability of results, and opens the scenario to further scrutiny. The Global Energy Assessment of IIASA [29] scores highest in the transparency checklist, while the New Lens Scenario of Shell [68] and the World Energy Scenarios of WEC [70] score lowest. The IEA scenarios under study are generally transparent, but more full disclosure is lacking at times in key areas such as general information, access to data, and full disclosure of cost assumptions. More than half of the scenarios under review did not fully disclose cost assumption. The area in which most scenarios performed weakest was related to how they did not fully show how there may have been variance in assumptions.

Results of the sustainability checklist are seen in Table 4. In general, The Global Energy Assessment satisfied the widest range of sustainability criteria., whereas the IEA and Greenpeace studies focussed narrowly on CO_2 emissions and mitigating climate change. In those scenarios, several important environmental criteria were not addressed in the analyses, and the same was observed for several social criteria. Economic criteria were handled adequately in each scenario, but fuller disclosure is needed.

5. Discussion

It has been argued that the Paris agreement of COP21 is “a historical achievement and a genuine triumph of reasoning”, and that it is now time to implement action [51]. At the same time, much of the policy needed to begin climate action is underpinned by energy system modeling, some of which is not readily transparent [75]. Therefore, the need for openess, fairness, accuracy, and constructive criticism of energy system scenario design has never been greater in order to “avoid the looming humanitarian tragedy” [51]. At the heart of future energy scenario design are the roles played by various energy resources, conversion technologies and storage systems. However, the prominence of these roles varies greatly in each of the scenarios under investigation. For these reasons, sustainability guardrails beyond the scope of CO_2 emissions has been employed in order to safeguard critical planetary boundaries.

Comparison of included energy technologies (Table 1, Fig. 3) shows the diversity of thought on the relevance of each in future energy

Table 1
Power generation technologies included in the scenarios. Adapted from [67].

Deployed power generation technologies	Scenario													
	Royal Dutch Shell [68]		IEA		WEC [70]		IIASA [29]			WBGU [21]	WWF [49]	Greenpeace [36]		Jacobson et al. [14]
	Mountains	Oceans	2DS hiRen [69]	450 [56]	Jazz	Sym-phony	Effi-ciency	Mix	Supply	Exemplary	The Ecofys Scenario	Energy [r] evolution	Advanced energy [r] evolution	WWS
Solar	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Wind	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hydro	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bioenergy	X	X	X	X	X	X	X	X	X	X	X	X	X	
Geothermal	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ocean			X	X						X	X	X	X	X
Nuclear	X	X	X	X	X	X	X	X	X					
Coal	X	X	X	X	X	X	X	X	X	X		X		
Gas (fossil)	X	X	X	X	X	X	X	X	X	X		X		
Oil	X	X	X	X	X	X	X	X	X	X		X		
CCS, after	~2020	~2040	~2020	~2020	~2035	~2030	~2040	~2030	~2025	2040				

scenarios. Firstly, it can be seen that the WWS scenario [14] is a clear outlier in the group since it excludes bioenergy altogether. However, it remains unclear as to why the previously identified potential (80–100 EJ/a) of sustainable biomass and waste cannot be utilized as energy resources, especially in light of vibrant forest and agriculture industries worldwide. Secondly, the role of CCS in future energy scenarios is not universally accepted. WBGU [21] assumes fossil CCS is introduced in the 2040 s and phased out by 2100. Interestingly, IIASA [29] claims that CCS and nuclear power are technological options, not necessities. IEA [48] does not justify or explain its value choice of having both nuclear and CCS capacity ramp-ups. Notably, IEA had three variant scenarios (no CCS, hiRen and hiNuc) in the Energy Technology Perspective report in the 2012 version [76], but has subsequently excluded them from the latest editions as equal options. However, the overall sustainability of CCS has been questioned (Section 2.1.4). These identified criteria are in line with Schellnhuber et al. [51], who claim there are three main reasons to reject "massive CO_2 removal or negative emissions". For one, carbon pricing will induce a prohibitively high cost and risk for investors in fossil fuels. For another, a global divestment campaign away from fossil fuels has already begun which may "demand leaving most of the fossil fuel resources in the ground". And the third reason is that the rapidly growing share of installed capacities of renewables will quickly force an implosion of the traditional, fossil fuel business paradigm. The reality of the rapidly increasing installed global capacities of solar PV and wind energy, combined with their rapidly decreasing costs, has not accurately been taken into account in energy scenarios featuring CCS and nuclear power. The same can be stated for battery storage, which is currently following a similar trajectory as solar PV and wind costs, and is equally described as too costly in the same scenarios.

The deployed energy storage technologies can be seen in Table 2. However, it proves that although energy storage technologies are discussed in the scenarios, the required capacities are not quantified. This result is in line with the findings of Koskinen and Breyer [72], who showed that global energy scenarios primarily assess storage demand qualitatively. Energy models should be able to quantify all technologies and their related costs. In addition, the dynamics and synergies of energy storage in different sectors of the energy system (power, heat, mobility) should be made evident, as is increasingly being done with continental and transcontinental energy system modeling [72]. It is insufficient to describe future energy storage with adjectives. Numbers must be used. In doing so on a global level, modellers can then estimate future costs of such technologies with greater accuracy. It follows that even the near to fully renewable scenarios with global scopes have not captured in detail how exactly the energy system would work on an hour-to-hour basis. This reveals substantial methodological shortcomings of all models used for the investigated scenarios, which also leads to a major questioning of how feasible the results of the investigated energy scenarios are at all, since a major future source of flexibility is missing in the analytical models. First insights from global analysis with hourly temporal resolution, based on real weather data and minimization of total system costs imply that global energy demand can be met in a cost-competitive manner entirely based on renewable energy technologies [14–17].

Next, Table 3 shows an assessment of transparency in the scenarios. Some of the boxes in the "General information" category are deemed yellow because it is judged they can be implicitly reasoned, although the best practice would be an explicit disclosure. A green color is given if the information is made available at least in supplementary materials online, to which there is a clear guidance in the main report. For example, the funding of the Solutions project (WWS scenario) is disclosed on the website of the project, and a great deal of supplementary materials to the scenario are also available online. Technically, WEC discloses references; however, as some of them are plain "WEC 2013", it is not possible to go to the alleged original source of information. Another stripe of yellow in the "Data" category is deemed for some scenarios, as no clear distinction is made whether presented values are output from the model or hand set (exogenous) values. The best practice of this is provided by IIASA [29], which explicitly states model inputs and outputs, and WBGU [21], which describes the climate scenario first without WBGU's own input, and then explains the modifications due to applying self-determined sustainability guardrails. However, WBGU does not provide cost assumptions, considers only one scenario fulfilling sustainability targets, and describes model properties only briefly. For scenario transparency, the best practice is set by IIASA GEA. For example, the costs are provided online with clear indication in the report, and several variant scenarios are assessed: no-nuclear, no-CCS, and level of mobility electrification varied to investigate the technical feasibility of climate targets via alternative pathways. The best practice of defining and achieving comprehensive sustainability targets is set by the visionary report by WBGU, around ten years before the other studies assessed.

The results from sustainability assessment (Table 4) highlight the absence of comprehensive sustainability targets in scenario studies, a finding which is in line with the review of environmental studies in the Global Environmental Outlook 5 (GEO 5): "Generally, the scenarios explore a wide range of possible outcomes but, importantly and by design, almost none involves meeting sustainability targets – or sets them out as objective" [77]. Based on the performed analysis, it is a clear outcome that global energy scenarios lack assessment of planetary boundaries, basic human needs and welfare, and economic prosperity, or genuine progress, as a goal instead of continued growth as measured

Table 2

Energy storage technologies and time resolution of the modeling in the assessed scenarios. H_2 = hydrogen, PtG = power-to-gas, CAES = compressed air energy storage, PHS = pumped hydro storage, TES = thermal energy storage, V2G = vehicle-to-grid. Adapted from [67].

Deployed storage technologies	Scenario													
	Royal Dutch Shell [68]		IEA		WEC [70]		IIASA [29]			WBGU [21]	WWF [49]	Greenpeace [36]		Jacobson et al. [14]
	Mountains	Oceans	2DS hiRen [69]	450 [56]	Jazz	Symphony	Efficiency	Mix	Supply	Exemplary	The Ecofys Scenario	Energy [r] evolution	Advanced energy	WWS
H_2/ PtG (renewable)	X		X		X		X			X	X	X		X
Batteries	X		X	X	X		X			X	X	X		X
V2G			X				X					X		X
CAES			X				X			X	X	X		
PHS			X	X			X			X	X	X		X
TES	X		X	X			X			X	X	X		X
Other, specified	fossil fuels, hydrogen		flywheels, super capacitators				ultra-capacitators			capacitors, flywheels		flywheels		no stationary batteries
Time-step	NA		Yearly[b]	Yearly – 5 years[d]	About 12 h, seasonal		5 years			5 years	Yearly	Hourly[e]		Yearly[f]
Total period	1960–2060[a]		2010–2050[c]	1990–2040	2010–2050		2000–2050[a]			2000–2100	2000–2050	2012–2050		2012–2050

[a] Some of the results extend to 2100.

[b] In the 2015 edition, an hourly linear dispatch model has been added to analyze the power sector.

[c] Some results provided up to 2075.

[d] . Power generation curves based on hourly data, according to shown results in WEO 2015.

[e] Representative weeks for the total year.

[f] Six year period with 30 s time-step analyzed only for the US.

Table 3
Transparency checklist for creating credible energy scenarios. Green: Explicitly stated, yellow: not fully disclosed, red: not available/ cannot be determined. Adapted from [67].

	Scenario								
Information accessibility (at least accessible through the main report; e.g. web link provided)	Royal Dutch Shell [68]	IEA [56]		WEC [70]	IIASA [29]	WBGU [21]	WWF [49]	Greenpeace [36]	Jacobson et al. [14]
	New Lens Scenarios	ETP (2DS)	WEO (450)	World Energy Scenarios	Global Energy Assessment	Exemplary	The Energy Report	energy [r]evolution	WWS
General information									
Author/ collaborators	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Ordered by whom	🟨	🟨	🟨	🟥	🟩	🟩	🟩	🟩	🟨
Funding acknowledged	🟨	🟨	🟨	🟥	🟩	🟩	🟩	🟩	🟩
Purpose of study	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Data									
References can be traced back to original sources	🟥	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩
Clear distinction of assumed, processed and modelled values	🟥	🟨	🟨	🟥	🟩	🟩	🟨	🟨	🟨
Assumptions									
Scenario frame explicitly defined	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Disclosure of costs	🟥	🟨	🟨	🟥	🟩	🟥	🟨	🟩	🟩
Climate/policy constraints considered	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩
Variants to main scenarios considered	🟥	🟩	🟥	🟨	🟩	🟨	🟥	🟥	🟥
Modelling									
Documentation traceable	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Model properties described	🟥	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩

conventionally as units of GDP. However, more appropriate indicators of progress have been developed, such as Human Development Index, Happy Planet index, Indicators of Sustainable Development (United Nations), Environmental Performance Index/Environmental Sustainability Index, Genuine Progress Indicator, and Green GDP [78].

The results of this work suggest that a greater diversity of sustainability criteria be used as guardrails in future energy scenario design. Such guardrails can be used more effectively to reduce risks for the future related to climate change. In addition, having a focus on more than just CO_2 emission mitigation would decrease the vulnerability of the system related to the broader spheres of sustainability, thereby resulting in greater overall system resilience. This observation is in line with O'Brien et al. [20], who conclude that because of the complexity of energy systems, major issue such as climate change cannot be analyzed on a single level. They argue that environmental problems must be addressed clearly in a social context. The study also advocates adherence to sustainability criteria that are hierarchical, but emphasise a need to view the hierarchy in more dynamic terms. Accordingly, they propose embracing the concept of a so-called "panarchy", within which "arrangements that include a wider group of stakeholders interacting across different levels, perhaps drawing on principles of coalition building or deliberate democracy, may better address the dynamics and complexities of climate change".

O'Brien et al. claim that there is a danger that new environmental contracts based only on CO_2 mitigation will serve to reinforce the power and economic structures that are the root cause of increased CO_2 emissions and climate change. Further, a purely environmental contract or solution that excludes social, economic and political factors would be "unlikely to change anything". For these reasons they argue that a more diverse, socio-ecological contract is preferred, one which must consider "debts to the past as well as obligations to future citizens". This idea is echoed by Folke [19], who states that the current socio-ecological system is vulnerable due to the fact that has lost resilience, which in turn has caused a lack of adaptability. They also highlight that through analyses of problems and solution on broader spatial and temporal scales, the panarchy, resilience can be recaptured. Likewise, Molyneaux et al. [79] reaffirm the idea that a broader size and scope of energy systems must be understood in order to ensure the resilience that enhances overall economic stability.

Sharifi and Yamagata [80] offer a complex conceptual framework upon which to analyze urban energy systems. This framework is also comprised of intertwined components and dimensions of sustainability which ultimately aim to ensure availability, accessibility, affordability, and acceptability of energy systems. They introduce an exhaustive list of principles that contribute to the abilities needed to ensure energy system sustainability and resilience. Upon developing 196 planning and design criteria for urban energy systems, the study divides them into five major themes: infrastructure; resources; land use, urban geometry and morphology; governance; and socio-demographic aspects and human behaviour. The authors caution that energy systems function across several scales (micro, meso, macro) and that these scales "cannot be disentangled".

Importantly, Sharifi and Yamagata [80] suggest that their broad conceptual framework and criteria can be used as an assessment tool. One of the purposes of such a tool is "to provide guidelines for future developments that can be communicated to citizens, planners, and policy makers". In this manner, the sustainability hierarchical proposed in this current work can serve as an assessment tool for energy system modellers during future energy scenario design and a more general audience who are influenced by global energy system scenario reports and publications. In the end, a more broadly informed society can engage in a more meaningful discourse on the future of energy globally.

The intention of this research was to provide a systematic review of previously published global energy scenarios in order to advance the field of energy scenario modeling. A new framework and sustainability checklist are proposed from a mix of new perspectives that are intended

Table 4
Sustainability checklist for global energy scenarios. Green: Explicitly stated, yellow: not fully disclosed, red: not mentioned. Adapted from [67].

Studies	IIASA GEA [29]		IEA WEO [56]		Greenpeace A sustainable world energy outlook [36]	
Indicators: Is there a scenario included, in which …	Yes/No	Page	Yes/No	Page	Yes/No	Page
Environmental						
a 2°C compatible pathway is presented?	Yes	1217, 1259	Yes[1]	55	Yes	
stress relief on phosphorus and nitrogen cycles is considered?	Yes/No[2]	39, 240	No[3]	481	No	
mitigation of biodiversity's rate of loss is assessed?	Yes/No[2]	240	No[4]	437	Yes[5]	223
land system change is limited (and restricted biomass for energy included)?	Yes[6]	241	No		Yes[5]	223-225
stress on freshwater use is assessed?	Yes[7]	242, 1506	Yes/No[8]	257, 338	No	
reduction of chemical pollution is assessed?	Yes/No[9]	241	No		No	
alleviation of stratospheric ozone depletion is considered?	Yes/No[2]	240	No		No	
mitigation of atmospheric aerosol loading is assessed?	Yes/No[2]	240	No		No	
mitigation of ocean acidification is assessed?	Yes/No[2]	240	No		No[10]	19
Social						
universal access to modern energy services by 2030 is considered?	Yes	1217, 1260, 1264	No[11]	107	No[12]	32
improved human health perspectives are assessed?	Yes	241, 1217, 1259	Yes/No[13]	300, 567	No	
a "nuclear phase-out" is considered?	Yes	1234, 1243	No		Yes	59
a "fossil fuel phase-out" is discussed?	Yes[14]	1284	No		Yes	59
an "energy democracy[15]" is considered?	No		No		Yes/No[16]	34
Economic						
The rate of efficiency improvements is speeded up?	Yes	1223, 1241	Yes/No[17]	396	Yes	270
diversification of primary energy mix is assessed?	Yes[18]	352, 1230	Yes/No[19]	348, 554	No	
a phase-out of pervasive energy subsidies[20] (direct incentives, breaks/credits, health/military sector expenditures, cost of emissions) is assessed?	Yes[21]	26, 42, 66	Yes/No[22]	27	Yes/No[23]	34

[1] The 450 scenario represents a pathway compatible with limiting global warming to 2 °C above the preindustrial era within the century; however, this plays a minor role in the report, which mostly builds on the"New Policies Scenario". The 450 scenario is discussed in a separate report [48].

[2] Boundaries acknowledged; energy scenario compatibility not explicitly assessed (i.e. boundaries are not endogenous to the used models).

[3] In the special assessment for India, over-consumption of nitrogen and phosphorus in fertilizers is acknowledged.

[4] In the special assessment for India, biodiversity loss in the case of using traditional biomass is acknowledged.

[5] Greenpeace applies strict sustainability criteria for biomass to ensure that biodiversity is enhanced and conflicts do not take place.

[6] Less than 15% global land cover converted to cropland. Limited bioenergy potential: 80 EJ/year in primary energy in 2050, 125 EJ/year in 2100.

[7] Global sustainable freshwater withdrawal is estimated to be in theto be in the range of 5000 – 9000 km^3/year (4000 – 6000 km^3/year for consumptive use). Current withdrawal estimated at 4000 km^3/year, of which about 3000 km^3/year is consumptive.

[8] Only coal power related freshwater consumption is assessed. Conflicts related to unconventional gas production and freshwater supply preservation acknowledged but boundaries not assessed.

[9] Pollutants contributing to human health and ecosystem damage reduced by 2030 and eliminated by 2050; no boundaries proposed or assessed.

[10] Ocean acidification is acknowledged; planetary boundaries are not promoted or proposed.

[11] Access to both electricity and clean cooking improve; however, universal access to modern energy services by 2030 is not investigated.

[12] Universal access to modern energy services is promoted, but not assessed in the scenarios.

[13] It seems reduction of local air pollution is an objective in the IEA modeling; however, boundaries are not presented for the global analysis.

[14] Fossil oil accounts for 9 – 15% of global primary energy in GEA pathways in 2050, and less than 1% by the end of the century.

[15] Here energy democracy means that the scenario's energy mix is made according to a public consultation; either existing question polls are used or stakeholders are included in the creation process of the scenario study.

[16] However, one of the key elements proposed by Greenpeace is that [renewable] energy support schemes have a public acceptance/ support.

[17] The IEA scenarios do not investigate a high electrification case in which primary energy consumption could be reduced by minimizing the share of thermal generators and internal combustion.

[18] The Shannon-Weiner Diversity Index [73] is mentioned as an example for assessing resilience of electricity generation. The"Mix"-scenario represents diversified energy portfolios.

[19] In the special assessment for India, diversification of primary energy mix, imported fuels and power generation are assessed. It is unclear whether diversification is an objective as such in IEA's modeling.

[20] Although studies usually call for the phase-out of energy subsidies, they are not usually defined or quantified in the scenarios. If such assessments, as done by IMF authors [57], were to be quantified, the intervention scenarios would likely show economic net benefits instead of costs. For a "missed benefits assessment" of global energy system, see [74].

[21] Phase-out of fossil fuel subsidies and benefits in air quality are quantified. However, more recent estimations suggest that health costs are underestimated in GEA [57].

[22] Phase-out of remaining end-user subsidies by 2030 called for in special report Energy and Climate Change [48].

[23] Phase-out of all fossil fuel subsidies is called for; however, these subsidies are not defined or assessed in the report.

to guide the creation of new, future energy scenarios by modellers. This novel checklist has been applied to three scenarios in an exemplary manner. However, it is left up to future researchers to decide exactly how to implement the recommendations in their own work. In addition, while it is beyond the scope of this work to state the full impacts of the application of the proposed guardrails, it must be acknowledged that these impacts would be significant. In essence, new sustainability goals are proposed, but it is left to future modellers to both test and find the most feasible methods of achieving them. Future scenarios should especially show the economic impacts of implementing stricter

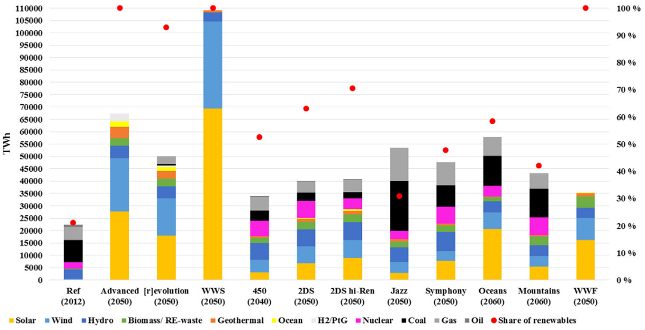

Fig. 3. Electricity generation (TWh) from different sources and share of renewable power in total generation (%) in the assessed scenarios. The reference generation for the year 2012 is based on Teske et al. [36]. For WWF and Shell scenarios the values are for final consumption, for WWS electricity generation is estimated from supplementary materials [71], and for the rest the values are for generated electricity. Adapted from [67].

sustainability criteria against alternative scenarios in a transparent manner. Part of this transparency will be acknowledging a fuller range of costs and benefits, and whether they are estimated, assumed, or real.

Future scenarios should also endeavour to show the technological challenges that may be associated with achieving greater sustainability. Moreover, adhering to the proposed sustainability guardrails may have a high relevance to future grid planning. For example, there are many ways to achieve universal access to modern energy services. In some parts of the world, this could best be achieved by expansion of high voltage grids. In others, it might be better to promote off-grid solutions or mini-grids. The challenge for scenario modellers will be to show that there may be several pathways towards sustainability, and that some may be more feasible than others in a given context. The ultimate goal of scenario modellers should always be to reduce uncertainty about the future, and to expand meaningful scientific and public discourse on the transition towards greater sustainability in global energy systems.

6. Conclusions

Visions of how to quantify sustainability targets in real world decision making are needed to start meaningful discussions about the futures we want, and to pave the way for informed actions. For this purpose, incorporating the planetary boundaries framework into national and global decision-making is a promising and active area of present and future research. Transparency and credibility of energy scenarios can be generally improved by:

- better disclosure and clear referencing of used sources of information,
- indicating how data are processed,
- providing a full set of cost assumptions,
- exploring how variations in cost assumptions influence the outcomes of the study,
- setting objectives on sustainability targets and measuring the results in that dimension,
- discussing the impact of the scenario results on given planetary boundaries,
- implementing adequate methodology for analytically describing the major flexibility characteristics of energy systems with high shares of renewables, such as storage capacities, function of grids, demand response, resource complementarity, supply side management and energy sector coupling
- disclosure of who has ordered the study by clarifying sources of funding.

Especially, low-cost PV combined with low-cost storage is to be investigated in future research. How to operationalize environmental, socio-economic and ethical dimensions in national and international decision-making is the challenge future research needs to answer as well. Given the quantifiable, safe operation limits of Earth systems, social conventions, such as contemporary market rules, laws, taxes, subsidies and political targets should contribute to limiting human actions to within the planetary boundaries.

Energy system models should show how scenarios achieve sustainability in a broader sense. This should not be an unmanageable burden if the hierarchical framework proposed in this work is observed during scenario design. Importantly, policymakers should now have a more complete framework upon which to judge the quality of various energy system scenarios beyond the current focus on CO_2 emissions. Indeed, it should also be possible to see past possible vested interests that too often are present in the modeling of future energy system scenarios. For government officials and lawmakers, if a more broad and comprehensive criteria of sustainability is adhered to throughout the process of policymaking, it should not only be possible to achieve goals related to climate change mitigation, but also create a more resilient energy system. This would fulfill a valid social contract with the future generations, who will also be the beneficiaries of such a long-lived socio-technical system.

According to this analysis, fully renewable energy system scenarios fulfill a set of environmental, socio-economic, and ethical sustainability objectives in the most comprehensive manner. For this reason, fully renewable energy system scenarios should thus be regarded as real policy options and set as references for alternative options.

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Publication III

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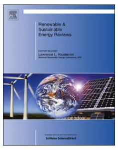

Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050

Michael Child*, Christian Breyer

Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

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ABSTRACT

An energy system based entirely on renewable energy (RE) is possible for Finland in 2050 based on the assumptions in this study. High shares of solar PV (photovoltaics) were deemed to be feasible at extreme northern latitudes when supported by flexibility harnessed from other aspects of the energy system, suggesting that high variations in solar irradiation throughout the year may not be a barrier to the implementation of solar PV closer to the poles. A 100% RE system corresponds to a highly competitive cost solution for Finland, as total system costs decrease through interaction between the power, heating/cooling and mobility sectors. We incorporate these sectors on an hourly resolution using historical data and the EnergyPLAN modelling tool. In addition, we offer full transparency of all assumptions regarding the Finnish energy system. In 2050, a 100% renewable energy scenario has the lowest overall annual cost, at 24.1 b€/a. This is followed by several scenarios that feature increasing levels of nuclear power, which range in annual costs to 26.4 b€/a. Scenarios were also modelled with varying levels of forest-based biomass. Results suggest that annual costs do not increase dramatically with reduced levels of forest-based biomass fuel use. At the same time, it must be kept in mind that assigning costs to the future is inherently uncertain. How future societies assign risk to technologies or place value on emissions can make the scenarios under investigation more or less attractive. The 100% RE scenarios under investigation were seen as less exposed to such uncertainty.

Contents

1. Introduction . . . 518
2. Materials and methods . . . 520
   2.1. The EnergyPLAN simulation tool . . . 520
   2.2. Verification of the EnergyPLAN simulation tool . . . 521
   2.3. Establishment of baseline scenarios . . . 522
      2.3.1. Establishment of baseline scenario for 2020 . . . 522
      2.3.2. Establishment of baseline scenario for 2050 . . . 522
   2.4. Establishment of test scenarios for 2050 . . . 523
   2.5. Cost assumptions for the Finnish energy system . . . 526
3. Results . . . 527
4. Discussion . . . 528
5. Conclusions . . . 533
Acknowledgements . . . 533
Appendix A. Supplementary material . . . 533

Abbreviations: RE, renewable energy; PV, photovoltaic; GHG, greenhouse gas; LPG, liquid petroleum gas; CHP, combined heat and power; DH, district heating; BAU, business as usual; $_e$, electric units; $_{th}$, thermal units; $_{gas}$, gas units; $_p$, nominal or peak capacity; TPED, total primary energy demand; PtG, Power-to-gas; PtL, Power-to-liquid; PtX, Power-to-chemical; V2G, Vehicle-to-grid; BEV, Battery electric vehicle; Capex, Capital expenditures; Opex, Operating and maintenance expenditures; LCOE, Levelized cost of electricity; WACC, Weighted average cost of capital; Crf, Capital recovery factor; GDP, Gross Domestic Product

* Corresponding author.
E-mail address: Michael.Child@lut.fi (M. Child).

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References 533

1. Introduction

Across the European Union, efforts are underway to achieve greenhouse gas (GHG) emission reduction targets set for 2020 [1]. Concurrently, many countries are looking beyond 2020 and examining the roles of various renewable energy technologies within energy systems. More and more, the concept of integrating the power, heating/cooling and transport sectors of the energy system becomes prominent in discussions [2–5], perhaps to the point that examining any of these sectors in isolation becomes almost meaningless. The most progressive actions to plan and model future energy systems appear to be in Denmark. Beginning in 2006, the Danish Association of Engineers (IDA) initiated discussions concerning the future of the Danish energy system for both 2030 and 2050 [6]. This work culminated in the IDA Energy Plan 2030 [7] and the IDA Climate Plan 2050 for Denmark. Since that time, several seminal studies of energy systems based entirely on renewable energy have been published [2,8–10]. Recently, the components and workings of a Smart Energy System were outlined based on the work of Coherent Energy and Environmental System Analyses (CEESA) researchers, also based in Denmark [11]. Such approaches aid in identifying least cost solutions for 100% renewable energy systems that fully integrate the power, heating/cooling and transport sectors, and unlock the potential flexibility throughout the entire energy system.

On a practical front, Germany has emerged as a global leader in deploying the physical elements of a Smart Energy System. According to the Fraunhofer Institute, Germany has more than 75 GW_e of installed capacity of wind and solar power plants, which reached a maximum output of almost 40 GW_e in late 2014 and 79 TWh_e in total for the year [12]. All renewable power systems reached a capacity of 93 GW_e by the end of 2014, generating electricity of 161 TWh_e in total for the year [13]. At the same time, the country is finding positive business models for energy storage solutions to support such high shares of RE, such as Power-to-Gas (PtG) [14], Power-to-Liquid [15], thermal energy storage [16] and battery storage [17]. These solutions not only provide the needed energy services for the entire country, but can provide the needed grid services often reserved for large, base load power plants.

Germany, Denmark and Finland are countries that share similar geographies, populations, levels of affluence, ways of life and climate. These similarities result in the question of whether an energy system based on high shares of renewable energy would be suitable for Finland. On the supply side, there appears to be great potential to add flexibility to the Finnish energy system [18] by integrating energy system components. However, the extent of this potential has not been explored in detail. It appears worthwhile at least to investigate how much more potential exists within the Finnish energy system, and to determine the components and workings of a fully-integrated, future energy system.

Several reports have documented the results of scenario-based modelling of the Finnish energy system [19–25]. In addition, peer-reviewed articles have recently appeared that have examined the role of high shares of variable renewable energy in Finland [18,26,27]. While each report and article has contributed greatly to discussions about the future of the Finnish energy system, each has its own limitations or lacks an essential quality. For this reason, new standards must be set for scenario modelling so that the following conditions are met:

- Analysis of integrated energy systems which include the power, heating/cooling and transport sectors
- Calculations made on at least an hourly resolution
- Incorporation of real demand and production data as much as possible
- Full transparency of technical and economic assumptions

The last criteria may be the most critical to the success of scenario modelling, which has two interrelated functions. First, it shows future possibilities in a detailed manner and invites comparison of several alternatives. Second, it invites reflection, criticism and discussion around the key assumptions and their sensitivities. The aim of modelling future scenarios must not be seen as prediction, nor must it be seen as directive ideology. Instead, it must be viewed as a representation of the possible or probable components of the future scenario under investigation given the assumptions used. In a best-case scenario, modelling will be robust enough to account for several plausible futures at the same time. In the end, the real value of future scenario modelling becomes the subsequent discourse around it. For there to be any real merit in such discourse, transparency is essential.

The most recent peer-reviewed study of the Finnish energy system [27] satisfies each of the above criteria. However, the main objective of determining a maximum limit to the integration of renewable energy into the existing energy system begs the question of how results might be different based on a future energy system that might be very different from the current one. In particular, the impact of high shares of solar PV, a technology emerging as a least cost solution around the world [12], is not well known in areas of such extreme northern latitudes. In many ways, Finland represents a proving ground for solar PV due to high variations in solar irradiation throughout the year. Although the country sees high amounts of sunlight in the summer months, the long, dark winters present a challenge for the energy system to find alternate resources at that time. Utilizing storage technologies to better match supply with demand seems obvious. However, the precise mix of production and storage technologies that would be optimal for Finland has not been explored for a fully integrated energy system. Further, demonstrating the feasibility of high shares of solar PV in Finland could have relevance to the other Nordic countries, and indeed serve as a model for other countries at high northern latitudes, such as Russia, the UK, Canada, and the USA. Results could even offer potential insights for countries at high southern latitudes. Naturally, such a future energy system would be speculative by nature and would therefore require several guiding principles to provide a framework of system requirements. These requirements will be discussed after a brief description of the components of the current Finnish energy system.

Demand for energy services in Finland is high due to the needs of an industrious society in a Nordic climate. Since 2000, Total Energy Consumption has stabilized at approximately 380 TWh_{th}, with final electricity consumption of approximately 85 TWh_e, final heat demand of 80 TWh_{th}, and transport demand of roughly 50 TWh_{th} [28]. Currently, the share of renewable energy of total consumption is 32% and is set to rise to at least 38% of final energy consumption by 2020 under Finnish commitments to EU energy climate targets [22]. In the power sector, the share of renewables is 41% [28]. The targets also include a 20% reduction in GHG emissions compared to 1990 levels, a 20% share of biofuel use in transport and a 20% increase in energy efficiency compared to 2007 levels. The sources of energy consumption are shown in

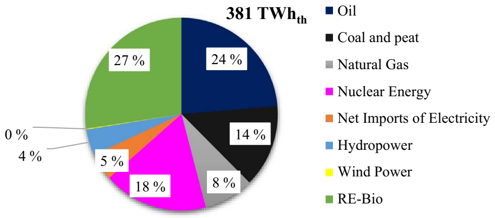

Fig. 1. Total Energy Consumption in Finland in 2012 by fuel source [28].

Fig. 1.

Renewable energy generation in Finland is currently dominated by hydropower (3111 MW_e of installed capacity) [28], but wind energy (627 MW_e at the end of 2014 [29]) and solar PV (13 MW_p at the end of 2013 [30]) are expected to be increased significantly in the years to come. In the case of wind power, a national feed-in tariff has led to high interest in developing wind power projects. Currently, more than 11,000 MW_e of wind power projects are in various stages of planning and development, including 2200 MW_e of offshore projects [31]. A national feed-in tariff also promotes biomass-based energy generation, but does not currently include incentives for solar power projects.

Of note is that Finland currently has one nuclear power plant nearing the end of construction (1600 MW_e) in addition to several that are nearing their end of life. Finnish parliament has recently granted a construction permit for another (1200 MW_e) to replace two reactors due to have their operating permits expire in 2018 but expected to be extended to 2040 (total 1760 MW_e), and two more expected to be decommissioned by 2030 (total 976 MW_e).

Nuclear energy generation in Finland is not without controversy. In particular, the Olkiluoto 3 project has experienced long construction delays and budget overruns. It has been reported that the 1 600 MW_e facility will have a final price of more than 8.6 b€ [32], similar to a facility in France where the same type of reactor has been constructed [33]. Moreover, estimates for the greenfield Fennovoima project are for a construction cost of 6 b€ for the 1 200 MW_e facility [34]. The expected technology provider for the Fennovoima project is faced with similar cost and time overruns in other projects [35] as the technology provider for the other Finnish and French plants. The latest European nuclear power project, Hinkley C in the UK, emphasizes the steady increase in cost, expected to be 24.5 bGBP for the 3200 MW_e facility [36]. This overnight cost does not include financing, waste management or decommissioning costs, which need to be considered in cost assumptions to reflect the real price of nuclear power. These specific controversies can be added to more general concerns related to long-term disposal of waste, increasing costs of securing nuclear plants against terrorism, and worries of nuclear accidents [37]. Comprehensive analyses for the past decades show budget and time overruns of more than 100% are the usual outcome for nuclear [38]. Also, due to a negative learning rate of nuclear, the latest projects are higher in cost than previous ones [39]. The negligibly small liability insurance for nuclear power projects represents a major subsidy [40] and is difficult to argue for in a post-Fukushima world. Recent research on nuclear disaster risk concluded that there is a 50% chance of a Chernobyl-type event occurring in the next 27 years [41]. This results in very challenging economics for nuclear energy being competitive in the future with solar and wind energy in Europe [42].

Oil and coal based energy generation is expected to decrease significantly in the years to come to achieve overall energy and climate change goals in Finland and globally [43]. The role of peat remains unclear, but it has been viewed as a strategic and important domestic energy resource [22].

The role of biomass in Finland is equally uncertain. On the one hand, total forest biomass in Finland is large and increasing [28]. At the same time, bioenergy from agricultural residues has great, almost untapped potential [44]. On the other hand, there is uncertainty regarding the amount of bioenergy that can be taken sustainably from forest and field. For that reason, it is at least tempting to investigate whether high shares of renewable energy generation can be achieved in a context of forest-based biomass being utilized only when it is a by-product of some other process. This would roughly correspond to the current situation in Finland, where forest biomass is not cultivated specifically as bioenergy, but is a derivative of the final harvesting of timber and pulpwood, or other forest management activities, such as thinning operations.

This work seeks to envision and analyse recarbonized energy system scenarios for Finland. In this work we defined a recarbonized energy system as one which seeks not only to eliminate or reduce overall carbon emissions, but to replace the fossil-based carbon within the energy system with carbon-based fuels derived from synthetic or biogenic sources. One of the first guiding principles of this analysis is that the structure of the current energy system should not place unnecessary restrictions on the design of a future energy system. At the same time, the demands put upon the Finnish energy system should still be met. Accordingly, the fundamental requirements of the Finnish energy system [22,45] are:

- To increase energy self-sufficiency
- To ensure sufficiency, adequacy and sustainability of energy services in a cost-efficient manner both currently and in the future
- To fulfil societal, Government, European Union and international commitments related to energy efficiency, use of renewable energy and climate change mitigation
- To maintain the competitiveness of Finnish industry

Added to these requirements, a key assumption of this work is that any future energy system must result in essentially zero emissions of greenhouse gases (GHGs). As a goal of Finland is to achieve an approximate 80–95% decrease in GHGs compared to 1990 levels by 2050, this greatly restricts emissions that can arise from the energy system. The 1990 GHG emission level assigned to Finland by United Nations Framework Convention on Climate Change (UNFCCC) was 71 Mtons of CO_2 equivalent [46]. This means that by 2050, Finland must reduce emissions to 4–14 Mtons to achieve the target. GHG emissions for Finland in 2012 were approximately 64 Mtons [28], with non-energy sectors such as agriculture, industry, construction, water supply, and waste management accounting for approximately 26 Mtons combined. If reductions beyond half of the current non-energy emissions may not be possible without severe disruption to way of life, achieving the minimum reduction goals can only come from drastic reductions in the energy sector. Therefore, GHG emissions from the energy sector must essentially be zero unless flexibility mechanisms, such as emission trading, are used extensively.

For these reasons, the primary aims of this study are as follows:

- To examine the components of a fully-integrated (power, heating/cooling and mobility) fully-functional, reliable and recarbonized energy system for Finland in 2050
- To determine the extent to which differing levels of nuclear power and forest-based biomass affect the cost of such an energy system
- To explore scenarios with high shares of variable renewable energy generation, with a particular focus on the roles of Power-to-Gas (PtG), Power-to-Liquid (PtL) and energy storage

technologies
- To develop future energy scenario modelling methodology in Finland that includes complete transparency of modelling assumptions
- To encourage discourse on energy-related issues that will contribute to the transformation of the Finnish energy system towards long-term sustainability

2. Materials and methods

The methodology of this study is divided into five main sections. First, the modelling tool EnergyPLAN is described. Second, a reference model for the year 2012 is built and verified for accuracy. Third, reference scenarios for the years 2020 and 2050 are presented to offer comparison of recognized baselines in Finland with eight test scenarios. The 2020 baseline is also constructed to promote transparency and allow analysis of how EnergyPLAN represents the baselines recognized by the Finnish Ministry of the Economy and Employment [20,22]. Fourth, eight recarbonized energy system scenarios are constructed for Finland in 2050 and compared to a Business As Usual (BAU) scenario for the same year [20,22]. A visual representation of the main starting parameters of all scenarios is shown in Fig. 2. Fifth, detailed assumptions related to costs within the Finnish energy system for 2020 and 2050 are introduced. Results for all simulations are then compiled and analysed. In the sections that follow, the main inputs to EnergyPLAN, including important assumptions and sources of information, will be outlined. However, a more thorough list of inputs, assumptions and sources are compiled in Appendices A and B.

2.1. The EnergyPLAN simulation tool

The EnergyPLAN system analysis tool is a deterministic, input/output computer model that can assist in the design of energy systems on a regional, national or multi-national level. The tool has been continuously developed since 1999 at Aalborg University in Denmark and the latest version (12.0) was released in January 2015. A full description of the tool and its uses can be found at [47]. The advantages of EnergyPLAN have been well documented [48] and the tool has been used successfully to simulate energy systems with high shares of renewable energy for several countries [2,8–11,49,50], including Finland [26,27]. Importantly, EnergyPLAN helps to meet all of the conditions for scenario modelling set in the Introduction. At the same time, EnergyPLAN does have limitations related to its ability to simulate the Finnish energy system. First, data concerning generation plants is handled as aggregate data, which means that a category such as Combined Heat and Power (CHP) is treated as a single power plant that covers the entire energy system. Consequently, this aggregation does not enable the inclusion of generation plants with varying ages, efficiencies or costs, so averages need to be determined. Related to this is the issue of availability. EnergyPLAN will treat the defined production capacity as being fully available during any given hour. This creates a problem in defining generating capacity. For example, Finland had 3111 MW of installed capacity of hydropower plants in 2012, but peak capacity of only 2595 MW was available [28]. A simple method of solving this problem is to define the capacity and use a correction factor, if necessary, to adjust energy output. However, a problem arises in how to determine the costs of such generation, as EnergyPLAN will calculate costs based on the peak capacity defined and not the actual installed capacity of the system. In general, users of EnergyPLAN can only assume that installed capacity and peak capacity are the same, something that is rarely true. Second, the representation of future power market prices is somewhat simplistic. While some elasticity of power market prices can be defined and the system is capable of creating new market prices based on variable levels of supply and demand, the accuracy of this function can only be seen as sufficient. Third, while the newest version of EnergyPLAN allows the user to represent losses in the distribution of heat, it lacks this capacity for power. Fourth, the tool cannot accurately account for the complexities of import and export power in Finland.

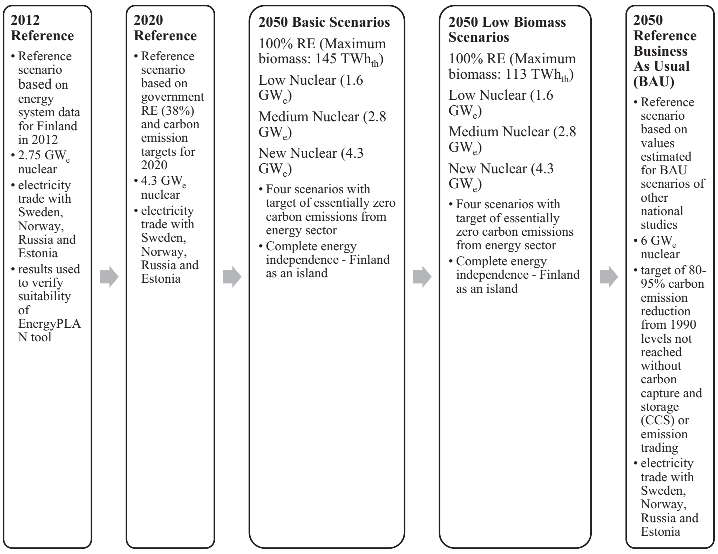

Fig. 2. Representation of main starting parameters of scenarios constructed for Finland.

Table 1
Comparison of Energy PLAN power production results with actual data for Finland 2012 [28].

Production mode	Annual production calculated by EnergyPLAN (TWh_e)	Actual annual production (TWh_e)	Difference
Hydro power	16.67	16.67	0
Wind power	0.49	0.49	0
Solar PV power	0.01	–	–
Condensing power	5.93	5.18	0.75
CHP, DH	14.33	14.51	−0.18
CHP, industry	8.78	8.78	0
Nuclear power	22.07	22.06	0.01
Total domestic production	68.28	67.69	0.59
Imports	16.89	19.09	−2.2
Net imports	16.83	17.44	−0.61
Total supply	85.11	85.13	−0.02

EnergyPLAN users must define an interconnection capacity with an external power system and the tool uses the interconnection one way in any given hour. The Finnish system, however, has multiple interconnections with neighbouring countries and the capacity to import is much higher than it is to export [51]. Finland also has interconnection to several different markets (Sweden North, Sweden Central, Norway, Estonia and Russia) that may have different power prices at a given time. Further, Finland is able to both import and export simultaneously, something that cannot be achieved with EnergyPLAN. Lastly, it is difficult to find a cost optimal energy system solution using EnergyPLAN when several categories of renewable energy generation are open in terms of their feasible capacities. In this regard, the user becomes the optimization solver. While EnergyPLAN can easily determine a cost-optimal capacity of a single category (such as onshore wind), the process of finding a cost-optimal solution for several categories simultaneously is more time consuming.

2.2. Verification of the EnergyPLAN simulation tool

In a similar manner to other studies [9,27] a reference model for Finland in the year 2012 was built and the accuracy of results were verified. Input data was based on information available from Statistics Finland [28] unless otherwise stated. Annual electricity demand was defined as 85 TWh_e and annual space heating demand as 81 TWh_{th}. In this case, hourly heat demand was based on actual power plant data provided by Fortum Heat and Power for 2012. This data was deemed representative of the distribution of heat demand throughout the entire country as it is an amalgamation of data from several heating plants. The indexed distribution (with 1 being peak demand) is shown in Appendix A. Hourly power demand was obtained from Nord Pool Spot [52]. A default hourly distribution of cooling demand was provided by the EnergyPLAN database, and the hourly production of natural cooling in Finland was derived from a default distribution available from the EnergyPLAN database and then modified with the help of an industry expert in district cooling from Fortum Heat and Power.

Annual fuel demands for Heating, Cooling, Industry and Transport were then specified. These values are available from Statistics Finland and official statistics of the Finnish Energy Industries [28,29], but some estimation was necessary for fuel demand related to space heating. While Statistics Finland specified a total space heating demand, fuel use was specified in detail for residential buildings only. At the same time, total consumption of district heating was available for both residential and other buildings (schools, hospitals, commercial buildings, etc.). This left fuel demand details for the individual boilers in non-residential buildings unknown, or a total of 8 TWh_{th} of heat demand unaccounted. This was resolved by adjusting the fuel level inputs to add 2.5, 3 and 2.5 TWh_{th} of heat demand to large oil, natural gas (NG) and biomass boilers, respectively. Estimates of population, the number of buildings and the relative share of different types of small, residential and large, other boilers for all scenarios are found in Appendix A. Inputs for industrial fuel use (excluding recycled process heat and electricity) as well as transport fuel use are also summarized for all scenarios in Appendix A.

On the supply side, power generating capacity was defined according to Table 7. Finnish Energy Industries provided the hourly distribution of nuclear, hydro and industrial power generation [29]. Hourly price data for 2012 for the Nord Pool market was found from the Nord Pool database [52]. In the case of all import and export of electricity, the Nord Pool system price was used [52]. To represent the hourly production of wind and solar photovoltaic (PV) power in Finland, distributions were constructed. This was deemed necessary considering that known data for wind and solar power production, quite limited in Finland in the reference year of 2012 (both geographically and in terms of installed capacity), could not be representative of a future energy system. In a similar manner to [53], solar irradiation and wind speed data (with spatial resolution of 0.45° latitude by 0.45° longitude) were obtained from the German Aerospace Center [54], based on NASA SSE data (Surface Meteorology and Solar Energy SSE Release 6.0) [55]. The distribution for fixed, optimally-tilted solar photovoltaic (PV) systems was derived by the same method as [53]. In addition, hourly data for both onshore and offshore wind power plants were determined for standard 3 MW wind turbines (E-101) with a hub height of 150 m.

The verification of the reference model for 2012 proceeded in the same manner as in [27], whereby outputs of heat and power were first observed and then manipulated by correction factors to reflect actual values as accurately as possible. This step was deemed necessary in order to calibrate the EnergyPLAN model to better represent the Finnish energy system. A comparison of output values with actual production data is found in Table 1.

Of notable concern were the variations seen for condensing power plants and imports, which may have been the result of the problems discussed previously of the EnergyPLAN assignment of import/export as being unidirectional in a particular hour whereas the real interconnections can accommodate simultaneous import and export. Another explanation may come from the previous comment that EnergyPLAN aggregates all generating capacity as a single, system-wide power plant with a single efficiency. In real life, less efficient individual power plants may be operating at such high marginal cost as to make imports more attractive at times. Therefore, EnergyPLAN would be incapable of displacing some power plant capacity with imports even though this could occur in reality. In addition, it was impossible to model operational disruptions and shutdowns that may have occurred to some of the capacity in real life. These same problems with verifying the reference model were also seen in Zakeri et al. [27], albeit to a lesser extent.

Other outputs were examined to determine the accuracy of the EnergyPLAN model, including total fuel consumption and CO_2 emissions. These results are compiled in Table 2. Total fuel consumption does not include such elements as heat from ambient air or industrial reactions, or recycled fuels. Emission factors for fuels used in EnergyPLAN simulations are listed in Appendix B.

Certain inputs in energy system modelling tools have inherent simplifications and generalizations. In the case of EnergyPLAN, for example, a single emission factor must be defined for each of the above fuel categories. In the case of oil, however, there are several categories, such as gasoline, diesel, fuel oil (light and heavy), LPG, etc. that individually have their own emission factors. The same

Table 2
Comparison of Energy PLAN fuel consumption results with actual data for Finland 2012 [28].

Consumption parameter	Fuel use by EnergyPLAN (TWh)	Actual annual fuel use (TWh)	Difference
Coal and Peat	51.29	52	−0.71
Oil	81.09	81	0.09
Natural gas	32.07	32	0.07
Biomass	96.82	100	−3.18
Nuclear fuel	66.89	67	−0.11
Wind	0.49	0.49	0
Solar	0.01	0	0.01
Hydroelectric	16.67	16.67	0
Total fuel consumption	345.33	349.16	−3.83
CO_2 emissions (Mtons)	48.145	46	2.145

could be stated for different types of biomass. EnergyPLAN also uses a single category that encompasses both coal and peat. Given these simplifications, the EnergyPLAN result for annual fuel use and CO_2 emissions are quite close to reality.

The EnergyPLAN tool was judged to be reasonably accurate in representing the current Finnish energy system. This accuracy is assumed to increase significantly as simplifications and generalizations of parameters of future energy systems become an inherent part of scenario design. For example, while EnergyPLAN may have difficulties representing, in an aggregated manner, all the thermal power plants of the current heterogeneous Finnish energy system, the difficulties will disappear when the thermal power plants of the future become more homogeneous by scenario design.

2.3. Establishment of baseline scenarios

2.3.1. Establishment of baseline scenario for 2020

The baseline scenarios in this work are designed to represent recognized baseline values established by previous scenario modelling [20,22]. It should be noted that since full transparency of all assumptions is not demonstrated in these reports, approximations are made for EnergyPLAN scenarios based on available data.

Hourly distributions of demand and production remain unchanged for all future scenarios. One advantageous feature of EnergyPLAN is that the tool will index all hourly distributions between values of 0 and 1, with 1 representing peak production or demand. Thereby, the magnitude of either production or consumption can be adjusted through manipulation of various technology capacities, but the relative hourly distribution stays the same.

Electricity demand for Finland is expected to be 95 TWh_e in 2020. Added to this is an electricity demand for transportation of 1.1 TWh_e. Demand for space heating is defined as 74 TWh_{th}, with approximately 30 TWh_{th} derived from district heating. Individual boiler share is defined in Appendix A. Cooling demand is expected to be 1.5 TWh_{th} in 2020, with approximately a third of this demand originating from electricity, natural cooling and adsorption heat pumps each. Industrial demand for fuel is expected to total 119.2 TWh_{th}, excluding electricity demand, with demands of 19.6, 20.9, 15.6 and 63.1 TWh_{th} for coal and peat, oil, natural gas, and biomass, respectively. Transport fuel demand is defined as 7.5, 31.5, 14.2, 3.5 and 0.5 TWh_{th} for jet fuel, diesel (includes 3 TWh_{th} biofuel), petrol (includes 1.5 TWh_{th} biofuel), natural gas and hydrogen, respectively. These transport demands represent 80 billion passenger km/a, excluding air travel.

On the supply side, capacities of major generation technologies are found in Table 7. In 2020, approximately 60% of district heat is assumed to originate from heat only plants (total capacity of 15 GW_{th}). Input shares of fuels used and efficiencies in thermal energy plants are shown in Table 3. It was assumed that a minimum capacity of 500 MW_e and 500 MW_e of CHP and condensing power plant capacity, respectively, was run at all times to provide grid stability.

Table 3
Fuel use and efficiency in thermal energy plants in Finland in 2020 [28].

Parameter	Heat only	Combined heat and power	Average power plant
Coal and peat	28.3%	38%	55%
Oil	3.4%	2%	5%
Natural gas	30.3%	30%	15%
Biomass	37.9%	30%	25%
Efficiency	$86\%_{th}$	$40\%_e$, $50\%_{th}$	$36\%_e$

Waste incineration of 1.2 TWh_{th} was assumed to have a thermal efficiency of 55% and electrical efficiency of 36%. Biomass was converted to biodiesel with 50% efficiency, and to biopetrol with 40% efficiency [56] with an additional 10% (of biomass) generation of heat for the district heating network. Next, 1 TWh_{th} of biogas was assumed to be derived from anaerobic digestion and landfill gas facilities that are connected to the Finnish gas grid. An electrolysis unit of 142 MW_e, converting electricity to hydrogen at 73% efficiency, was assumed in addition to a 2 GWh_{th} capacity of hydrogen storage. Thermal storage in the district heating network of 20 GWh_{th} was assumed based on current available capacity of 17.3 GWh_{th} plus an increase of roughly 10% related to projects that are currently being considered [57,58]. In Finland, the dominant method of thermal storage involves underground cave reservoirs, although some smaller thermal tanks are also employed [59]. Other research has shown that thermal storage of up to 100 GWh_{th} could be feasible in Finland [18,60]. However, those studies do not consider the full range of storage options or the interaction between energy sectors presented here. Initial scenario testing in this work originally utilized higher capacities of storage (50 GWh_{th}) that were not fully utilized, and were therefore reduced to prevent unnecessary costs. Lastly, 1000 and 50,000 GWh_{th} of natural gas and oil storage, respectively, are assumed based on current available capacity [61].

For 2020 Finland, a market-economic simulation was performed using EnergyPLAN, which identifies the least cost solution for the energy system based on the costs of energy generation for individual units compared with the cost of electricity that can be derived from the import market. Thereby, generation was reduced when cheaper electricity was available from the defined market. Market data was used for the 2012 Nord Pool market to represent the 2020 market.

2.3.2. Establishment of baseline scenario for 2050

For the 2050, BAU scenario, several scenario parameters were changed, again to reflect a recognized baseline for that year [22], but also to reflect assumed changes in energy conversion efficiencies used in eight test scenarios for 2050. Unless otherwise stated, all other parameters previously introduced remain unchanged from the 2020 scenario.

Electricity demand for Finland is assumed to be 95 TWh_e in 2050, of which 2 TWh_e is introduced as flexible demand. This means that up to 1500 MW_e of power could be shifted from any given hour by EnergyPLAN and distributed to other hours over a following 24 hour period according to the actual electricity balance up to a maximum of 2 TWh_e per year. Added to this is an electricity demand for Transportation of 7 TWh_e. Demand for space heating is defined as 65 TWh_{th}, with approximately 30 TWh_{th} derived from district heating. Individual boiler share is

Table 4
Fuel use and efficiency in thermal energy plants in Finland in the 2050 BAU scenario.

Parameter	Heat only	Combined heat and power	Average power plant
Coal and peat	0%	0%	25%
Oil	0%	0%	0%
Synthetic natural gas or natural gas	0%	30%	50%
Biomass	0%	70%	25%
Efficiency	–	40%$_e$, 50%$_{th}$	50%$_e$

defined in Appendix A. Cooling demand is expected to be 3 TWh_{th} in 2050, with approximately a third of this demand originating from electricity, natural cooling and adsorption heat pumps each. Industrial demand for fuel is expected to total 120 TWh_{th}, not including electricity demand, with demands of 20, 5, 30 and 65 TWh_{th} for coal and peat, oil, natural gas, and biomass, respectively. Transport fuel demand is defined as 10, 19, 5, 2 and 2 TWh_{th} for jet fuel, diesel (includes 12 TWh_{th} biofuel), petrol (includes 2 TWh_{th} biofuel), natural gas and hydrogen, respectively. These transport demands represent 80 billion passenger km per year, excluding air travel.

On the supply side, capacities of major generation technologies are found in Table 7. In 2050, no district heat is assumed to originate from heat only plants, but will come exclusively from CHP plants and heat pumps (1000 MW_e and COP of 4.5). CHP plants are divided equally in two cost categories: small decentralized and large centralized. CHP is supported by DH boilers with a capacity of 3000 MW_{th}. Input shares of fuels used and efficiencies in thermal energy plants are shown in Table 4. It was assumed that a minimum capacity of 500 MW_e and 500 MW_e of CHP and condensing power plant capacity, respectively, was run at all times to provide grid stability. Overall, a share of total electricity production can be designated as coming from so-called grid-stabilizing units, such as nuclear plants, large thermal power plants or hydropower. In reference scenarios, this share is set at 30%, a recommended level by the designers of EnergyPLAN [47]). For the 2050 BAU scenario, it was assumed that 50% of power plants were combustion plants for either pulverized coal or biomass running at 40% efficiency, and that 50% of plants were combined cycle gas turbine plants running at 60% efficiency. This represents an average efficiency for condensing power plants of 50%.

Waste incineration of 2.2 TWh_{th} was assumed to have a thermal efficiency of 50% and electrical efficiency of 40%. This represents a 1 TWh_{th} increase from 2020 to reflect greater efforts on a national level to utilize waste as a fuel [22]. Biomass was converted to biodiesel with 60% efficiency, and to biopetrol with 40% efficiency [56] with an additional 10% (of biomass) creation of heat for the district heating network. Next, 1.5 TWh_{th} of biogas was assumed to be derived from anaerobic digestion and landfill gas facilities that are connected to the Finnish gas grid. An electrolysis unit of 570 MW_e, converting electricity to hydrogen at 73% efficiency, was assumed in addition to a 10 GWh_{th} capacity of hydrogen storage. Next, 3 TWh_{th} synthetic methane was created in a CO_2 hydrogenation facility of 500 $MW_{th,gas}$ capacity. This facility consisted of an electrolyser operating at 73% conversion efficiency and a methanation unit that required 0.289 TWh_e per TWh_{th} of CO_2 recycled from air. In addition, it was assumed that 0.252 Mt of CO_2 would be needed per TWh_{th} of synthetic methane produced. As the methanation step of the PtG process is exothermic, it was assumed that 25% of the total electricity dedicated for the entire PtG process would be recovered as usable heat for the district heating system. Thermal storage in the district heating network of 20 GWh_{th} was assumed based on current available capacity [57]. Lastly, 1000 and 15 000 GWh_{th} of natural gas and oil storage, respectively, are assumed based on estimates of needed capacity.

For 2050 Finland, a technical simulation was performed using EnergyPLAN, whereby EnergyPLAN balanced both heat and electricity demands within the domestic energy system when possible. This method was selected to facilitate comparison to other test scenarios for 2050 where interconnections with neighbouring countries were restricted in order to create greater energy self-sufficiency. Trade of energy carriers was only performed when the domestic energy system was insufficient to provide for itself. Electricity market data was used for the 2012 Nord Pool market to represent the 2050 market.

2.4. Establishment of test scenarios for 2050

The main aim of test scenarios for 2050 was to create a functional and highly independent energy system for Finland without the use of fossil fuels. For this reason, a target of zero CO_2 emissions was sought outside of a small amount that would arise from the combustion of the non-biogenic portion of waste. In addition, scenarios were modified through several steps of iteration to eliminate the import of either electricity or natural gas. In the case of electricity import, the interconnections with neighbouring countries were removed and Finland was treated essentially as an island in terms of power. For this reason, excess electricity production, in other scenarios available for export, is treated as power that needs to be curtailed. Scenarios were modified through iteration if curtailment amounted to greater than 5 TWh_e, a level deemed to be too wasteful due to the fact that it represented more than 5% of end user demand.

Another important distinction was made for 2050 test scenarios involving acceptable levels of biomass. Scenario parameters were first devised that put limits on the amount of biomass that could be used to generate energy. In the so-called Basic Scenarios, a maximum value of 145 TWh_{th} of biomass fuel could be utilized. This level is based on a maximum sustainable estimate of biomass availability in Finland [62], a value similar to the one proposed by Zakeri *et al.* [27]. In the so-called Low Biomass Scenarios, a maximum value of biomass of 113 TWh_{th} was used. This value represents an amount of forest-based biomass that is currently being used for energy purposes (92 TWh_{th} in 2012) plus 21 TWh_{th} of agricultural residues estimated to be available in Finland [44]. A summary of maximum biomass potentials for scenarios is found in Table 5. Throughout modelling, scenarios were modified through iteration to keep biomass levels within acceptable limits. At the same time, utilization of maximum values were sought as well as relatively similar values (within 3 TWh_{th}) for different scenarios within the designation of Basic or Low Biomass.

Another main parameter that distinguished the test scenarios was the amount of installed nuclear power capacity. Four test scenarios (100% RE, Low Nuclear, Mid Nuclear, New Nuclear) were

Table 5
Summary of biomass potentials used for scenarios (TWh_{th}).

Parameter	2012	2020	2050 Basic scenarios	2050 Low biomass scenarios
Biomass for heat and power	36	49	68	36
Biomass for small-scale housing	18	18	18	18
Industrial liquors for energy generation	38	38	38	38
Agricultural residues for energy generation	–	10	21	21
Total biomass	92	115	145	113

created that reflected different future possibilities. In the 100% RE scenarios, there was no nuclear power capacity. In the Low Nuclear scenarios, only one nuclear power plant was in operation, equivalent to the 1600 MW_e facility already under construction. In the Mid Nuclear scenarios, two nuclear power plants existed, equivalent to 2800 MW_e of installed capacity. The New Nuclear scenarios assumed an additional facility of 1200 MW_e being constructed, for a total of 4000 MW_e.

Electricity demand for Finland is assumed to be 95 TWh_e in 2050, of which 5 TWh_e is introduced as flexible demand. This means that up to 3000 MW_e of power could be shifted from any given hour by EnergyPLAN and distributed to other hours over a following 24 hour period according to the actual electricity balance up to a maximum of 5 TWh_e per year. Added to this is an electricity demand for transportation of 10 TWh_e. Demand for space heating is defined as 65 TWh_{th}, with approximately 30 TWh_{th} derived from district heating. Individual boiler share is defined in Table 1. Cooling demand is expected to be 3 TWh_{th} in 2050, with approximately a third of this demand originating from electricity, natural cooling and adsorption heat pumps each. Industrial demand for fuel is expected to total 95 TWh_{th}, not including electricity demand, with demands of 30 and 65 TWh_{th} for synthetic grid gas, and biomass, respectively. It should be kept in mind that this reduction is assumed to be a result of energy efficiency measures, electrification and fuel switching in industry. One of the key industries in Finland is steelmaking, which provides the greatest challenge for both electrification of services and fuel switching. There are two blast furnaces operated in Finland that would be impossible to electrify. For these furnaces it is assumed that fuel switching to higher shares of natural gas would be possible, based on recent research in Japan [63], as well as utilization of biocoal in the form of char produced from the process of torrefaction or hydrothermal carbonization [64]. This would secure a solid fuel similar to lignite coal with a heating value of approximately 25 MJ/kg, a minimum level needed for steelmaking [65]. Transport demand, in addition to electricity demand already mentioned, is defined as 7, 12, 2, 2 and 2 TWh_{th} for jet fuel (includes 7 TWh_{th} biofuel), diesel (includes 12 TWh_{th} biofuel), petrol (includes 2 TWh_{th} biofuel), synthetic natural gas and hydrogen, respectively. These transport demands represent 80 billion passenger km per year, excluding air travel. In an effort to reduce overall biomass demand in Low Biomass Scenarios, half of the liquid biofuel amounts (jet fuel, diesel and petrol) are created using the PtL process (called Chemical Synthesis by EnergyPLAN) [66–68]. In such a process, fully synthetic liquid fuels are created from synthetic natural gas available from the gas grid. The efficiency of conversion was defined as 80% for each process.

On the supply side, capacities of major generation technologies are found in Table 7. In 2050 test scenarios, district heat is assumed to originate exclusively from CHP plants and heat pumps (1000 MW_e and COP of 4.5). CHP plants are divided equally in two cost categories: small decentralized and large centralized. CHP is supported by DH boilers with a capacity of 3000 MW_{th}. Input shares of fuels used and efficiencies in thermal energy plants are shown in Table 6. In all test scenarios, no minimum power plant capacity was designated to provide grid stability. This decision is similar to one made in [2]. In such a case, it is assumed that increased flexibility added to the energy system as well as improvements in provision of ancillary services by solar PV plants, wind turbines and batteries will allow for periods when no thermal power plants are operating. It must also be remembered that Finland has a large provision of hydropower that will still be used to provide grid stability. In all test scenarios, the minimum share of nuclear, large thermal power plants and hydropower needed to maintain grid stability is reduced to 18% to accommodate higher shares of renewable energy generation. For the 2050 Basic and Low Biomass scenarios, it was assumed that 50% of power plants were open cycle gas turbines running at 40% efficiency, and that 50% of plants were combined cycle gas turbine plants running at 60% efficiency. This represents an average efficiency for condensing power plants of 50%.

Table 6
Fuel use and efficiency in thermal energy plants in Finland in 2050 test scenarios.

Parameter	Heat only	Combined heat and power	Average power plant
Coal and peat	0%	0%	0%
Oil	0%	0%	0%
Synthetic natural gas	0%	40%	100%
Biomass	0%	60%	0%
Efficiency	–	$40\%_e$, $50\%_{th}$	$50\%_e$

Waste incineration and biogas production remain the same as the 2050 BAU scenario. Further amounts of biomass were utilized in Basic and Low Biomass scenarios to produce synthetic natural gas by gasification for supply to the gas grid. The efficiency of conversion was defined as 90% and the total plant capacity was assumed to be 2500 $MW_{th,gas}$. The amounts of biomass differed in each scenario as it was one of several variable parameters that will be described subsequently. An electrolysis unit of 570 MW_e, converting electricity to hydrogen at 73% efficiency, was assumed in addition to a 10 GWh_{th} capacity of hydrogen storage. Next, synthetic methane was created in a CO_2 hydrogenation facility. As the methanation step of the PtG process is exothermic, it was assumed that 25% of the total electricity dedicated for the entire PtG process would be recovered as usable heat for the district heating system. The amount of gas created and the total capacity of facilities were unique for each scenario and represents a variable parameter that will be discussed subsequently. This facility consisted of an electrolyser operating at 73% conversion efficiency and a methanation unit that required 0.289 TWh_e per TWh_{th} of CO_2 recycled from air. In addition, it was assumed that 0.252 Mt of CO_2 would be needed per TWh_{th} of synthetic methane produced. Thermal storage in the district heating network of 20 GWh_{th} was assumed based on current available capacity [57]. For all test scenarios, 20 GWh_e of stationary electric battery (lithium ion) storage was introduced, equivalent to an average of approximately 10 kWh_e of capacity for each of the 2 million estimated buildings. In reality, however, not all buildings would house battery units and capacity per unit would depend on user requirements. The total grid-to-battery connection was set at 3333 MW_e, giving an energy-to-power ratio of 6 h. The same ratio was used for the battery-to-grid connection and efficiency was set at 0.975 for both battery loading and discharging. Battery storage was also made available from electric vehicles. Three million vehicles were estimated to each have a 100 kW h lithium ion battery, totalling 300 GWh_e of capacity. It was assumed that the maximum share of cars travelling during peak electricity demand would be 20%, the share of parked cars that were grid connected would be 70%, and that the capacity of connection between the grid and batteries would be 25 000 MW_e. Half of the transport electricity demand was classified as a one-way, dump charge, and the other half was classified as having the capacity to be a two-way, smart charge. Therefore, only half of the battery capacity was available for Vehicle-to-Grid (V2G) services. This decision is admittedly conservative. However, higher participation rates in V2G connections may require a level of financial incentive that will not be explored in this study. Lastly, grid gas storage was adjusted upward from the current level of 1000 TWh_{th} to a level that prevented any need for imports. This level was adjusted for each test scenario. Annual gas storage is shown for the Basic 100% RE scenario in Appendix A.

Table 7
Installed capacities for major technologies.

Technology	Installed Capacity (GW_e)										
	2012	2020	2050 Basic 100% RE	2050 Basic Low Nuclear	2050 Basic Medium Nuclear	2050 Basic New Nuclear	2050 Low Biomass 100% RE	2050 Low Biomass Low Nuclear	2050 Low Biomass Medium Nuclear	2050 Low Biomass New Nuclear	2050 BAU
Wind onshore	0.17	1.6	30	23	18.1	13	36.5	31	26.5	23.5	3
Wind offshore	0	0.9	5	5	5	5	6	6	6	6	1.5
Solar PV	0.01	0.1	30	30	30	30	35	35	35	35	1
Hydropower	2.60	3.11	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
CHP - DH	3.49	3.5	9.4	8	7.5	7	9	8.3	7.8	5.8	4
Condensing	2.04	1.5	0	0	0	0	0	0	0	0	3
Nuclear	2.75	4.3	0	1.6	2.8	4	0	1.6	2.8	4	6
PtG (CH_4)	0	0	23.5	23.5	19.6	19.6	32.3	31.3	27.4	25.4	1.0
PtG (H_2)	0	0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Levels of renewable energy generation were defined according to Table 7. First, offshore wind capacity was set at 5000 MW_e in Basic scenarios and 6000 MW_e for Low Biomass scenarios. While the western coast of Finland sees numerous places with very good wind profiles [69], the limiting factors are the number of places available with shallow enough sea depths to make development of offshore wind economically viable as well as socially acceptable. One study has suggested that up to 6000 MW_e of offshore wind capacity could be installed [20]. However, a more conservative value was chosen for the Basic scenarios. At the same time, no authoritative inventory of offshore wind resources exists in Finland. Second, solar PV capacity was defined as 30 GW_p for the Basic Scenarios and 35 GW_p for Low Biomass scenarios. In a recent study [30], the current market demand for solar PV in Finland was determined to be 24 GW_p. However, the authors determined this value based on a current analysis of power demands. They also acknowledged that a "considerably higher market potential" could be realistic in the future once the electrification of further energy services and demands from the heat and mobility sectors for electricity were taken into account. In all scenarios, it is assumed that half of the solar PV capacity would be located on residential or commercial rooftops and the other half in larger, ground-mounted plants. Therefore, the land area requirement for such ground-mounted facilities, based on an assumed density of 0.2 km^2/MW_p [30], would be no more than 700 km^2, or about 0.2% of total Finnish land mass (338,400 km^2).

The capacity of hydropower in Finland is estimated to be 3500 MW_e, a slight increase on the current level of 3111 MW_e. Currently, several hydropower plants in Finland are being renovated and modernized, so some increase in efficiency and capacity is likely. In addition, much more "technically and economically significant" capacity exists for hydropower in Finland, up to 4257 MW_e [70]. However, much of this capacity is located in rivers that are currently protected due to environmental sensitivity, thereby creating sustainability issues. For this reason, only a small portion of this potential is likely to be exploited. Test runs of scenarios with higher shares of hydropower capacity were explored in this research, but the benefits of using higher capacities of hydropower in the Finnish energy system were deemed costly and insufficient to justify such a large potential sustainability issue.

It is assumed that the theoretical potential of Finnish onshore wind capacity could approach 100 GW_e in terms of the range of sites classified for having good (or better) wind resources [69]. The limiting factors for wind power development, therefore, have little to do with resource availability, but concern overall cost of electricity generation, social acceptance and possible land-use conflicts. For simplicity, it was assumed that no more than 4% of Finnish land area would be usable for onshore wind power generation and that the density of wind turbines would equal 8 MW_e/km^2 for standard, 3 MW_e (E-101) turbines with hub height of 150 m. This translates to approximately 108 GW_e of installed capacity, and closely resembles the capacity based on theoretical potential mentioned previously. This value was set as a maximum capacity for wind power in 2050 test scenarios, introducing another variable parameter.

Other RE technologies were available as tools within the EnergyPLAN tool, most notably concentrating solar thermal power (CSP), solar thermal energy, and geothermal electricity production. In addition, the category of pumped hydro storage was available for use in place of stationary battery storage (only one could be selected). However, each was rejected for use in this study for various reasons. CSP was deemed an economically uncompetitive alternative to solar PV electricity production combined with energy storage solutions based on previous studies [71,72]. Furthermore, the required high level of direct solar irradiance is not available in Finland [73,74]. Solar thermal energy production was assumed to remain on a relatively small scale in Finland in the future, most likely for individual production of hot water and not utilized on a wide scale for space heating [75]. This will also be driven by better economics of PV-based systems delivering a comparable energy service [76]. Next, the economically feasible potential for geothermal electricity generation is a rather low 300 MW, which may result in less than 2 TW h of elelctricity production annually [77]. At the same time, as costs of these or other technologies, or their efficiencies, improve, future analyses may need to take more serious account of these potentials.

With the set parameters defined and several variable parameters available (capacity and volume of CO_2 hydrogenation, maximum acceptable level of excess electricity production, installed capacity of wind power, installed capacity of condensing and CHP plants, maximum amount of biomass available as fuel), a series of complex iterations were undertaken to find a least-cost solution for each scenario. The process for defining the costs of system elements will be outlined in the following section. For the Power-to-Methane process [78,79], a minimum number of full load hours was established as 2000 hours per year. Iterations would continue until all the above conditions were met and there was no need for imported electricity or natural gas. An iteration was ended when all conditions were met and any changes to the parameters did not result in a decrease in total annual costs of more than 10 M€.

For 2050 Finland, a technical simulation was performed using EnergyPLAN, whereby EnergyPLAN balanced both heat and electricity demands within the domestic energy system when possible. Import of energy carriers of any type was forbidden in all test scenarios. All excess electricity production was designated as curtailment. Exports of excess synthetic natural gas was made possible. Market data was used for the 2012 Nord Pool market to represent the 2050 market.

2.5. *Cost assumptions for the Finnish energy system*

The EnergyPLAN tool contains a current cost database for almost all elements of energy systems [80], and this was used as a starting point for all cost assumptions. The most recent cost database was updated in January, 2015 and is based on an extensive analysis of energy technology cost data, including comprehensive work done by the Danish Energy Agency [81] and International Energy Agency [82]. A full disclosure of cost parameters used in this analysis is found in Appendix B. In many cases, the EnergyPLAN cost database was used directly. In others, parameters were changed based on information specific to the Finnish context or if more recent information was found. In some cases, a learning-curve approach was employed, meaning that capex costs could change for newer technologies as new capacity developed. EnergyPLAN cost distributions were developed for 2020 (also applied to the 2012 reference scenario), 2050 test scenarios, and the 2050 BAU. Scenario results were also examined using several different costs assumptions for biomass. In 2012 and 2020, biomass is assumed to have a base cost of 18 €/MWh_{th}. In 2050, this cost is assumed to rise to 21.6 €/MWh_{th}. This cost represents the price of raw material in the forest and is comparable to price estimates established by [83]. EnergyPLAN allocates additional costs for distribution, storage and refining separately. These costs can be found in Appendix B. In all scenarios, a weighted average cost of capital of 7% is assumed.

A number of cost assumptions were the result of calculations or were not originally part of the EnergyPLAN cost database. The first of these affects condensing power plants. As previously mentioned this category is an amalgamation of different types of power plants, each with its own level of cost and efficiency. Therefore, an average power plant cost category was created to reflect the amalgamation. In most cases, new condensing power plants will be based on relative cheap gas turbines. However, in some scenarios either coal or biomass-based combustion was used. These types of plants are generally much more expensive. The resulting average price may seem unrealistically high, especially when compared to CHP plants, which may appear unrealistically low. The price of CHP plants listed in Appendix B also does not include back-up boilers or thermal heat storage, both of which are accounted separately. The cost used for CHP plants was also an average based on equal shares of Small, decentralized and Large, centralized CHP plants listed in Appendix B. Through the processes of iteration mentioned above, it was noticed that very low electricity generation was occurring in condensing power plants (less than 1 TWh_e) and that some scenarios did not require any condensing power at all. Those that did generally demanded condensing power only for short periods in the summer. At the same time, EnergyPLAN allows for CHP capacity to be used in both condensing and back-pressure mode. For this reason, it was deemed sufficient to eliminate all condensing plant capacity in test scenarios.

Cost assumptions concerning some forms of power generation need further explanation. It should be kept in mind that all cost assumptions made in this study reflect future costs that may be quite different from present costs. For many technologies, such as solar PV, wind power, storage solutions and PtG, a learning/experience curve concept can be applied related to the relationship between cumulative installed capacity and costs per unit of capacity. In these cases, costs decrease as cumulative capacities increase. Conversely, some technologies show the opposite effect, and costs increase over time. This is the case for hydropower and nuclear power generation.

The learning curve concept as applied to solar PV was recently discussed in [84,85]. Accordingly, under a so-called Fast growth scenario, global cumulative capacity of PV modules is estimated to go from the current level of approximately 178 GW_p to more than 14 000 GW_p by 2050. In such a scenario, PV module price is expected to drop from the current level of slightly more than 500 €/kW_p to just over 100 €/kW_p. Moreover, Balance of System components are expected to decrease in such a scenario, resulting in overall PV system price of 320 €/kW_p for a 1MW_p, ground-mounted system. These system costs are expected to be lower still for larger ground-mounted installations (e.g. 10–50 MW_p) and somewhat higher for residential rooftop systems. In this light, this study's assumption of 300 €/kW_p (Appendix B) for ground-mounted system and 400 €/kW_p for residential rooftop systems is reasonable in an environment of fast growth, such as the one assumed for Finland in all 2050 scenarios.

Based on recent estimates of the current and future construction costs of nuclear facilities in Finland [33,34], new nuclear facilities are assumed to cost 5000 €/kW_e of installed capacity. It is also assumed that at least 10% should be added to expected construction cost to cover the costs of waste management and decommissioning. Currently, money to cover such costs is raised as a tax and put aside in the Finnish State Nuclear Waste Management Fund mandated by the Ministry of Employment and the Economy. This results in a figure of 5500 €/kW_e for 2020. From this figure, it is assumed that costs will increase roughly 6% per decade due to a negative learning rate for nuclear power. Please also note information given on nuclear power generation in the Introduction. This results in the assumption of 6500 €/kW_e for 2050 shown in Appendix B.

Concerning transport, the costs of vehicles themselves were not accounted in this study. However, the price of batteries for electric vehicles was accounted, as were the costs of connection points for Battery Electric Vehicles (BEVs). In the case of BEV battery packs, rather conservative cost estimates were used [86,87] although recent research suggests even lower costs have been forecast [88]. Details of costs can be found in Appendix B. At the same time, it was assumed that charging of vehicles, even those not participating in vehicle-to-grid services, would occur in such a manner as to not create burdens or extra costs for the electricity distribution system. Lassila *et al.* [89] describe how electric vehicles could result in significant burdens for distribution companies unless charging optimization could be achieved. It is assumed that such optimization can be achieved by 2050. Therefore, no additional costs are incurred for BEV charging demands in test scenarios.

Next, the cost of the district heating and cooling infrastructure needs further explanation. First, the number of district heating and cooling customers was specified, as were the shares of residential and commercial customers for district heating. The need for this was that substation/connection costs are quite different for residential customers (e.g. single house) than they are for larger commercial connections. District heating grid costs were determined as a product of a known cost of production (72 €/MWh_{th}) [81] and the total end-user heat demand for each scenario. Opex was assumed to be 150 €/connection [81]. From this value, it was possible to calculate opex as a percentage of capex, a number that would be used in EnergyPLAN calculations. For district cooling, very little data is publically available in Finland, so the cost of district cooling was crudely estimated. This was based entirely on the assumed capacity of the network and a known cost per unit of capacity (0.6 M€/MW_{th}) [81]. The results of this method is summarized in Appendix B.

Cost estimates were made for both the electricity and gas transmission and distribution grids based on current available data and calculations. Complicating such estimation are the many unknown variables of the future regarding levels of distributed generation. In many places, the need for grid services may be expanded, but in others they may even be eliminated. Therefore, since such uncertainty existed in all 2050 scenarios, the electricity grid costs were assumed equal in all scenarios. Similarly for the gas grid, it remains difficult to estimate how much production would be distributed and how much would be centralized, making cost estimates for the future troublesome. For this reason, gas grid costs are assumed equal in all scenarios. These current annualized costs are calculated to be 464 M€/a for electricity transmission system operation based on [90], 1340 M€/a for electricity distribution system operations based on [91], and 201 M€/a for gas transmission system operations based on [92].

3. Results

Table 7 shows the resulting capacities determined for the major technologies after iteration. Simplified flows of energy from fuel consumption to end-user demand in the form of Sankey diagrams for the 2012, 2050 Basic 100% RE, 2050 Low Biomass 100% RE and 2050 BAU scenarios are found in Appendix A.

According to EnergyPLAN outputs, the Annual Fuel Consumption needed to fuel the Finnish energy system in all scenarios is shown in Fig. 3 and associated carbon emissions in Appendix A. This category of Annual Fuel Consumption differs slightly from Total Energy Consumption in that it does not include several categories used in Fig. 1, such as refinery gases, recycled fuels, and reaction heat of industry. These were included in the categories of natural gas, oil and RE-Bio, respectively, in the calculation of Total Energy Consumption so that the final total would match official statistics. This accounts for the difference in reporting a value of 381 TWh_{th} of Total Energy Consumption for 2012 and Annual Fuel Consumption of only 345 TWh_{th} in Fig. 3. Test scenarios differ from reference scenarios primarily by their absence of fossil fuels. In test scenarios, the roles of renewable energy resources are expanded, with biomass and wind energy providing the backbone of the Finnish energy system. Test scenarios also feature primary energy that is produced domestically, unlike the current energy system or reference scenarios for 2020 and 2050 that feature high shares of imported fossil fuels. Biomass contributes to primary energy by 143 TWh_{th}, about 38%, in the Basic 100% RE scenario. A significant share of hydrogen in primary energy is noted in each test scenario, ranging from 38–64 TWh_{th}, with higher values in the Low Biomass scenarios.

In general, higher values are seen in Low Biomass test scenarios than in the Basic scenarios, reflecting higher primary energy demand in the form of onshore wind energy needed to compensate for lower availability of biomass. In test scenarios, primary energy demand increases with installed capacity of nuclear power. With the notable exception of the New nuclear scenario in the Low Biomass scenarios, each test scenario has a lower primary energy demand than the BAU scenario. Biomass contributes to primary energy by 112 TWh_{th}, about 28%, in the 100% RE scenario. The level of biomass available in the Finnish energy system, therefore, appears to have an effect on the overall level of primary energy consumed. Each test scenario shows essentially no emissions of carbon dioxide equivalent from the energy system. The BAU scenarios exhibits a 50% reduction from the 2012 and 2020 scenarios.

Electricity production (Fig. 4) increases significantly in test scenarios, led by wind and solar power. Despite lower values of onshore wind observed in scenarios with increasing shares of nuclear power, onshore wind power remains the dominant production form in Finland in test scenarios. Fig. 4 also shows that overall production is much higher in test scenarios than in reference scenarios. As shares of renewable energy in the energy system increase, so too does overall electricity generation. Conversely, higher values of nuclear generation in 2050 seems correlated to lower overall energy production. Higher production of electricity is noticed in Low Biomass scenarios than Basic scenarios due to higher shares of solar PV and wind power needed to compensate for lower forest-based biomass usage.

Fig. 5 shows electricity consumption for Basic and Low Biomass scenarios. In reference scenarios, there is a much closer relationship between total production and consumption. In test scenarios, there is a large demand for electricity in the PtG process, mostly in the case when synthetic methane is the end product. In each case, electricity consumption associated with PtG decreases with installed capacity of nuclear power. In other regards, electricity consumption in 2050 appears similar in all scenarios. The small role of flexible demand is highlighted in Fig. 5 when compared to the entire magnitude of electricity consumption. Losses associated with the charging and discharging of batteries in the V2G operation mode decrease with increasing installed nuclear capacity.

The total annual costs of the Finnish energy system are shown in Fig. 6. In 2050, the Basic 100% RE scenario has the lowest overall cost at 24.1 b€/a. Costs increase with increasing capacities of

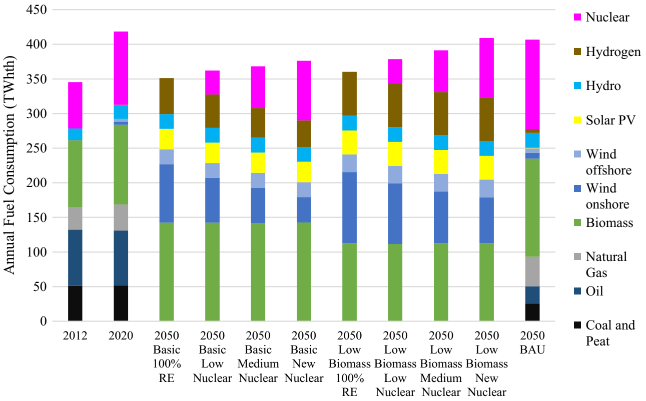

Fig. 3. Annual Fuel Consumption for all scenarios. See Appendix A for numerical values. The accounting of hydrogen as a fuel was deemed important even though it represents secondary energy and is part of the storage system.

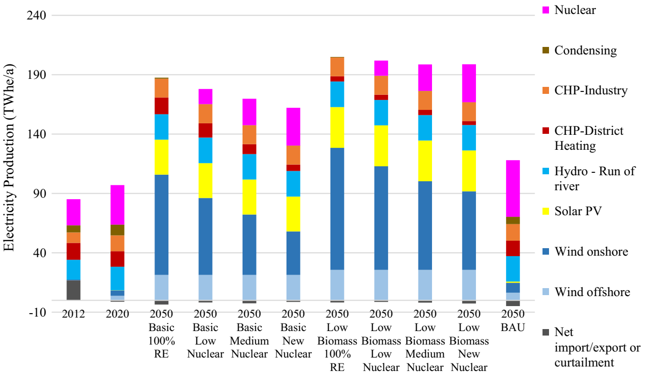

Fig. 4. Total electricity production for all scenarios.

nuclear power. Only four scenarios appear lower in cost to the 2050 BAU scenario: Basic 100% RE, Low Biomass 100% RE, Basic Low Nuclear and Basic Medium Nuclear. In 2050 test scenarios, total annual costs are dominated by annualized investment costs and fixed operational costs, whereas costs of fuel and CO_2 are significantly lower than in reference scenarios. In each scenario, total variable costs (fuel and other) are associated with increasing shares of nuclear power generation. Appendix A will also show a breakdown of major annualized investment costs for all scenarios.

Full load hours for the major energy production elements are shown in Table 8. Full load hours for solar PV in 2012 and 2020 appear larger due to rounding errors associated with very low installed capacities. Values in other scenarios are more reflective of reality. Full load hours for PtG in the 2050 BAU scenario appear inflated due to a very low installed capacity for the PtG process in that scenario (500 MW_{th}). Of particular interest are the values for CHP and synthetic methane production, which are quite low. These low values also seem to be linked to higher levels of recarbonization of the energy system in general. At the same time, specific patterns in full load hours for these technologies are difficult to discern. Levelized cost of electricity calculations are shown in Table 9. In addition, the levelized cost of energy was calculated using the same method as in Table 9 for the PtG (CH_4). Capex was assumed as 870 €/kWh_{th}, $opex_{fixed}$ as 3.3%, electricity cost of 40 €/MWh_e based on the LCOE of onshore wind (Table 9), lifetime of 30 years, overall conversion efficiency of 51% and full load hours of 2 400 h (Table 8, Basic Medium Nuclear Scenario). The result was 11.9 €cents/kWh_{th}.

4. Discussion

Given the assumptions made in this analysis, results suggest that an energy system based on 100% renewable energy is not only possible, but is competitive in cost compared to the scenarios explored, which featured variable shares of nuclear power generation. What is more, a high level of energy independence can be achieved for the Finnish energy system. Prominent roles of renewable energy generation and energy storage solutions should therefore be considered in all modelling of future Finnish energy systems and all future discourse surrounding energy policy in Finland. At the same time, the role of forest-biomass in the future

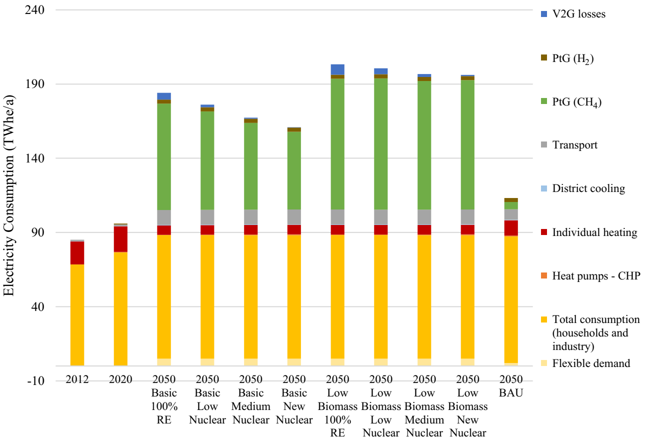

Fig. 5. Total electricity consumption for all scenarios.

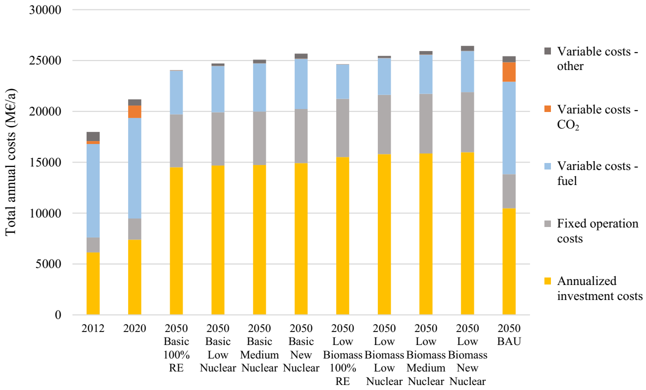

Fig. 6. Total annual costs of the energy system for all scenarios.

energy system will need to be considered carefully. Lower shares of biomass could result in higher costs and begin to favour a Business As Usual scenario that perpetuates Finnish dependence on imported fossil fuels, violates emissions reduction targets and does little to limit global warming to less than 2 °C [93]. In addition, with this BAU scenario comes an increased exposure to the risk represented by the price of carbon emissions. As the price of carbon emissions increases beyond the level chosen for this study (75 €/tCO_2), this scenario becomes less favourable. Annual costs of the BAU scenario will rise approximately 250 M€/a for every increase of 10 €/tCO_2.

The first aim of this study, given the fundamental requirements set out in the Introduction, was to examine the components of a fully-integrated, fully-functional, reliable and recarbonized energy system for Finland in 2050. Results indicate that electricity is an energy carrier that can successfully cross each sector of the energy system and can facilitate synergies between the sectors that result from use of energy stored over time in various forms. For example, electricity generated during a summer day by solar PV panels can potentially be used directly, stored in batteries for use in the evening, used to create hydrogen to power a car, or ultimately be converted to synthetic natural gas. In turn, this gas can then be stored for long periods of time for use by numerous end users that are radically displaced from the original production. So, the main feature of the type of energy system needed for Finland in the future is flexibility. Such a system will not only involve flexibility in energy generation, but should also involve some flexibility of demand by end users. One consequence of this flexibility is that a future, recarbonized energy system will be radically different from the system that currently exists. The results suggest that a future energy system will have very little need for base load generation and require power plants to follow demand and intermittent generation to a greater extent [94–98]

Recent studies of the Finnish energy system suggest that high shares of RE would be possible for Finland [60,99]. The former of these studies is a general review of storage solutions that uses Finland only in examples and has a strong focus on the power sector. At the same time, it discusses at length a range of storage and flexibility options, many of which have been employed in this current modelling work. The latter of these studies suggests that high shares of wind power would be complemented well by heat storage in the DH sector. However, this current study utilizes a wider range of storage and flexibility options, including flexible demand, V2G and stationary batteries as well as greatly expanded gas storage related to the PtG process, which has never before been considered for a fully-integrated energy system in Finland for 2050. Broader energy system integration gives rise to flexibility measures being able to cross over to other sectors at no additional cost, resulting in lower overall system costs. It is, therefore, not surprising that the results found here differ significantly from those of other studies.

Results indicate that the role of solar PV power generation is significant in all but the BAU scenario. Installed capacities of 30 GW_p in the Basic scenarios and 35 GW_p in the Low Biomass scenarios are several orders of magnitude higher than the installed capacity reported for the 2012 scenario of about 0.01 GW_p for

Table 8
Full load hours for major technologies in all scenarios.

Category	Full load hours										
	2012	2020	2050 Basic 100% RE	2050 Basic Low Nuclear	2050 Basic Medium Nuclear	2050 Basic New Nuclear	2050 Low Biomass 100% RE	2050 Low Biomass Low Nuclear	2050 Low Biomass Medium Nuclear	2050 Low Biomass New Nuclear	2050 BAU
Wind onshore	2800	2819	2816	2816	2816	2816	2816	2816	2816	2816	2817
Wind offshore	–	4278	4280	4280	4280	4280	4280	4280	4280	4280	4280
Solar PV	1000	1000	982	982	982	982	981	981	981	981	980
Hydropower	6424	6403	6123	6123	6123	6123	6123	6123	6123	6123	6123
CHP - DH	4106	3829	1591	1536	1120	797	542	545	568	590	3275
Condensing	2900	6020	–	–	–	–	–	–	–	–	2657
Nuclear	8025	7749	–	7963	7964	7963	–	7963	7964	7963	7963
PtG (CH_4)	–	–	3628	3353	3549	3180	3240	3355	3754	4065	6000
PtG (H_2)	–	3521	3509	3509	3509	3509	3509	3509	3509	3509	3509

Table 9
Levelized cost of electricity (LCOE) calculations. LCOE is expressed as levelized cost of energy (heat included) for CHP plants. WACC-Weighted annual cost of capital; crf-capital recovery factor.

For 2050 Basic Medium Nuclear Scenario	Units	Wind - onshore	Wind - offshore	Solar PV - ground mounted	Solar PV - rooftop	Hydropower - Run of the river	CHP plants	Nuclear plants
Capex	**€/kW$_e$**	900	1800	300	400	3060	820	6500
Opex$_{fixed}$	**% of capex**	4.5%	4.5%	2%	1%	4.0%	3.7%	3.5%
Opex$_{variable}$	**€/MWh$_e$**	0	0	0	0	0	2.7	0
Fuel	**€/MWh$_e$**	0	0	0	0	0	27.3	5.4
Efficiency	**%**	–	–	–	–	–	90%	37%
Lifetime	**Years**	30	30	40	40	50	25	40
Full load hours	**Hours**	2816	4280	982	982	6123	1120	7963
WACC	**%**	7%	7%	7%	7%	7%	7%	7%
crf	**%year^{-1}**	8.1%	8.1%	7.5%	7.5%	7.25%	8.6%	7.50%
LCOE	**€ cents/kWh$_e$**	4.0	5.3	2.9	3.5	5.6	12.3	10.4

Finland. Child *et al.* [100], in a separate publication, outline several challenges to high levels of solar PV, not the least of which is geography. Indeed, countries at high latitudes (both north and south) experience quite different solar PV production when compared to so-called sun-belt countries closer to the equator. For countries such as Finland, there are high amounts of solar irradiation during summer months, while winter months see considerably less. However, upon a detailed analysis of hourly data related to the Basic 100% RE scenario, it was concluded that solar PV generation can be supported by various energy storage solutions and seasonally complemented by other forms of variable RE generation, such as wind and hydro power, as well as dispatchable generation of synthetic gas and biomass-based energy in CHP plants. On a daily basis, both flexible demand and V2G batteries had noticeable association with PV generation, also observed in another more detailed study by the authors [101].

Further, in the Basic 100% RE scenario, it was determined that solar PV would generate approximately 29 TWh$_e$ of energy in 2050, which represented 16% of annual electricity production and 28% of end user electricity consumption. About 45% of this production was calculated to be used directly by end users, suggesting that storage solutions must play a strong role in solar PV systems located at high latitudes [100]. When also considering the intermittent nature of wind energy production, [101] found that, in the same scenario, approximately 47% of solar PV and wind energy combined was used directly, and confirmed the importance of storage solutions.

At the same time, [100] remind that it is not only technological challenges that must be overcome in order to facilitate such high shares of solar PV in Finland. A wide range of stakeholders (from individual consumers to political leaders and to incumbent energy companies) have vested interests which may compete against or provide barriers to high capacities of solar PV. Such vested interests as well as other political, institutional, economic and behavioural barriers are also discussed in [102]. In each case, a variety of business model, policy, regulation and behavioural options are proposed related to how such barriers can be overcome [100]. While some of these options may be seen as specific to the Finnish context, many others may be applicable to other similar countries at high latitudes. Despite the challenges of a transition towards a very different kind of energy system of the future, solar PV offers empowerment of a wide variety of stakeholders, not the least of which are individual prosumers who can gain access to a low-cost form of electricity generation.

One of the key assumptions of this study was that the future, recarbonized energy scenarios should result in essentially zero GHG emissions. While the results of this study suggest this was achieved for all the test scenarios (Table 12 in Appendix A), it must be remembered that these values do not reflect GHG emissions throughout the life cycle of all technologies. While this study was not intended to be a full life cycle assessment of the technologies utilized, some comment is necessary with regards to GHG emissions and energetic requirements related to the production of such large installed capacities of solar PV and wind power. Several studies have examined life cycle sustainability aspects of wind power and solar PV technologies and concluded that energy payback time (EPBT) and GHG emissions were far lower than fossil fuel-based or nuclear technologies [94–98,103]. Further, other emissions were consistently lower for solar PV throughout its life cycle, such heavy metals, sulphur dioxide and nitrogen-based air pollutants (NO_x). These studies also show how such life cycle impacts are also affected by the learning-curve concept, and are set to be even lower for some technologies as global installed capacities increase.

Of course, there may still be subjective aspects of sustainability that merit further societal discourse and valuation in order to ensure completeness. While these aspects remain outside the scope of this study, high installed capacities of solar PV (rooftop and ground-mounted) as well as wind turbines (onshore and offshore) may awaken feelings of both resistance and acceptance due to possible impacts on the aesthetic qualities of landscapes. It may be argued that such highly visible and widespread installations could affect tourism, property values or an individual's peace of mind (positively or negatively). Although no attempt is made in this study to assign such value, these remain important issues.

The second aim of this study was to determine the extent to which differing levels of forest-based biomass and nuclear power affect the cost of such an energy system. From the results, it appears that forest-based biomass should be utilized to maximum levels that do not violate sustainability criteria related to overall harvesting levels. Low Biomass test scenarios resulted in higher costs for the energy system, so much higher that the BAU scenario became favourable to all but the 100% RE Low Biomass option. Interestingly, the cost differences between the Basic and Low Biomass scenarios are not large, approximately 0.5 b€/a for the 100% RE scenarios. If benefits outside of the energy system could be found for minimizing forest-based biomass usage (e.g. increasing natural beauty, creating nature preserves, boosting forest-based ecotourism, gaining credits for expanding a carbon sink, etc.), these could affect the overall evaluation of the Low Biomass scenarios, making them more attractive.

With regards to nuclear power, the increase in costs of the energy system in all test scenarios (Basic and Low Biomass) was directly related to the installed capacity of nuclear power. Similar results have been found recently for the case of France [104]. In Basic scenarios, costs increased by 1.5–5% with increasing capacities of nuclear power. In Low Biomass scenarios costs increased by 3–6%. Also significant to future energy system planning is that nuclear power production represents one of the least flexible elements of an energy system. In a future energy system that requires little or no base load power, large nuclear power plants become cumbersome.

It is also important to examine the nature of annual costs. In the present Finnish energy system and in baseline scenarios, costs are dominated by variable costs related to fuel and CO_2 emissions. The test scenarios, on the other hand, are dominated by investment costs and fixed operational costs. Results indicate that approximately 10 b€ in annual costs are associated with imported oil, coal, natural gas and CO_2 in the 2050 BAU scenario. Conversely, test scenarios involve only domestic fuels. In addition, Vakkilainen *et al.* [105] assume that investment costs associated with biomass-based energy and wind power are 60% domestic and that operations and maintenance costs are 50% domestic. What is more, the same authors estimate that increasing RE in Finland can result in increased employment in the order of 100 000 person-years per year. Several other studies reach similar conclusions concerning the link between renewable energy and job creation [2,8,10].

Importantly, IRENA [106] confirms the link between renewable energy and jobs. On the manufacturing side, it is unclear how many new jobs could be created in Finland. Although solar PV panels, wind turbines, wind turbine components, and various power electronic elements are manufactured in Finland, the future of impact of domestic manufacturing would most certainly depend on levels of political support for such industry as well as on competition with lower cost imports. However, on the construction side, [106] reports that 8.6, 18.1, and 17.9 new jobs would be created (average values for OECD countries) for each installed MW of new capacity of onshore wind, offshore wind, and solar PV, respectively. Further, more permanent jobs would be created on the operations and maintenance side. [106] also reports that 0.2, 0.2, and 0.3 permanent jobs would be created for each MW of new capacity of onshore wind, offshore wind, and solar PV, respectively.

Beyond costs related to nuclear power, some comment is necessary related to the overall sustainability of this type of power generation. In terms of environmental sustainability, there are several issues of note, despite an overall excellent record for environmental safety in nuclear power plant operations in Finland. First, in the context of climate change and mitigation of CO_2, life cycle emissions of carbon equivalent are significantly higher for nuclear power than for renewable energy. Sovacool reports that while nuclear power generation does not directly emit greenhouse gases, emissions associated with the entire fuel cycle (including mining), plant construction, operation and decommissioning are higher (66 gCO_2/kWh_e) than those associated with wind energy and solar PV (9 and 32 gCO_2/kWh_e respectively) [107]. The Sovacool report has been deemed more authoritative than others [108] that claim life cycle emissions to be higher for renewable energy technologies (under 50 gCO_2/kWh_e) than nuclear power plants (5 gCO_2/kWh_e) due to the fact that a limited number of reactor types were used in the latter study and that full life cycle emissions were not considered. Similarly, [109] reports that lifecycle GHG emissions were lower for selected nuclear power (10 gCO_2/kWh_e) and higher for selected wind power plants (15 gCO_2/kWh_e) and solar PV (55 gCO_2/kWh_e). However, Verbruggen *et al.* [109] remind that the “low-carbon chip is a bit attenuated when considering the life-cycle CO_{2eq} emissions of the nuclear fission cycle and its being embedded in a largely fossil fuel-driven energy economy”. In addition, the authors see nuclear power as a barrier to a low-carbon economy rather than a driver.

Upon examination of the fuel chain for nuclear power in Finland, a recent environmental incident stands out. In 2013, the Finnish Radiation and Nuclear Safety Authority found uranium concentration in a pond near the Talvivaara mine at levels 6 times higher than are deemed to be the upper limit for safe drinking water [110]. This incident comes after leaks of several toxic chemicals were first noted a year earlier in one of the mine's waste water ponds. In other ways, nuclear power plants represent serious risk of catastrophe for both environmental and personal safety. Wheatley *et al.* estimate that an event similar in magnitude to the disaster at Fukushima has a 50% chance of occurrence every 60–150 years [111]. The authors also point out that although such accidents are currently occurring less frequently, their severity has increased. Such risks to the environment and health can be added to the risks of nuclear weapons proliferation and possibilities of terrorist attacks on nuclear power plants.

Other environmental concerns surround both decommissioning of nuclear power plants and the disposal of nuclear waste. In Finland, nuclear plants are not expected to be recovered back to so-called green fields, as is easily achievable with forms of renewable energy generation such as wind or solar power. Nuclear plant sites remain permanently affected by previous operations, an environmental damage that is never recovered. This fact, coupled with the long lifetime of nuclear waste introduces an inter-generational ethical dilemma of whether current societies have the right to affect the environment for such long periods of time. It would be a violation of sustainability criteria to impose such a decision of future generations without their consent. Other sustainability issues associated with nuclear power are also social in nature. Leuraud *et al.* established a link between protracted low-dose radiation exposure in workers from the nuclear industry and an increased risk of leukaemia [112]. In addition, [113] estimates that over the period of 1950 to 2014, approximately USD 265 billion has accumulated in property damage, 182 794 fatalities have occurred from a collective 686 accidents. Such accidents as those seen in Chernobyl and Fukushima are also known to influence ecosystems irreparably in an evolutionary sense through effects on genetic mutations in flora and fauna [114] as well as over large geographical distances [115,116].

Considering these facts, it is difficult to conclude that nuclear power is a sustainable choice for Finland in the future. At the same time, the final conclusion must be made by an informed society, one that has a clear idea of all of the alternative choices for a low-carbon future. However, [109] concludes that proponents and opponents of nuclear power have not been engaging in productive scientific debate and that alternative perspectives to the prevalent attitude that nuclear power must play a strong role in a low-carbon energy future have largely been silenced.

The third aim of this study was to explore scenarios with high shares of variable renewable energy generation, with a particular focus on Power-to-Gas (PtG), Power-to-Liquid (PtL) and energy storage technologies. Energy storage solutions feature prominently in future energy systems that are recarbonized. The robust and flexible roles of PtG (up to 15 GW_e) and PtL (up to 10 TWh_{th} production of liquid biofuels) processes were significant in solving the problem of how to compensate for the fact that solar, wind, and to a lesser extent hydropower, are intermittent resources. These numbers emphasize the increasing relevance of methane-based infrastructure (NG, SNG, biomethane) in Finland. The results for the Finnish energy system are roughly comparable to results for Germany [5,117], which shows very high shares of RE in 76 GW_e and 87 GW_e of PtG capacities for a peak load in the power of about 80 GW_e. The relative difference can be explained by higher full load hours for PtG in Germany but also in more limited German research results, since neither of the two studies comprises a fully-integrated energy system. At the same time, the potential for Finnish industry to apply this technology is already expected to be profitable for the first niche applications today [118] and the application to other areas of production seems provocative. Specifically, there may be opportunities outside of the energy sector to utilize the Power-to-X (PtX) concept [117], mainly in the chemical industry. Both hydrogen and oxygen have other uses in industrial production or can be sold for a variety of end-uses. In addition, various hydrocarbons can be created using the same technology that could have industrial applications. This could help increase the full load hours of all PtX technologies within the scenarios studied.

The fourth aim was to develop more accurate future energy scenario modelling methodology in Finland that includes transparency of modelling assumptions. The authors have endeavoured to show the sources of all inputs as well as specifically list those that are based on estimations or calculations. Also, there are several limitations, both general and specific, that have been acknowledged throughout this study. Uncertainty remains regarding optimum levels of renewable energy resources that can be utilized in Finland. To date, no comprehensive and authoritative inventory exists on the magnitude of renewable energy that can be harvested. This knowledge, coupled with the costs of harvesting, would assist in a more accurate representation of an optimum mix of technologies. Specifically, questions remain somewhat open regarding levels of biomass, wind energy (both onshore and offshore) and solar PV that can feasibly be exploited. In addition, the storage potential related to Finnish hydropower production is unknown. While the Finnish system is classified as a Run-of-the-River system, there may be a significant, untapped potential of storage within the system that could contribute positively to an energy system based on high shares of variable generation. In simple terms, a better inventory can result in better scenario design, and a higher level of optimization. It is expected that lower costs could thereby result from minimizing levels of storage or reductions in other power plant capacities.

A critical parameter for the results was not possible to control within EnergyPLAN, the weighted average cost of capital (WACC). The used value of 7% is a compromise, since only one value for all technologies can be used. However, it is known that the WACC for wind and solar projects can be lower than the assumed 7% [119], in particular due to lower technical and societal risks compared to coal and nuclear investments. Investors starting new coal and nuclear projects have to take into account the real risk of stranded investments [37,38,43], reflected in a substantially higher WACC in the range of 10–15%. This in turn would substantially increase the costs of the scenarios containing nuclear and fossil technologies. This effect can be accounted as 0.78 b€, 1.38 b€, 1.96 b€ and 3.05 b € annually for the Basic scenarios (Low, Medium, New Nuclear) and the BAU, respectively, at a WACC of 15%. The impact of a substantially higher risk profile of unsustainable energy technologies on WACC may be therefore the real differentiator for future energy scenarios since this effect can only increase the system cost, up to 13% for the case of the BAU scenario. The risk of stranded investments should be reduced as far as possible, triggered by societal and political discourse.

The last aim of this study was to encourage discourse on energy-related issues that contribute to the transformation of the Finnish energy system towards long-term sustainability. While it is clear that a 100% RE scenario is the lowest cost of all the 2050 scenarios examined, total annual costs in the Basic Scenarios range between 24.1 and 25.6 b€, a difference of roughly 6%. For the Low Biomass Scenarios, the range is between 24.6 and 26.4 b€, or approximately 7%. Given the level of estimation involved in energy system modelling work in general, perhaps one can conservatively conclude that all of the 2050 scenarios modelled in this study are relatively similar in terms of measured energy system costs. Therefore, one must look to other sustainability constraints (societal and environmental) to determine the most preferred scenario. For this reason, discourse on energy-related issues becomes paramount.

It is clear that several different possible futures exist that can reach the general requirements set out in the Introduction. What is more, they may achieve these goals at costs that are similar. Discourse must then evolve beyond energy system simulation results or answering questions concerning what options exist and what they may cost. The discourse must involve deeper thought and questioning concerning how, exactly, people want to live. How will they perceive risk in personal, environmental and financial terms? Which option will benefit them most in a broader sense? What kind of world do they want to leave generations that will follow? How will they define safety and security? How will they want to utilize their natural resources? What will their relationship be with the energy that they need for their daily lives? At one extreme, answers could be very pragmatic, and energy could be a commodity/utility like so many others. At the other, a deep, ecological, almost spiritual relationship with energy could direct choices. Naturally, there are other answers along the continuum in between. In all cases, choices would be equally justified, but radically different. At the same time, however, the technologies that are chosen will be the enablers of specific choices made or values conceived by society. In this regard, the role of Futures Research, such as [120], becomes an essential tool in the creation of future modelling scenarios.

It has been shown how the WACC and cost of carbon emissions can affect the overall cost of each scenario, leading some scenarios to be more or less preferable in economic terms. From the above observation that scenarios are similar in terms of measured costs, one can determine how those same scenarios are unequally affected by WACC and cost of carbon emissions. Indeed, it is the two 100% RE scenarios that have the least exposure to the risk of such extra costs. Scenarios with shares of nuclear power are particularly sensitive to the risk of higher WACC being assigned to nuclear power technology that may result in stranded investments should a social or political decision be made to reduce capacity. Such stranded investments are already being witnessed in a post-Fukushima world. In addition, the BAU has the additional sensitivity to the price of carbon emissions as the energy system has not been fully recarbonized nor decarbonized. The two 100% RE scenarios are not sensitive to such risks or costs, an observation that may make them more preferable.

While the scope of this study was limited to the tracking of annualized costs of operating the energy systems defined by each scenario, further comment can be made on the broader economic implications of a transition away from the current Finnish energy system dominated by fossil fuels and nuclear power. The purpose of such comment is to outline the major economic issues related to high shares of renewable energy production, the future of nuclear power, and the phasing out of the fossil fuel infrastructure. Moreover, the result of such discussion is intended to expand future discourse on these economic issues in Finland, which remain underdeveloped at this time but will become increasingly relevant in the future. It is, therefore, important to point out that the discussion that follows is not a direct conclusion based on the results of this study, but a review of relevant conclusions already found in the scientific literature and a presentation of other relevant facts. It should also be stressed that further discourse on such issues specific to the Finnish context is needed in both scientific and broader socio-political contexts.

Interestingly, Creutzig *et al.* [121] suggest that increasing levels of renewable energy and higher energy efficiency could be a great benefit to the Eurozone as it struggles to recover from economic crisis. They argue that public and private expenditures on renewable energy technologies and infrastructure could provide "economic stimulus, decrease trade deficits, and possibly have positive employment effects", particularly in areas of Southern Europe that have felt the pressure of austerity measures as a consequence of the Eurozone crisis. As such, mitigating climate change and improving the overall European economy become two birds caught with "one renewable stone", something that could also result in renewed solidarity between the member states due to the need for cooperation and common policy development.

Several studies have shown a relationship between modes of energy production and economic growth. Bhattacharya et al. [122] analysed the 38 top renewable energy consuming countries between 1991 and 2012, and found that renewable energy consumption had a positive effect on the economic output of a majority of these countries (57%). Importantly, Finland was among this list of countries that showed such an effect. Next, positive impacts on economic growth were seen as resulting from increased renewable energy consumption for new member states of the European Union over the period of 1990–2009 in a separate study [123]. Similarly, Chang *et al.* [124] observed a bidirectional causal relationship between renewable energy consumption and economic growth in the G7 group of countries during the period of 1990–2011. Further still, Saidi *et al.* [125], after studying 9 developed countries over the period 1990–2013, establish a bidirectional causality between renewable energy consumption and real GDP growth per capita, going as far as to state that renewable energy "is a crucial component for economic growth". At the same time, no such causality was found between nuclear energy consumption and real GDP growth. Lastly, Varho *et al.* [126] point out that the economic interests and possible opportunities for small-scale, distributed energy production has received relatively little attention in Finland. However, the authors note the potential economic opportunities offered by distributed energy systems to "producers, retailers and installers of energy devices".

The economics of future nuclear power plants in Finland are difficult to discuss at this point in time. Of the plants currently operational, all will exceed their lifetimes by around 2030. And as stated previously, the only other possible plants are one that is still under construction and has experienced both time and cost overruns, and one that has only recently been granted a construction permit. Should they be completed, both are expected to be operational until at least 2075. It would be impossible to estimate the cost to Finnish society if a decision was made to phase out nuclear power before 2050, at least without knowing an exact timeframe. However, it must be acknowledged that there would be some cost. As stated previously, these costs have not been accounted in the annualized costs of each scenario.

In terms of the economic implications of transitioning away from fossil fuels, there would be little or no impact from phasing out fossil-fuel based energy production if such a decision were made soon. If one assumed an average lifetime of oil and gas based power plants of 35 years and a lifetime of 40 years for coal power plants [127], then none of the currently installed fossil-based power capacity would need to be decommissioned early in order to achieve the transition towards renewables by 2050. From data obtained from [128] and [129], and compared with that obtained from [130], the latest fossil-based plant, an oil fired back-up power plant installed in 2013, will reach its operational lifetime by about 2048. In this regard, Finland appears to be at a very critical crossroads to make decisions about the next generation of power plants. It is unclear if the same would be true of heat generating plants, many of which use peat as a fuel. While some of these plants also co-fire with biomass already and could be modified to become biomass-only plants, others may need to be decommissioned a few years before their average lifetimes. There could also be some negative economic impact on peat farmers and other employees unless other uses could be found for Finland's peatlands, for example, conversion into solar PV plants, wind farms or forest. However, these negative impacts could also be offset by the gains in employment related to renewable energy deployment presented above.

Of note is that the current and future natural gas-based energy technology and infrastructure will be very important for the transition towards high shares of renewable energy. In each of the test scenarios, PtG was an important aspect of the energy system. Therefore, current gas infrastructure will provide a bridge towards the use of synthetic methane in the future. In such scenarios, there is no worry of stranded investments in gas technology nor infrastructure. Indeed, it would need to be expanded significantly by 2050. The only other notable change is that imports of natural gas, which comprise all of Finnish natural gas supplies, could be eliminated, thereby improving the national trade balance. All in all, it may be claimed that the transition towards a 100% renewable Finnish energy system by 2050 may be more easily achieved in Finland than in many other countries that have more significant oil, coal and nuclear fuel-based energy generation.

5. Conclusions

This study concludes that future discourse and research concerning energy system planning in Finland needs to involve the vision of energy futures based on 100% renewable energy. It has been demonstrated that a future, highly independent Finnish energy system based entirely on renewable energy is possible, while still fulfilling the primary requirements of the nation. What is more, results indicate that this could be a competitive cost option for Finland in 2050. It is also hoped that a new level of transparency regarding modelling assumptions has been established for all future work related to the Finnish energy system. Lastly, scenario modelling at an hourly resolution of the complete Finnish energy system (power, heating/cooling and mobility) should be seen as a new standard. This work is the first of its kind for Finland, and has admitted limitations. However, it is hoped that future work will draw on, improve and expand results, and allow for better decision-making by policymakers and the general public.

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Appendix A. Supplementary material

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Appendix A: Scenario parameters

Table A1. Population, building and boiler statistics and assumptions.

Parameter	**2012**	**2020**	**2050**	**2050 BAU**
Population	5 308 485	5 500 000	6 000 000	6 000 000
Buildings	1 474 653	1 500 000	1 750 000	1 750 000
Residential heating (total)	1 258 095	1 280 000	1 500 000	1 500 000
Oil boilers	218 665	170 329	0	0
NG boilers	86 155	21 128	174 929	174 929
Biomass boilers	398 221	402 737	314 873	314 873
Heat pumps	101 281	161 721	736 544	552 408
Electric	346 773	399 085	73 654	257 790
DH	107 000	125 000	200 000	200 000
Other heating (total)	216 558	220 000	250 000	250 000
Oil boilers	126 593	110 000	0	0
NG boilers	46 640	42 000	30 811	36 254
Biomass boilers	13 326	17 000	55 459	65 258
Heat pumps	0	20 000	129 730	114 488
Electric	0	0	0	0
DH	30 000	31 000	34 000	34 000

*Table A2. Annual Fuel Consumption in all scenarios (TWh). *The accounting of hydrogen as a fuel was deemed important even though it represents secondary energy and is part of the storage system. Negative numbers for Grid Gas represent export.*

	2012	2020	2050 Basic 100% RE	2050 Basic Low Nuclear	2050 Basic Medium Nuclear	2050 Basic New Nuclear	2050 Low Biomass 100% RE	2050 Low Biomass Low Nuclear	2050 Low Biomass Medium Nuclear	2050 Low Biomass New Nuclear	2050 BAU
Coal and Peat	51.29	51.5	0	0	0	0	0	0	0	0	25.5
Oil	81.09	79.4	0	0	0	0	0	0	0	0	25
Grid Gas	32.07	37.8	-0.18	-0.03	-0.04	-0.35	-0.35	-0.32	-0.12	-0.39	42.8
Biomass	96.82	115.1	142.4	142.3	141.9	142.8	112.6	111.6	112.6	112.7	141.6
Wind onshore	0.49	4.51	84.5	64.8	51.0	36.6	102.8	87.3	74.6	66.2	8.4
Wind offshore	0	3.85	21.4	21.4	21.4	21.4	25.7	25.7	25.7	25.7	6.4
Solar PV	0.01	0.1	29.4	29.4	29.4	29.4	34.3	34.3	34.3	34.3	1.0
Hydro	16.67	19.9	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4
Hydrogen*	0	0.5	52.1	48.3	42.8	38.6	63.5	63.7	62.4	62.8	5.4
Nuclear	66.89	105.8	0	34.4	60.3	86.1	0	34.4	60.3	86.1	129.1
Total	345	418	351	362	368	376	360	378	391	409	407

Table A3. Carbon emissions and shares of RE for all scenarios

Category	2012	2020	2050 Basic 100% RE	2050 Basic Low Nuclear	2050 Basic Medium Nuclear	2050 Basic New Nuclear	2050 Low Biomass 100% RE	2050 Low Biomass Low Nuclear	2050 Low Biomass Medium Nuclear	2050 Low Biomass New Nuclear	2050 BAU
CO_2 -equivalent emissions Mt	48.2	49.0	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	25.1
Cost of CO_2 -equivalent emissions (MEUR)	289	1224	12	14	14	17	11	17	16	18	1879
Renewables share of primary energy (%)	33	34.3	100	89.1	81.2	74	100.2	89.2	81.9	74.9	43.1

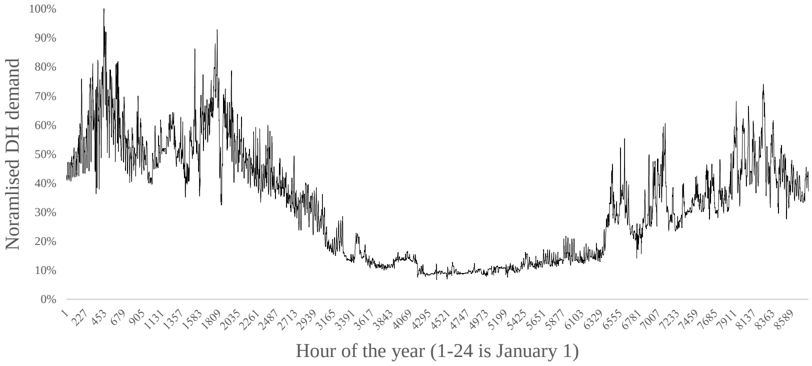

Figure A1. Hourly demand for district heating in Finland

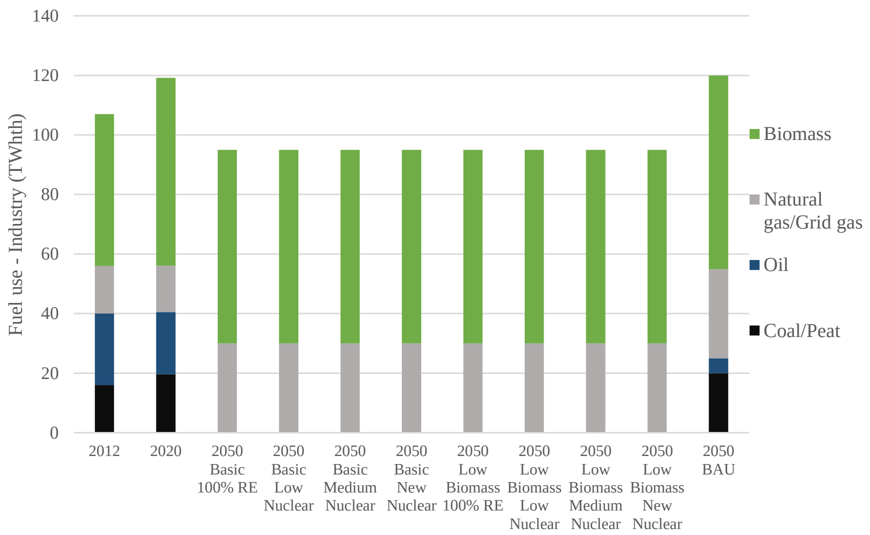

Figure A2: Industrial fuel use in all scenarios

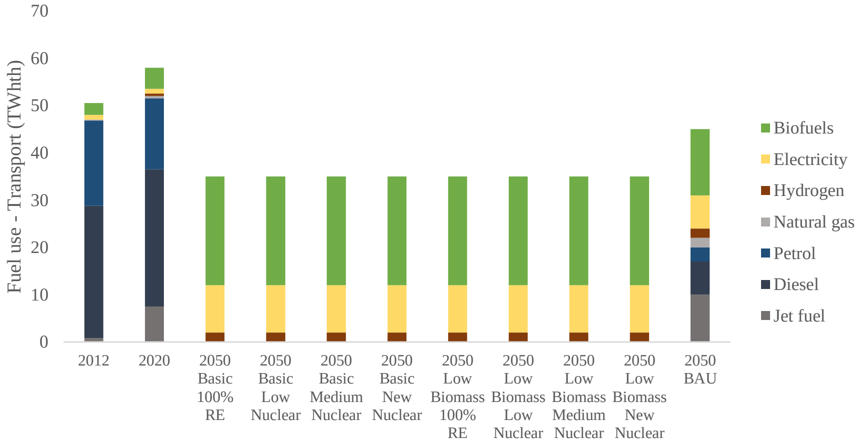

Figure A3: Transport fuel use in all scenarios

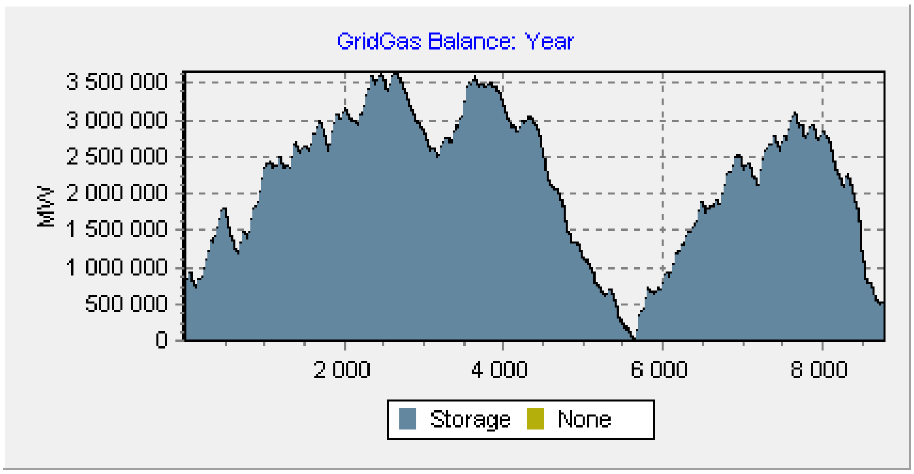

Figure A4. Annual gas storage balance for the Basic 100% RE scenario. Units on the y-axis are MWh_{th}

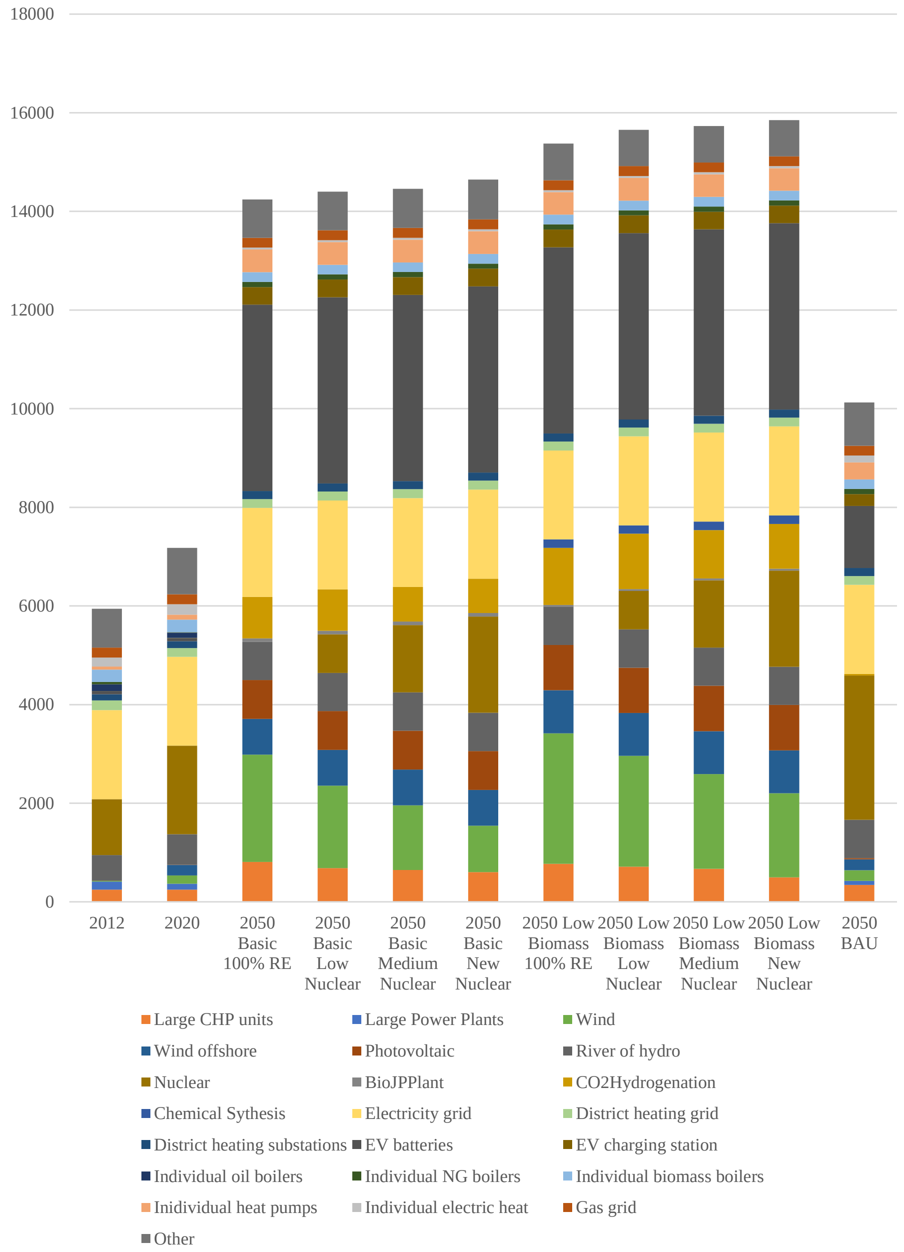

Figure A5. Annualized investment costs (M€/a) by category.

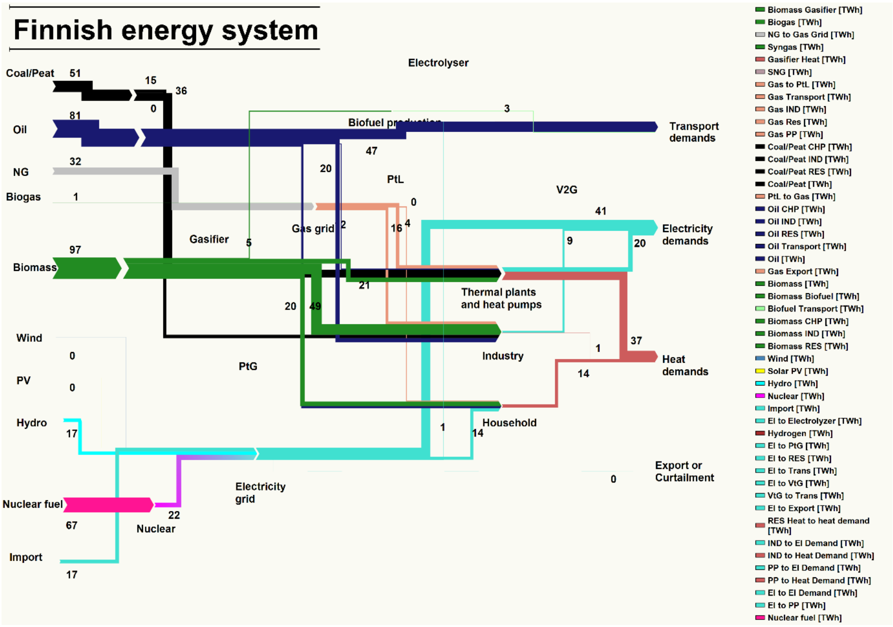

Figure A6. Simplified energy flows for Finland, 2012

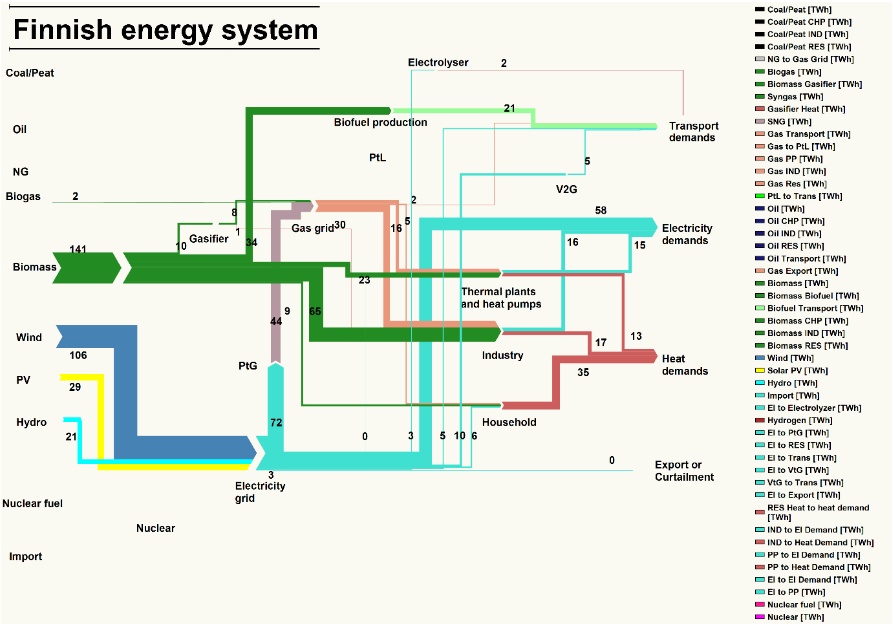

Figure A7. Simplified energy flows for Finland, 2050 Basic 100% RE scenario

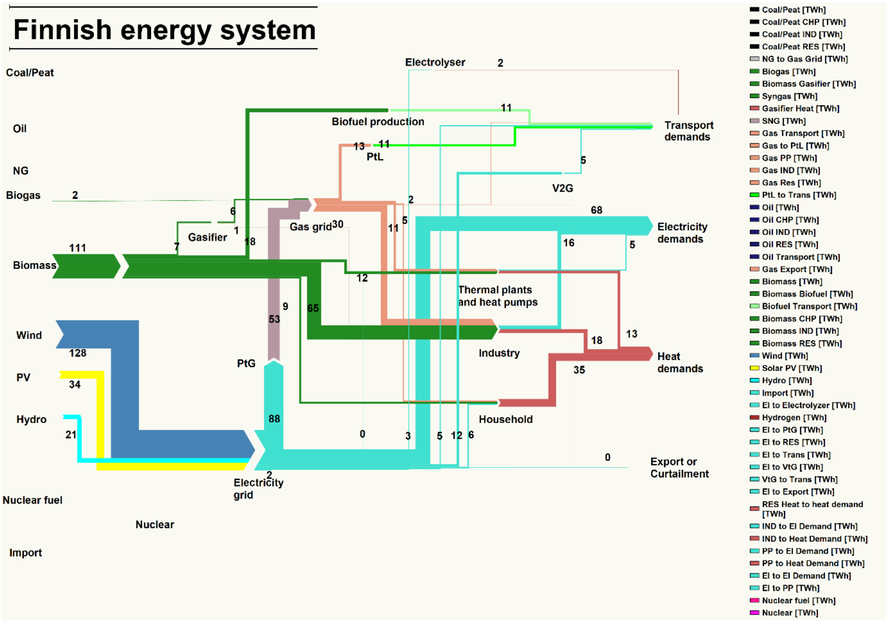

Figure A8. Simplified energy flows for Finland, 2050 Low Biomass 100% RE scenario

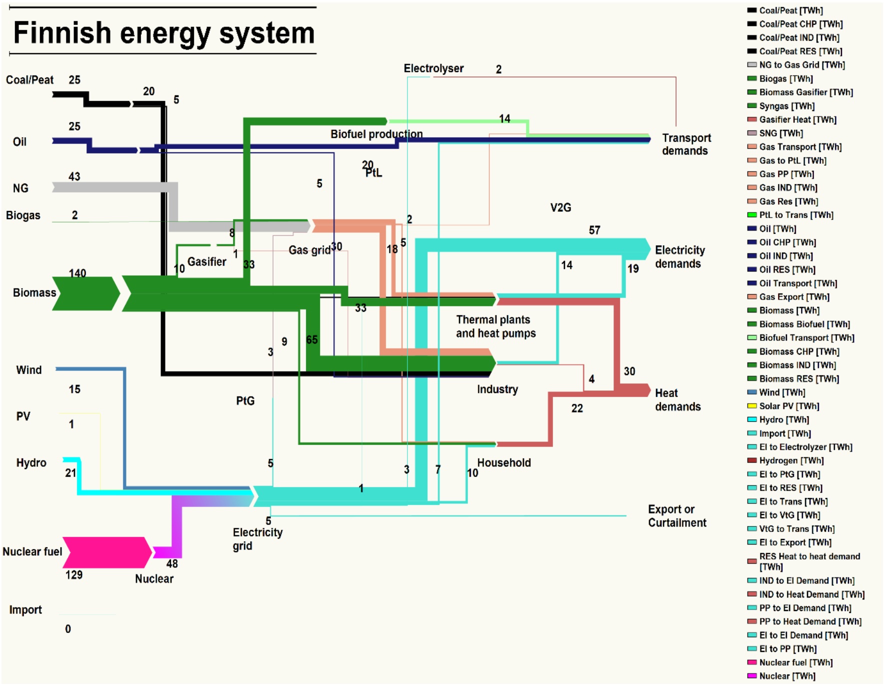

Figure A9. Simplified energy flows for Finland, 2050 BAU scenario

Appendix B: Cost parameters

For all values in Appendix 2, source ‘a’ refers to an assumption, extrapolation or calculation made by the authors.

Table B1. Cost assumptions for renewable energy.

Renewable energy production		**Unit**	**2020 Value**	**Source**	**2050 Value**	**Source**
Onshore wind	Capex	€/kW$_e$	1100	[1]	900	a
	Lifetime	Years	20	[1]	30	a
	Opex fixed	% of investment	4.26 %	[2]	4.51 %	[2]
Offshore wind	Capex	€/kW$_e$	2500	[1]	1800	a
	Lifetime	Years	20	a	30	a
	Opex fixed	% of investment	4.26 %	[2]	4.55 %	[2]
Solar PV - ground-mounted	Capex	€/kW$_e$	900	[3]	300	[4]
	Lifetime	Years	30	[3]	40	[5]
	Opex fixed	% of investment	2.00 %	a	2.00 %	a
Solar PV - rooftop	Capex	€/kW$_e$	1200	[3]	400	[4]
	Lifetime	Years	30	[3]	40	[5]
	Opex fixed	% of investment	1.00 %	a	1.00 %	a
Hydropower - Run of the river	Capex	€/kW$_e$	2750	[2]	3060	[2]
	Lifetime	Years	50	[6]	50	[6]
	Opex fixed	% of investment	4.00 %	[2]	4.00 %	[2]
Biomass gasification plant	Capex	€/kW$_{th}$	420	[6]	300	[7]
	Lifetime	Years	25	[6]	30	a
	Opex fixed	% of investment	5.30 %	[6]	4.00 %	[7]
		Efficiency	80 %	a	80 %	a
Biodiesel plant	Capex	€/kW$_{th}$	3420	[6]	2770	a
	Lifetime	Years	20	[6]	30	a
	Opex fixed	% of investment	3.00 %	[6]	3.00 %	a
		Efficiency	60 %	a	60 %	a
Biopetrol plant	Capex	€/kW$_{th}$	790	[6]	790	a
	Lifetime	Years	20	[6]	30	a
	Opex fixed	% of investment	7.70 %	[6]	7.70 %	a
		Efficiency	40 %	a	40 %	a
Biojetpetrol plant	Capex	€/kW$_{th}$	790	[6]	790	a
	Lifetime	Years	20	[6]	30	a
	Opex fixed	% of investment	7.70 %	[6]	7.70 %	a
		Efficiency	40 %	a	40 %	a
CO_2 Hydrogenation plant (P2G)	Capex	€/kW$_{th}$	1750	[8]	870	[8]
	Lifetime	Years	30	[8]	30	[8]
	Opex fixed	% of investment	4.00 %	[8]	3.30 %	[8]
		Efficiency	63 %	[6]	70 %	a
SOEC Electrolyser	Capex	€/kW$_e$	590	[1]	480	a
	Lifetime	Years	20	[1]	30	a
	Opex fixed	% of investment	2.50 %	[1]	2.50 %	a
		Efficiency	73 %	a	73 %	a

Biogas plant	Capex	€/kW$_{\mathrm{th}}$ input	240	[6]	194	a
	Lifetime	Years	20	[6]	30	a
	Opex fixed	% of investment	7.00 %	[6]	7.00 %	a
Biogas upgrading	Capex	€/kW$_{\mathrm{th}}$	300	[6]	240	a
	Lifetime	Years	15	[6]	25	a
	Opex fixed	% of investment	15.80 %	[6]	15.80 %	a
Gasification gas upgrading	Capex	€/kW$_{\mathrm{th}}$	300	[6]	240	a
	Lifetime	Years	15	[6]	25	a
	Opex fixed	% of investment	15.80 %	[6]	15.80 %	a

Table B2. Cost assumptions for thermal generation plants.

			2020		**2050**	
Thermal plants		**Unit**	**Value**	**Source**	**Value**	**Source**
Large heat pump for DH and CHP	Capex	€/kW$_{\mathrm{e}}$ required	3430	[6]	2220	[6]
	Lifetime	Years	20	[1]	30	a
	Opex fixed	% of investment	2.00 %	[6]	2.00 %	[6]
	Variable costs	€/MW$_{\mathrm{e}}$ required	0.27	[6]	0.27	[6]
		COP	2.9	[1]	4.5	[1]
Small CHP plant	Capex	€/kW$_{\mathrm{e}}$	1200	[6]	1200	[6]
	Lifetime	Years	25	[6]	25	[6]
	Opex fixed	% of investment	3.75%	[6]	3.75%	[6]
	Variable costs	€/MWh$_{\mathrm{e}}$	2.7	[6]	2.7	[6]
Large CHP plant	Capex	€/kW$_{\mathrm{e}}$	820	[6]	790	[6]
	Lifetime	Years	25	[6]	25	[6]
	Opex fixed	% of investment	3.66 %	[6]	3.66 %	[6]
	Variable costs	€/MWh$_{\mathrm{e}}$	2.7	[6]	2.7	[6]
		Efficiency	90 %	a	90 %	a
DH/CHP boiler	Capex	€/kW$_{\mathrm{th}}$	100	[6]	100	[6]
	Lifetime	Years	35	[6]	35	[6]
	Opex fixed	% of investment	3.70 %	[6]	3.70 %	[6]
	Variable costs	€/MWh$_{\mathrm{th}}$	0.15	[6]	0.15	[6]
		Efficiency	90 %	a	90 %	a
Electric Boiler DH/CHP	Capex	€/kW$_{\mathrm{e}}$ required	750	[6]	750	[6]
	Lifetime	Years	20	[6]	30	[6]
	Opex fixed	% of investment	1.50 %	[6]	1.50 %	[6]
	Variable costs	€/MW$_{\mathrm{e}}$ required	1.35	[6]	1.35	[6]
		Efficiency	90 %	a	90 %	a
Condensing power plant (average)	Capex	€/kW$_{\mathrm{e}}$	1000	[6, 9]	1000	[6, 9]
	Lifetime	Years	27	[6, 9]	30	[6, 9]
	Opex fixed	% of investment	3.00 %	[6, 9]	2.00 %	[6, 9]
	Variable costs	€/MWh$_{\mathrm{e}}$	2.654	[6, 9]	0	[6, 9]
		Efficiency	40 %	a	50 %	a
OCGT	Capex	€/kW$_{\mathrm{e}}$	600	[1]	600	[1]
	Lifetime	Years	30	[1]	30	a
	Opex fixed	% of investment	1.51 %	[6]	2.00 %	[10]
	Variable costs	€/MWh$_{\mathrm{e}}$	3.4	[1]	3.4	[1]
		Efficiency	40 %	[1]	40 %	[1]

CCGT	Capex	€/kW$_e$	820	[1]	820	[1]
	Lifetime	Years	30	[1]	30	[1]
	Opex fixed	% of investment	3.66 %	[1]	3.80 %	[1]
	Variable costs	€/MWh$_e$	2.5	[1]	2.5	[1]
		Efficiency	60 %	a	60 %	a
Coal/Peat-fired power plant	Capex	€/kW$_e$	2030	[1]	1890	[1]
	Lifetime	Years	40	[1]	40	[1]
	Opex fixed	% of investment	3.03 %	[1]	3.26 %	[1]
	Variable costs	€/MWh$_e$	2.2	[1]	2.2	[1]
		Efficiency	40 %	a	40 %	a
Biomass-fired power plant	Capex	€/kW$_e$	1700	[9]	1600	[9]
	Lifetime	Years	30	[9]	30	[9]
	Opex fixed	% of investment	2.50 %	[9]	2.50 %	[9]
		Efficiency	40 %	[9]	40 %	[9]
Waste CHP plant	Capex	€/MW$_{th}$ input	216	[6]	216	[1]
	Lifetime	Years	20	[6]	20	[1]
	Opex fixed	% of investment	7.40 %	[6]	7.40 %	[1]
		Efficiency	97 %	[1]	97 %	[1]
Individual boiler (30 kW Oil)	Capex	€/unit	6600	[1]	6600	[1]
	Lifetime	Years	20	[1]	20	[1]
	Opex fixed	% of investment	4.10 %	[1]	4.10 %	[1]
		Efficiency	85 %	[1]	85 %	[1]
Individual boiler (20 kW NG)	Capex	€/unit	6000	[1]	6000	[1]
	Lifetime	Years	20	[1]	20	[1]
	Opex fixed	% of investment	3.91 %	[1]	3.91 %	[1]
		Efficiency	90 %	a	90 %	a
Individual heat pump (5 kW$_{th}$)	Capex	€/unit	2100	[1]	1800	[1]
	Lifetime	Years	20	[1]	20	[1]
	Opex fixed	% of investment	1.62 %	[1]	1.89 %	[1]
		COP	3.2	[1]	4.5	[1]
Individual electric heat (5 kW$_{th}$)	Capex	€/unit	4000	[1]	4000	[1]
	Lifetime	Years	30	[1]	30	[1]
	Opex fixed	% of investment	1.00 %	[1]	1.00 %	[1]
		Efficiency	100 %	[1]	100 %	[1]
Nuclear	Capex	€/kW$_e$	5500	[11-13]	6500	[11-16]
	Lifetime	Years	40	a	40	a
	Opex fixed	% of investment	3.50 %	[17]	3.50 %	a
		Efficiency	33 %	[18]	37 %	[19, 20]

Table B3. Cost assumptions for energy storage systems

Energy storage systems		Unit	2020 Value	Source	2050 Value	Source
Heat storage CHP	Capex	€/kWh$_{th}$	3	[6]	3	[6]
	Lifetime	Years	20	[6]	30	[6]
	Opex fixed	% of investment	0.70 %	[6]	0.70 %	[6]

Hydrogen storage	Capex	€/kWh$_{th}$	20	[6]	20	[6]
	Lifetime	Years	30	[6]	30	[6]
	Opex fixed	% of investment	0.50 %	[6]	0.50 %	[6]
Grid gas storage	Capex	€/kWh$_{th}$	0.05	[8]	0.05	[8]
	Lifetime	Years	50	[8]	50	[8]
	Opex fixed	% of investment	3.30 %	[8]	3.30 %	[8]
Lithium ion stationary battery	Capex	€/kWh$_e$	300	[8]	75	a
	Lifetime	Years	10	[8]	20	a
	Opex fixed	% of investment	3.30 %	[8]	3.30 %	a
Lithium ion BEV	Capex	€/kWh$_e$	200	[21, 22]	100	a
	Lifetime	Years	8	a	12	a
	Opex fixed	% of investment	5.00 %	a	5.00 %	a

Table B4. Cost assumptions for infrastructure. Based on [23]

Infrastructure		**Unit**	**2020 Value**	**2050 Value**
District heating grid	Capex	€/MWh$_{th}$	72	72
	Lifetime	Years	40	40
	Opex fixed	% of investment	1.25 %	1.25 %
District heating substation - Residential	Capex	€/unit	6200	5000
	Lifetime	Years	20	20
	Opex fixed	% of investment	2.42 %	3.00 %
District heating substation - Commercial	Capex	€/unit	21500	21500
	Lifetime	Years	20	20
	Opex fixed	% of investment	0.70 %	0.70 %
District cooling network	Capex	€/kW$_{th}$	6000	6000
	Lifetime	Years	25	25
	Opex fixed	% of investment	2.00 %	2.00 %

Table B5. Cost assumptions for fuel and CO_2

Fuel and CO_2	**Unit**	**2020 Value**	**Source**	**2050 Value**	**Source**
Coal/Peat	€/MWh$_{th}$	11.2	[6]	12.2	[6]
Oil	€/MWh$_{th}$	42.8	[6]	58.0	[6]
Oil	USD/bbl	107.4	[6]	142	[6]
Diesel	€/MWh$_{th}$	54.0	[6]	70.6	[6]
Petrol	€/MWh$_{th}$	54.7	[6]	70.9	[6]
Jet fuel	€/MWh$_{th}$	58.0	[6]	74.2	[6]
NG	€/MWh$_{th}$	32.8	[6]	43.9	[6]
Liquid biofuels	€/MWh$_{th}$	84.8	[10]	65.0	[10]
Biomass (weighted average)	€/MWh$_{th}$	18.0	[6]	21.6	a
Uranium (including handling)	€/MWh$_{th}$	5.4	[6]	5.4	[6]
CO_2	€/t $CO_{2\ eq}$	25	[2]	75	[2]

Table B6. Cost assumptions for fuel handling (storage, distribution and refining). Based on [6]

Fuel handling (storage, distribution and refining)	**Unit**	**2020 Value**	**2050 Value**
Fuel oil to central CHP and PPs	€/MWh$_{th}$	0.943	0.943
Fuel oil to industry and DH	€/MWh$_{th}$	6.858	6.858
Diesel for transportation	€/MWh$_{th}$	9.767	9.767
Petrol / Jet fuel for transportation	€/MWh$_{th}$	7.502	7.502
NG to central CHP and PPs	€/MWh$_{th}$	1.483	1.483
NG to industry and DH	€/MWh$_{th}$	7.380	7.380
NG for transportation	€/MWh$_{th}$	11.326	11.326
Biomass to conversion plants	€/MWh$_{th}$	5.688	5.688
Biomass to central CHP and PPs	€/MWh$_{th}$	5.688	5.688
Biomass to industry and DH	€/MWh$_{th}$	4.270	4.270
Biomass to individual households	€/MWh$_{th}$	10.746	10.746
Biomass for transportation (biogas)	€/MWh$_{th}$	4.270	4.270

Table B7. Emission factors for fuels

Carbon content in fuels	**Unit**	**2020 Value**	**Source**	**2050 Value**	**Source**
Coal	kg CO$_{2eq}$/MWh$_{th}$	363.6	[24]	363.6	[24]
Peat	kg CO$_2$_eq/MWh$_{th}$	381.24	[24]	381.24	[24]
Oil	kg CO$_{2eq}$/MWh$_{th}$	283.68	[23]	283.68	[23]
NG	kg CO$_{2eq}$/MWh$_{th}$	198.14	[23]	198.14	[23]
Waste (related to inorganic portion)	kg CO$_{2eq}$/MWh$_{th}$	114.48	[23]	114.48	[23]
Solid biomass	kg CO$_{2eq}$/MWh$_{th}$	396	[24]	396	[24]

Table B8. Calculating costs for district heating and cooling infrastructure

Parameter	**Unit**	**2020**	**2050**
Number of DH customers	Thousand	145	150
Total heat demand	(TWh$_{th}$)	33.39	30
Grid costs	(€/MWh$_{th}$)	72	72
Total grid costs	(M€)	2404.08	2160
Number of residential customers	Thousand	116	120
Cost of residential substation	(€/unit)	6200	5000
Number of commercial customers	Thousand	29	30
Cost of commercial substation	(€/unit)	21500	21500
Total substation costs	(M€)	1342.7	1245
Substation opex	(M€)	21.75	22.5
Substation opex	(% of capex)	1.62 %	1.81 %
Capacity of district cooling	(MW)	220.00	440
Cost of district cooling grid	(M€/MW)	0.6	0.6
Total cost of DC	(M€)	132	264

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The role of energy storage solutions in a 100% renewable Finnish energy system

Michael Child[*], Christian Breyer

Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

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Abstract

A 100% renewable energy scenario was developed for Finland in 2050 using the EnergyPLAN modelling tool to find a suitable, least-cost configuration. Hourly data analysis determined the roles of various energy storage solutions. Electricity and heat from storage represented 15% of end-user demand. Thermal storage discharge was 4% of end-user heat demand. In the power sector, 21% of demand was satisfied by electricity storage discharge, with the majority (87%) coming from vehicle-to-grid (V2G) connections. Grid gas storage discharge represented 26% of gas demand. This suggests that storage solutions will be an important part of a 100% renewable Finnish energy system.

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Keywords: energy system modeling; storage solutions; 100% renewable energy; Finland; vehicle-to-grid; power-to-gas

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1. Introduction

Variability and uncertainty are inherent qualities of energy systems as supply and demand of energy services vary over time, space and sometimes in unpredictable ways. The challenge of mitigating such imbalance has always required a high level of flexibility, often provided by energy resources, particularly fossil fuels. However, climate

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[*] Corresponding author. Tel.: +358-40-829-7853.
E-mail address: Michael.Child@lut.fi

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change and sustainability challenges require that future energy systems have increased levels of renewable energy (RE) generation, much of which is intermittent or variable, creating a different need for flexibility measures that can ensure reliability, stability and quality of energy supply. Moreover, demand must be met in a responsible manner that does not place unnecessary burdens on society in terms of how disruptive or expensive solutions are to implement. Energy storage technologies are increasingly viewed as essential elements of flexibility in future energy systems, capable of bridging “temporal and geographic gaps between energy supply and demand” [1]. Such geographic gaps are filled in such cases when energy storage is portable, or stored energy can be transmitted or transported over distance. Additionally, energy storage may bring reliable energy services to areas that have poor energy infrastructure, or are seen as off-grid.

Finland represents an interesting case study of future energy systems due to strong diurnal and seasonal variation in variable energy generation (hydro, wind, solar) that is typical of countries at high latitudes. What is more, it is a highly industrialised nation with a strong need for a reliable energy supply that meets the needs of individual consumers while also ensuring a competitive industrial sector. Further, Finland has committed to an 80-95% reduction (compared to 1990 levels) in greenhouse gas emissions by 2050 [2].

Finland represents a challenge to high levels of solar photovoltaic (PV) and wind power in an energy system. While there are high amounts of solar irradiation during the summer months, the opposite is true during winter. Moreover, there is noticeable seasonal variation for both onshore, and offshore wind power, with more wind energy produced in the winter months. Further, there is also a seasonal element to hydro power, as the Finnish system is dominated by run-of-river hydro power with limited reservoir capacity of approximately 5.5 TWh_e [3], equivalent to approximately 6.5% of current electricity demand [4]. Hydro power is used as seasonal storage of energy in Finland, as most energy inflow occurs during the spring runoff in May. Reservoirs are kept relatively full until energy is needed during the winter months of December-April. At the same time, it must be remembered that Finnish hydro power experiences interannual variation in total annual production of 10-17 TWh_e, thereby demonstrating its somewhat intermittent nature [4].

On the demand side, the need for energy services in the form of heat and electricity is naturally higher during long, dark Finnish winters. So, finding the flexibility in the Finnish energy system has always been a significant task. In a future energy system based on high shares of variable RE, the need for energy storage solutions (ESS) on a daily, weekly and seasonal basis seems obvious. This extreme situation could then serve as a model for other countries at high latitudes, both north and south, of how variable renewable energy generation can play a role in a highly developed and industrious society.

For these reasons, an energy system based entirely on renewable resources was considered in previous work by the authors [5]. The scenario of a 100% renewable energy system was seen as being highly cost competitive to those with increasing shares of nuclear power installed capacity as well as a Business As Usual scenario. In other work, Child et al. [6] examined the role of solar PV for the case of a 100% RE Finnish energy system for 2050, which showed that storage technologies could play a prominent role in facilitating high shares of solar PV. However, this current study seeks to explain the nature and significance of energy storage solutions in more detail. This will include the roles of Gas storage, Power-to-Gas (PtG) technologies, Thermal Energy Storage (TES), stationary batteries, and Vehicle-to-Grid (V2G) connections. The significance of ESS in this future energy system will be determined by answering the following key questions:

- How much wind and solar PV power is used directly?
- How much of the annual energy demand is covered by ESS?
- How much stored energy comes from stationary batteries and V2G connections?
- How much stored energy comes from TES?
- How much stored energy comes from gas storage?

2. Methods

The EnergyPLAN advanced energy system analysis computer model [7] was used to represent a 100% RE scenario for Finland in 2050. This scenario was one of several used in the study by Child and Breyer [5], and was selected for the case of a basic biomass resource availability for further detailed analysis as it represented the most cost competitive of the scenarios studied. A thorough description of the tool used and the scenario parameters can be found in [5]. In addition, the main inputs to EnergyPLAN for the 100% RE scenario can be found in [6] as well as a summary of important assumptions and scenario parameters.

In order to explore a broader context and to investigate the possible seasonality of different types of energy production, a number of the hourly distributions were examined for the entire year. These included annual electricity demand and production by category as well as levels of electric storage, DH storage, and gas storage for the entire year. Hourly end-user consumption data for Finland were based on actual values from 2012 obtained from Fingrid [8] and hourly hydro power and industrial CHP production data were based on actual values from 2012 obtained from Finnish Energy Industries [9]. Wind and solar PV distributions were derived from Child and Breyer [5], based on data originating from [10, 11].

To determine the relative contributions of energy storage options investigated in this study, total energy consumption was determined based on electric and thermal energy end-user demand which were inputs to EnergyPLAN. In total, 170.3 TWh of energy was consumed for the year, represented by 105 TWh of electricty and 65.3 TWh of heat. Several hourly and annual outputs from the EnergyPLAN analysis were readily available, including V2G storage discharge, stationary battery storage discharge, and thermal storage discharge. However, both the annual electricity and heat that were ultimately derived from stored gas were calculated according to the following equations:

$$CHP_e = \sum_{i=1}^{8784} \frac{Gas_{stored,i}}{Gas_{demand,total,i}} \times Gas_{demand,CHP,i} \times \eta_{e,conversion,CHP} \tag{1}$$

$$PP_e = \sum_{i=1}^{8784} \frac{Gas_{stored,i}}{Gas_{demand,total,i}} \times Gas_{demand,PP,i} \times \eta_{e,conversion,PP} \tag{2}$$

$$IND_e = \sum_{i=1}^{8784} \frac{Gas_{stored,i}}{Gas_{demand,total,i}} \times IND_{e,total,i} \times \frac{Gas_{IND}}{Fuel_{IND}} \tag{3}$$

$$Gas_e = CHP_e + PP_e + IND_e \tag{4}$$

$$CHP_{th} = \sum_{i=1}^{8784} \frac{Gas_{stored,i}}{Gas_{demand,total,i}} \times Gas_{demand,CHP,i} \times \eta_{th,conversion,CHP} \tag{5}$$

$$HH_e = \sum_{i=1}^{8784} \frac{Gas_{stored,i}}{Gas_{demand,total,i}} \times Gas_{demand,HH,i} \times \eta_{th,conversion,HH} \tag{6}$$

$$BOILER_{th} = \sum_{i=1}^{8784} \frac{Gas_{stored,i}}{Gas_{demand,total,i}} \times Gas_{demand,BOILER,i} \times \eta_{th,conversion,BOILER} \tag{7}$$

$$Gas_{th} = CHP_{th} + HH_{th} + BOILER_{th} \tag{8}$$

CHP_e is the total annual electricity generation from stored gas in CHP plants operating in backpressure mode, $Gas_{demand,CHP,i}$ is the amount of gas used in CHP plants for each hour of the year (1-8784), $Gas_{demand,total,i}$ is gas used by all sources for each hour, $Gas_{stored,i}$ is the amount of gas discharged from storage in each hour, and $\eta_{e,conversion,CHP}$ is the efficiency of converting gas to electricity in a CHP plant (40%). PP_e is the total annual electricity generation from stored gas in CHP plants operating in condensing mode, $Gas_{demand,PP,i}$ is the amount of gas used in CHP plants for each hour, and $\eta_{e,conversion,PP}$ is the efficiency of converting gas to electricity in a CHP plant (40%). IND_e is the total annual electricity generated by industrial power plants, $IND_{e,total,i}$ is the amount of electricity produced by industry for each hour of the year, Gas_{IND} is the amount of gas used by industry annually (30 TWh), and $Fuel_{IND}$ is the amount of total fuel used by industry annually (125 TWh). Gas_e is the total amount of electricity produced by stored gas. CHP_{th} is the total annual heat generation from stored gas in CHP plants operating in backpressure mode, and $\eta_{th,conversion,CHP}$ is the efficiency of converting gas to heat in a CHP plant (50%). HH_{th} is the total annual heat generation from stored gas in individual households, and $\eta_{th,conversion,HH}$ is the efficiency of converting gas to heat in individual households (95%). $BOILER_{th}$ is the total annual heat generation from stored gas in district heating boilers, and $\eta_{th,conversion,BOILER}$ is the efficiency of converting gas to heat in district heating boilers (90%). Gas_{th} is the total amount of heat produced by stored gas.

To determine the direct usage of solar PV and wind energy, the sum of these categories of production (solar PV + onshore wind + offshore wind) was divided by total supply of electricity from all sources. This ratio was multiplied by the amount of total electricity consumption to determine the proportion of wind and solar PV power that was directly consumed. The same ratio was multiplied by the total amount of power going to electricity storage (stationary batteries + V2G batteries + PtG electrolysers) to determine the amount of wind and solar going to storage. The share of solar PV and wind energy that was directly consumed was determined by the ratio of directly consumed solar PV and wind energy to total electricity consumption by all sources. These calculations were performed for each hour of the year and then summed to acquire annual totals. Results were compiled, tabulated and analysed.

3. Results

Annual results are compiled in Figures 1-5 for electricity production, electricity consumption, electricity storage, thermal storage and grid gas storage components of the energy system. Results of calculations are shown in Figure 6, and Tables 1 and 2.

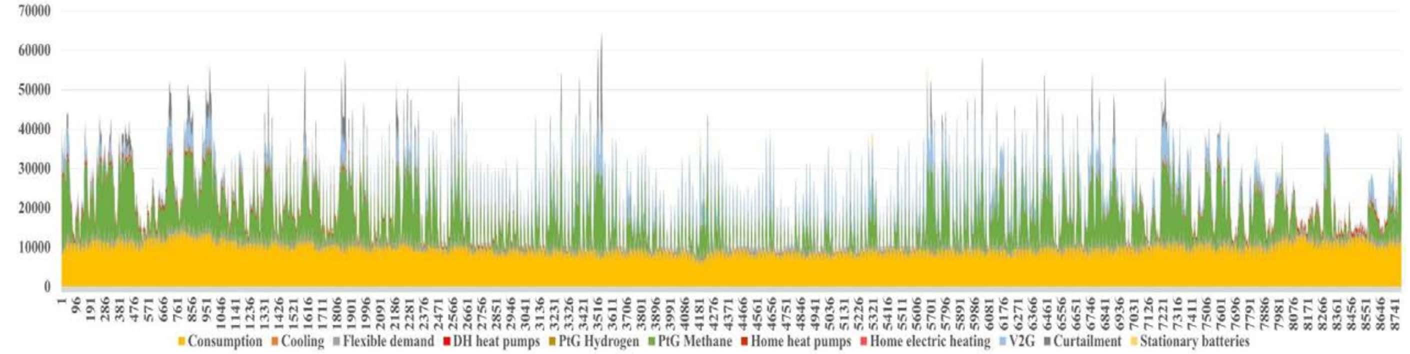

Fig. 1. Annual hourly power demand by category (MW_e). Flexible demand and electric vehicle charging aids in reducing high peaks in electricity demand and fills valleys in demand during night hours and at midday. Curtailment of electricity is less than 3.5%.

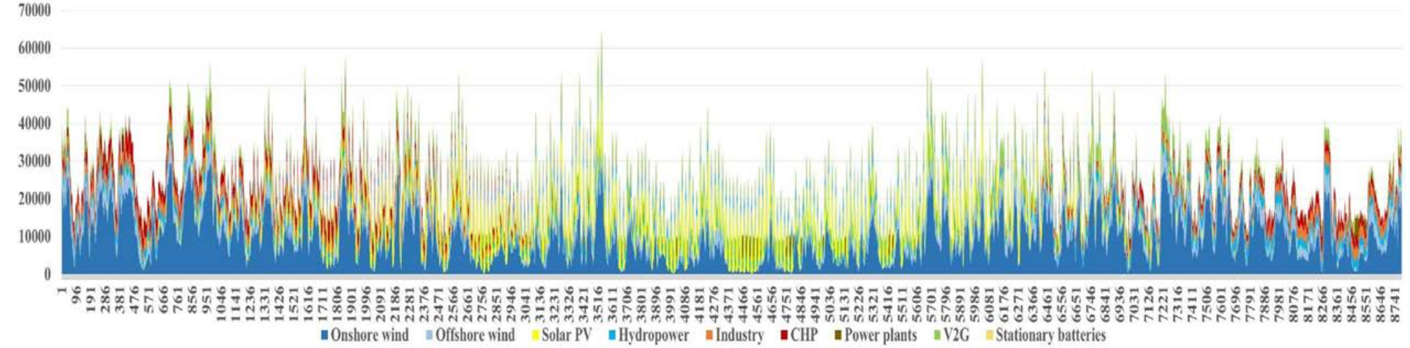

Fig. 2. Annual hourly power consumption by category (MW_e). A seasonal complement is seen between solar PV and CHP electricity production. To a lesser extent, solar PV is also seasonally complemented by wind power.

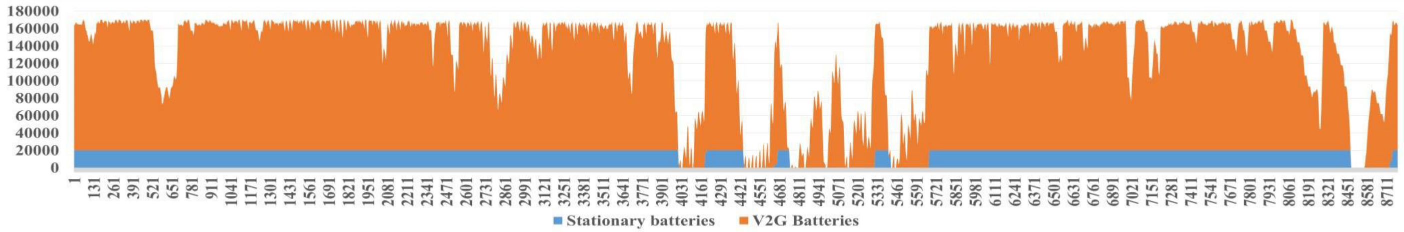

Fig. 3. Hourly electric storage levels (MWh$_e$) for entire year. Maximum storage capacity is 170 000 MWh$_e$. The utilization of stationary batteries by EnergyPLAN seems at odds with how such energy storage devices would be used in reality. EnergyPLAN used stationary batteries as a storage of lowest priority, while future prosumers may use them with the highest priority. V2G batteries were a high priority storage solution for EnergyPLAN.

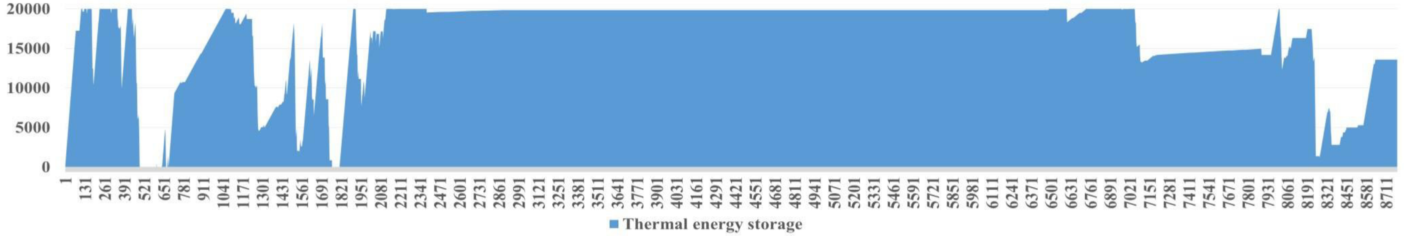

Fig. 4. Hourly thermal storage levels (MWh$_{th}$) for entire year. Maximum storage capacity is 20 000 MWh$_{th}$. Finland currently has high levels of thermal energy storage associated with the DH system. Much of it is unused during the summer months, but it has an important function during the winter.

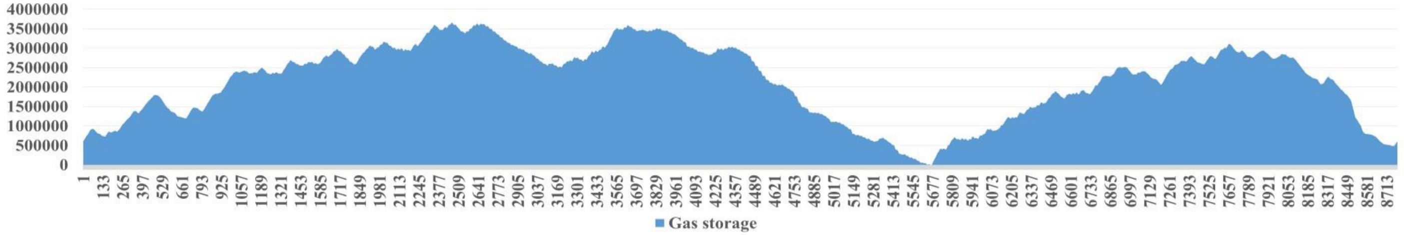

Fig. 5. Hourly grid gas storage levels (MWh$_{gas}$) for entire year. Maximum storage capacity is 3 800 000 MWh$_{gas}$. High levels of gas storage are generally associated with high production of wind power. Gas storage decreases during the summer months when solar PV generation is high.

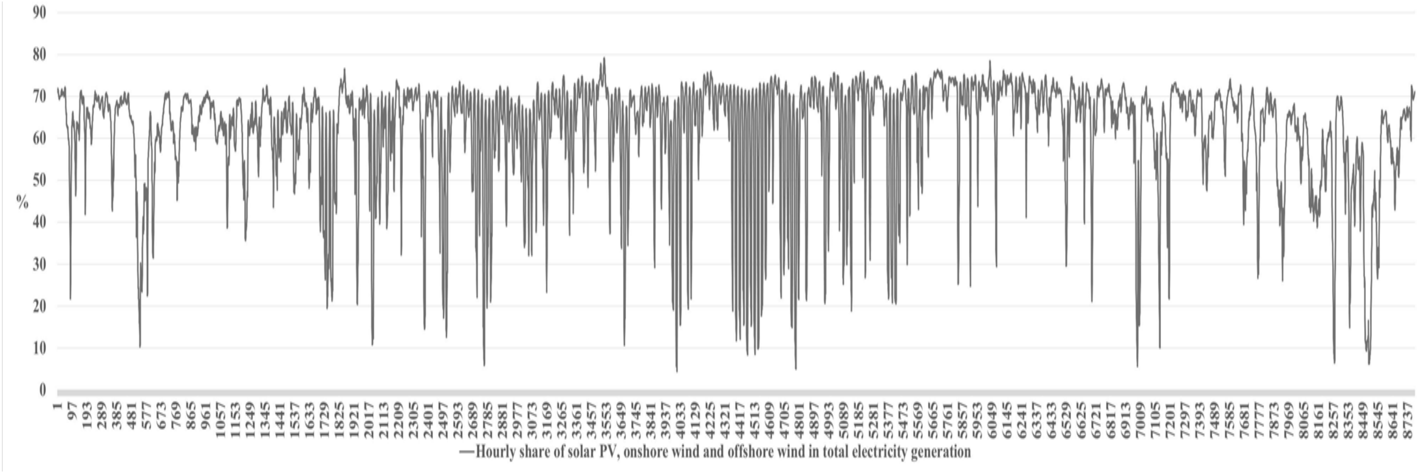

Fig. 6. Percentage of solar PV, onshore wind and offshore wind that is directly consumed. Values range between 4-80% with a mean of 62%.

Table 1. Summary of calculations related to electricity and heat from gas storage.

CHP electricity from gas discharge (TWh_e)	PP electricity from gas discharge (TWh_e)	Industry electricity from gas discharge (TWh_e)	Total electricity from gas discharge (TWh_e)	CHP heat from gas discharge (TWh_{th})	Individual household heat from gas discharge (TWh_{th})	Boiler heat from gas discharge (TWh_{th})	Total heat from gas discharge (TWh_{th})
1.16	0.73	1.14	3.01	1.44	1.13	0.01	2.58

Table 2. Summary of calculations related to ratios of storage discharge to consumption.

Parameter	Unit	Value
Electricity consumption	TWh_e	105
Heat consumption	TWh_{th}	65.3
Total energy consumption	TWh	170.3
V2G discharge	TWh_e	19.4
Stationary Batteries discharge	TWh_e	0.1
Electricity from stored gas	TWh_e	2.7
Heat from stored gas	TWh_{th}	2.6
DH storage discharge	TWh_{th}	0.2
Solar PV and wind directly consumed	TWh_e	63.5
as % of total solar PV and wind production		46.6%
as % of total electricity production		70.8%
as % of final electricity consumption		60.5%
Solar PV and wind to electric storage	TWh_e	69.3
as % of total solar PV and wind production		50.9%
Solar PV and wind to curtailment	TWh_e	3.5
as % of total solar PV and wind production		2.5%
Total storage discharge	TWh	25.0
as % of total consumption		14.7%
Electricity storage discharge	TWh_e	22.2
as % of electricity consumption		21.1%
V2G discharge	TWh_e	19.4
as % of all electricity storage discharge		87.2%
Thermal storage discharge	TWh_{th}	2.8
as % of heat consumption		4.3%
Gas storage discharge	TWh_{gas}	14.0
as % of grid gas consumption		26.5%

4. Discussion

Solar PV and wind power make a roughly 60% contribution to final energy consumption and are 70% of total electricity generation, but that contribution is quite variable throughout the year. In addition, that contribution is at times concentrated during daytime, necessitating both short and long-term storage. Approximately 47% of variable RE is utilized directly, with the balance going to storage (51%) and a small amount being curtailed (2.5%). At the same time, hydro power production was quite high during times of curtailment, suggesting that curtailment may not be necessary if the full potential of hydro reservoir storage was harnessed. Electric storage discharge totalled 22.2 TWh_e, or 21% of end-user consumption. On a daily basis, V2G batteries seem to have a much greater role (87%) than stationary batteries, raising the question of whether stationary batteries may be necessary at all in the context of higher V2G connection. The answer to this question is beyond the scope of this current study, but must include careful consideration of the needs of off-grid consumers, barriers against V2G connections, and an overall cost/benefit analysis for both grid operators and end-users. Due to the use of block heaters in winter, Finns are already accustomed to plugging their cars in, and electrical connections for vehicles are already widespread throughout the country. The potential evolution of this behaviour and technical capacity seems rather straightforward, but cannot be assumed without a clear demonstration of technical feasibility and net benefits to society. Currently, Finnish local low voltage distribution grids and typical household connections may not support the high power exchanges needed to offer a full range of V2G services. How this possible barrier can be overcome in the future requires more detailed study.

On a daily, weekly and seasonal basis, PtG technology bridges the gaps between demand and supply at times when generation is most intermittent. At the same time, this technology is available to provide base loads of electricity, heating, cooling and mobility when they are needed. These results are in line with those for Germany [12, 13]. Gas storage arising from PtG, biomass gasification and biogas generation amounts to 14 TWh_{gas}, or 26% of annual gas usage.

Thermal energy storage in Finland is rather plentiful, but utilization is rather minimal when annual numbers are examined. Thermal storage discharge amounted to 2.8 TWh_{th}, which represented only 4% of end-user heat demand. However, the role of thermal storage was rather significant during some periods of the year (autumn and winter), and would be expected to be quite vibrant in urban areas compared to rural areas. As EnergyPLAN considers the energy system as one single heating system, rather than a collection of distributed systems, one could expect greater utilization of thermal storage when the energy system is divided into smaller regions. Further study is needed in this regard that would necessitate utilization of a different modelling tool.

The seasonal complement of solar PV and wind power production in Finland appears obvious (Figure 2), despite the intermittent nature of each. This intermittency appears manageable by the storage technologies utilized in this study. In total, 25.3 TWh of heat and electricity are discharged from storage, representing 15% of total end-user consumption. One must also remember the important role of hydro power in Finland. Up to 20% of end-user electricity consumption can be supplied by hydro power. This study also does not fully explore the full potential of hydro storage available in Finland. Indeed, a full accounting of the potential to utilize hydro storage in Finland is lacking. Harnessing further flexibility in hydro power production could lessen the need for other storage capacity, such as batteries or PtG production. Alternatively, there may be less need for thermal energy generation. Each of these reductions may in turn result in a decrease in overall costs.

5. Conclusions

The integration of high shares of renewable energy sources in future energy systems will require a variety of complementary storage solutions. It has been previously determined that electricity storage devices will be needed once 50% of power demand is met with variable RE, and that seasonal storage devices will be needed once more than 80% of electricity demand is met by RE [14, 15]. Currently, there is a long list of energy system flexibility measures available to support high levels of intermittent RE [16]. Developing a 100% RE scenario for a nation requires careful consideration of the right mix of these measures for each context. In turn, these measures should be suited to and complemented by the energy generation technologies that make up the energy system. Such is the case for variable RE and the energy storage technologies investigated in this work. Variable RE and energy storage solutions can play a significantly role in a future energy system for Finland based on 100% renewable energy generation.

Acknowledgements

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The role of solar photovoltaics and energy storage solutions in a 100% renewable energy system for Finland in 2050

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Article

The Role of Solar Photovoltaics and Energy Storage Solutions in a 100% Renewable Energy System for Finland in 2050

Michael Child [1],*, Teresa Haukkala [2] and Christian Breyer [1]

[1] School of Energy Systems, Lappeenranta University of Technology, 53850 Lappeenranta, Finland, Christian.Breyer@lut.fi
[2] Department of Management Studies, Aalto University School of Business, 00076 Helsinki, Finland; Teresa.Haukkala@aalto.fi
* Correspondence: Michael.Child@lut.fi; Tel.: +358-40-829-7853

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Abstract: There are several barriers to achieving an energy system based entirely on renewable energy (RE) in Finland, not the least of which is doubt that high capacities of solar photovoltaics (PV) can be feasible due to long, cold and dark Finnish winters. Technologically, several energy storage options can facilitate high penetrations of solar PV and other variable forms of RE. These options include electric and thermal storage systems in addition to a robust role of Power-to-Gas technology. In an EnergyPLAN simulation of the Finnish energy system for 2050, approximately 45% of electricity produced from solar PV was used directly over the course of the year, which shows the relevance of storage. In terms of public policy, several mechanisms are available to promote various forms of RE. However, many of these are contested in Finland by actors with vested interests in maintaining the *status quo* rather than by those without confidence in RE conversion or storage technologies. These vested interests must be overcome before a zero fossil carbon future can begin. The results of this study provides insights into how higher capacities of solar PV can be effectively promoted and managed at high latitudes, both north and south.

Keywords: PV economics; energy system modelling; storage; 100% renewable energy; Finland

1. Introduction

The Finnish energy system is at a crossroads due to an aging system of power generation, opinions about different modes of low-carbon energy generation, responsibilities to mitigate climate change, worries of fluctuating energy prices, and goals regarding national energy security. In addition, there is a wish to both retain a competitive industrial sector and meet the needs of a future society. Recently, the country has committed to an 80–95% reduction (compared to 1990 levels) in greenhouse gas (GHG) emissions by 2050 [1]. However, how these reductions will be shared across different sectors of life and the economy has not been fully explained. Currently, approximately 80% of all GHG emissions originate from the energy system (electricity, heating/cooling and transport). The balance of emissions comes from sectors such as agriculture and forestry, manufacturing, aviation, and waste management, among others [2]. Given that significant reductions in the agricultural and manufacturing sectors may be difficult, prohibitively expensive or disruptive to society [3], achieving essentially zero carbon emissions in the energy sector may be the only way of achieving the nation's overall goals without dependence on carbon flexibility measures, such as emissions trading. Recently, the Finnish Ministry of Employment and the Economy stated that rapidly developing technologies such as solar power may create opportunities and offer the possibility of a 100% renewable energy system for Finland [4].

For these reasons, an energy system based entirely on renewable resources was considered in previous work by the authors [5]. The scenario of a 100% renewable energy system was seen as being highly cost competitive to those with increasing shares of nuclear power installed capacity as well as a Business As Usual scenario. However, this study did not have within its scope a description of how such a system would work in detail nor did it provide suggestions in policy terms related to how such high levels of renewable energy generation, particularly solar photovoltaics (PV), could be achieved.

In many ways Finland represents a challenge to high levels of solar PV penetration in an energy system. While the country has very high amounts of solar irradiation during the months around the summer solstice, the opposite is true during the months around the winter solstice. The need for storage technologies on a daily and seasonal basis seems obvious [6]. This observation and the role of energy storage in mitigating the intermittency of high shares of solar PV and wind energy for Finland were recently described in [7,8]. This extreme situation could then serve as a model for other countries at high latitudes, both north and south, of how solar PV can play a role in a highly developed and industrious society. If it can work in Finland, perhaps it can work almost anywhere.

In 2014, total energy consumption in Finland was approximately 372 TWh_{th}, with about 32% of primary energy coming from renewable sources (mostly hydropower and biomass) [2]. Electricity consumption was 83.3 TWh_{e}, with about 22% of this total coming from net imports. Peak electricity consumption of 14,367 MW_{e} occurred on 20 January at 8–9 a.m., while peak output of 13,022 MW_{e} occurred on 12 January at 6–7 a.m. [9]. Of total output capacity, solar PV represented only 11.38 MW_{e}, or 0.1% [10]. There are currently only five solar PV plants operating in Finland which are greater than 500 kW_{p}, and the total installed capacity is approximately 20 MW_{p} [11]. At the time of writing, the two largest installations were found on the rooftops of supermarkets (both 900 kW_{p}) in the city of Turku [12] although there are several utility-scale projects in the range of 8.7 MW_{p} (single axis horizontal tracking) that are currently planned for different parts of the country [13]. No comprehensive statistics are currently available on small-scale ownership. However, it is estimated that a great majority of solar PV panels in Finland are roof-mounted and that a minor part of the installed capacity is grid-connected. Interestingly, the panels (each one is 285 W_{p}) of an 853 kW_{p} plant in the Kivikko neighbourhood of Helsinki are rented for a monthly fee of €4.40 to individual customers, who can then deduct the energy each panel produces from their electricity bill provided they are a customer of that distribution company [14]. Solar irradiation values for Lappeenranta, Finland and other European cities are found in Figure 1 [15,16].

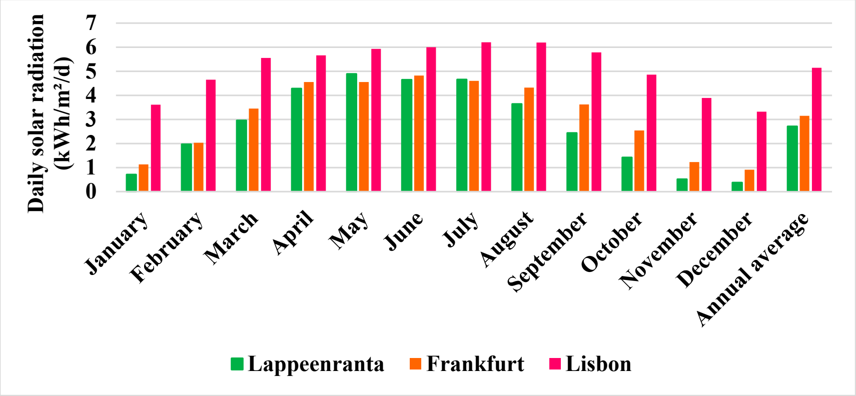

Figure 1. Daily solar radiation for three cities in Europe [15,16].

The 100% renewable energy scenario developed for Finland in 2050 in [5] has a very different composition from the current system, as seen from the representation of Annual Fuel Consumption for 2012 and 2050 in Figure 2. From the figure it is clear that the movement away from fossil-based energy includes greatly expanded roles for wind, bio-based and solar energy. For solar PV, this would represent 30 GW_p of installed capacity, roughly half of which would be rooftop and the other half ground-mounted. The associated annual energy, 29.5 TWh_e, represents only 10% of annual final energy consumption and 16% of total electricity generation, but solar PV dominates production in certain periods during the summer, and is quite insignificant during some periods of the winter.

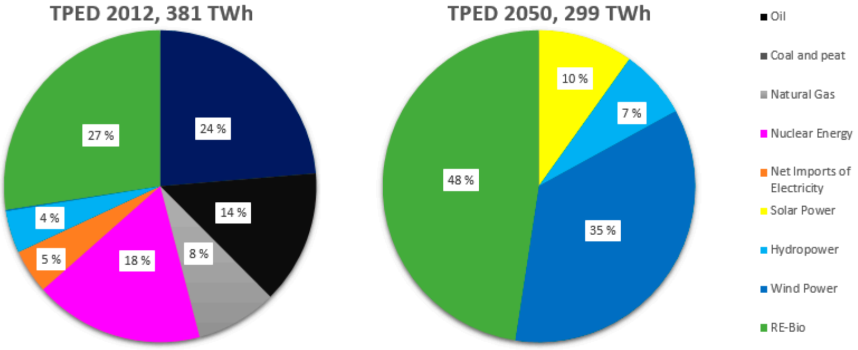

Figure 2. Annual Fuel Consumption in Finland in 2012 [1] and 2050 [4].

The huge leap from the current 20 MW_p of installed solar PV capacity to 30 GW_p allows consumers access to a generation technology that has already reached retail grid parity in Finland and appears to be one of the lowest cost sources of energy for the future [17,18]. Indeed, solar PV has reached a high level of competitiveness throughout Europe, and northern latitudes will see grid parity for rooftop PV prosumers in the near future [19]. This is due to a steep positive learning rate associated with solar PV that shows overall cost reductions as capacity is increased, unlike technologies such as hydro or nuclear power, which tend to show a negative learning rate [20]. Using Stockholm as an analogue for Helsinki, a recent report suggests that the levelised cost of electricity (LCOE) of solar PV could be below 40 €/MWh_e by 2050 [21]. This is based on a real weighted average cost of capital (WACC) of 5%, learning rate of 20% and solar PV module efficiency improvements of 0.4% per year from 2030 to 2050. Additional reasons for exploring the role of solar PV in this study is to determine if there may be some complementary relationship between solar PV and batteries, as has been documented in [22–25], whether there may be benefits for individual prosumers of energy [26], and if there would be a seasonal advantage of using more energy from solar PV during the long, bright, Finnish summers, and wind energy, biomass or gas based Combined Heat and Power (CHP) during the long, dark winters.

Achieving such high levels of solar PV capacity is not unheard of even in northern areas of Europe. Germany already has installed capacity of almost 40 GW_p and this number is set to grow in the years to come [27]. In addition, solar irradiation in northern Germany does not differ greatly from that of southern areas of Finland, where most of the population lives. Northern Germany has a solar irradiation on optimally inclined surfaces of approximately 1250 $kWh/(m^2 \cdot a)$ while southern Finland's is approximately 1100 $kWh/(m^2 \cdot a)$ (Figure 1). The amount of land required (not including rooftops) to achieve 30 GW_p of installed solar PV capacity represents only a fraction of Finland's land area, about 0.1%, given a future density of installation of 0.02 km^2/MW_p. So, even though the leap in solar PV installed capacity may seem prohibitively huge (growth by more than 2700%), in truth even greater growth has already occurred in the past two decades with the same technology just across the Baltic Sea in Germany. Finland would have 35 years to reach the 2050 level of the scenario described. High shares of solar PV and 100% renewable energy systems are already being discussed at high levels in Finland [4].

In this work, the results of Haukkala [28] describing several impediments to future solar PV installations for Finland are revisited and expanded. Primary among these impediments is widespread doubt that solar PV can ever be a competitive solution for a land at such northern latitudes. The work of Child and Breyer [5] confirms that solar PV can be an integral part of a competitive future energy system, leading the authors to wonder if any of the other barriers to implementation can so easily be disputed. Further, there is a need in Finland to not only dispel myths surrounding solar PV, but to begin discourse which will ultimately make the social and economic climate around all forms of renewable energy more favourable. Recent studies in Finland [29,30] have already advanced the discussion about distributed generation of renewable energy in terms of barriers, key drivers, benefits and the implementation of policies that would support future development.

Barriers to renewable energy technology (RET) penetration in general and to PV energy specifically are very much global. In addition, they appear quite similarly in extant literature, with only some country or technology specific differences. Painuly [31] has categorised major barriers to RET penetration in six categories: market failure/imperfection, market distortions, economic and financial, institutional, technical, and social, cultural and behavioural. These include, for instance, lack of information and awareness, favouritism towards conventional energy production, disregard of externalities, economic unviability, clash of interests, lack of Research and Development (R&D) culture, lack of professional institutions, lack of skilled personnel/training facilities and lack of consumer acceptance of the product.

Margolis and Zuboy [32] have drawn on a broad literature search to determine nontechnical barriers to solar energy use, including market, institutional and political barriers. In addition, according to [33], the main technical barriers include batteries and unresolved problems of storage. The economic barriers mainly consist of system costs. Cost comparisons are made with established conventional technologies that exploit economies of scale, have uncounted externality costs, receive public subsidies, and have accumulated industry experience. Path dependence and lock-in have been identified as barriers also in other studies [32,34]. Institutional barriers include the lack of a skilled workforce. The role of bureaucracy in delaying investment efforts in PV is also discussed in [35].

It was assumed at the beginning of this work that part of the doubt surrounding solar PV is the country's lack of experience with such technology as well as an overall lack of understanding of how solar PV would work as part of the energy system [28]. For that reason the first part of this work is dedicated to determining how electricity from solar PV would be utilised either directly, or through utilization of daily and seasonal storage technologies. The roles of Power-to-Gas (PtG), Vehicle-to-Grid (V2G) connection, stationary batteries as well as gas and thermal energy storage (TES) solutions were explored. The second part of this work focussed on examining a more complete range of barriers to achieving high penetrations of renewable energy in Finland, particularly with regards to solar PV. From this knowledge, several possible solutions towards overcoming such barriers were compiled and final suggestions were made regarding policies that could best support the realisation of a 100% renewable energy system for Finland in 2050.

2. Materials and Methods

In the first part of this work, the EnergyPLAN advanced energy system analysis computer model [36] was used to represent a 100% renewable energy (RE) scenario for Finland in 2050. This scenario was one of several used in the study by Child and Breyer [5], and was selected for further detailed analysis as it represented the most cost competitive of the scenarios studied. A thorough description of the tool used and the scenario parameters can be found in [5]. In addition, the main inputs to EnergyPLAN and other important assumptions and scenario parameters can be found in the Supplementary Material.

From the outputs of the model, hourly data was gathered and analysed to determine the detailed workings of several aspects of the energy system. EnergyPLAN provides yearly output graphics on an hourly resolution for production, demand and storage of electricity, district heating and grid-based gas (in this case biogas, Synthetic Natural Gas from biomass gasification and PtG methane). From these yearly graphics, several weeks of interest were identified and represented in more detail to determine how energy in various forms was being generated, and how it was possibly being stored and ultimately consumed. Although hourly data of boiler-based home heating is not included by EnergyPLAN, an examination of the three categories of electricity use, district heating and grid gas is assumed to provide a reasonably full picture of energy demand, supply and storage to allow for interpretation of results. The weeks of interest corresponded to those which witnessed:

1. Peak electrical consumption—Hour 810 of the year.
2. Minimum electrical consumption—Hour 4204 of the year.
3. The summer solstice—21 June.
4. The winter solstice—21 December.

The period of study was then chosen as the week surrounding the hour or day of interest, with that moment of interest as close to the midpoint of the study period as possible while maintaining the start of the study period as the first hour of a calendar day (01:00) and the final hour of the study period being the last hour of a calendar day (00:00). Due to the time around the summer solstice being extremely popular for beginning summer holidays and temporarily shutting down businesses and reducing industrial output, this was also the period of minimum electricity consumption. Therefore, the three weeks of study were: 1–7 February (Hours 744–912), 20–26 June (Hours 4104–4272), and 20–26 December (Hours 8469–8664). Tables 1–3 show the categories of demand, supply and storage that were represented on an hourly basis for each of the weeks of study. Results were then compiled and analysed.

Table 1. Study categories for electricity.

Electricity Demand (MW_e)	Electricity Supply (MW_e)	Electricity Storage (MWh_e)
End-user consumption (individual and industry)	Onshore wind	Stationary batteries
Cooling	Offshore wind	V2G batteries [1]
Flexible demand (individual, industry and electric vehicles [1]	Solar PV	
DH heat pumps	Hydropower	
PtG Hydrogen	Industrial power production	
PtG Methane	Combined heat and power	
Residential heat pumps	Condensing power plants	
Residential electric heating	V2G	
V2G (Smart charge BEVs and storage)	Stationary batteries	
Stationary batteries		
Curtailment		

[1] Demand for electricity for electric vehicles was divided into two categories using EnergyPLAN. Half of the estimated 3 million vehicles are so-called Smart Charge Vehicles. The other half represented a so-called Dump Charge. This Dump Charge is found within the category of Flexible Demand in the Demand column due to the integration of these elements by EnergyPLAN. In the Supply column, the category V2G represents the discharging of storage into the electricity grid. In the demand column, V2G represents the charging of storage that takes into account the driving patterns and demands of end-users. It is further assumed that 20% of Smart Charge Vehicles will be in use during periods of peak demand and that the share of parked Smart Charge Vehicles that are grid connected is 70%. For these reasons, charging and discharging of V2G vehicles can occur simultaneously at times.

Table 2. Study categories for district heating (DH).

DH Demand (MW_{th})	DH Supply (MW_{th})	DH Storage (MWh_{th})
End-user demand	Waste heat from PtG, biogas production, and gasification of biomass [1]	Thermal energy storage capacity
Storage	Waste-to-energy	
	CHP	
	CHP heat pumps	
	Boilers	
	Storage	

[1] EnergyPLAN treats these categories as a single constant heat supply even though production of gas is in fact quite variable. This is an unfortunate limitation of EnergyPLAN.

Table 3. Study categories for gas.

Gas Demand (MW_{th})	Gas Supply (MW_{th})	Gas Storage (MWh_{th})
Individual heating	Biogas	Gas storage
Transportation	Gasification	
Industry	Methanation	
Export	Storage	
CHP		
Boilers		

In order to put the study periods in a broader context and to investigate the possible seasonality of different types of energy production, a number of the hourly distributions were examined for the entire year. These included CHP electricity production, solar PV electricity production, onshore wind electricity production, offshore wind electricity production, and annual electricity consumption. CHP and consumptions data for 2012 was derived from [37]. Wind and solar PV distributions were derived from Child and Breyer [5], based on data originating from [38,39]. In addition, the state of charge (SOC) of stationary batteries, V2G batteries, DH storage and grid gas storage were examined for each study week and for the year as a whole.

In the second part of this work, the categories of barriers to success originally posited by Haukkala [28] that involved all relevant stakeholders including industry, utilities, firms, consumers, non-governmental organisations (NGOs), experts, policy makers and professional associations, were revisited and updated. A range of barriers constraining the deployment of solar energy technologies can be categorised, for instance, as technological, economical and institutional [33] or as economic, political, and behavioural [40]. Barriers to the larger deployment of solar PV in Finland which were identified in [28] were revised according to the results of a new survey on the barriers to the implementation of higher shares of renewable energy in Finland conducted in spring 2015. The new survey involved 31 people from the Finnish Local Renewable Energy Association and active citizens interested in the energy transition campaign. Barriers were divided into four categories: technological, economical, institutional-political and behavioural. Possible solutions to the barriers were then compiled and analysed following a more current literature search.

3. Results

Results are compiled in Figures 3–8 and 11–13 for the electricity components of the energy scenario under study for each of the three study weeks. DH and grid components are presented in the Supplementary Material. Annual hourly distributions are presented in Figures 14–18. Annual SOC data are presented in the Supplementary Materials.

3.1. The Energy System

In the first study period (see Figures 3–5), peak consumption of 14,369 MW_e of electricity was reached at Hour 810, near the beginning of a period of extreme cold. As is typical during Finland, such peaks are reached when it is not only cold, but also quite windy, facilitating the need for more heat in general, and electric heat more specifically. At the same time, due to generally high levels of wind energy and CHP production during winter months, electric storage was at maximum capacity. The SOC of stationary batteries was 100% for the entire week, and was above 95% for V2G batteries during the same period. Solar PV production was noticeable during a three-hour period surrounding midday. Both flexible demand and PtG were used effectively during these times to utilise corresponding peaks in electricity generation. As wind levels increased, so too did various forms of heat production: heat pumps, CHP and heat from PtG. The result was that the combination of electric production from wind power, CHP and solar PV meant that eventually curtailment was necessary. However, it can be noticed that DH storage was not filled to its maximum. This is due to the fact that the DH heat pumps are used by EnergyPLAN to create heat for the DH system but not for DH storage. In reality this may not be the case. It is also unclear why CHP plants are operating at a time of high availability of both heat and electricity. Instead of curtailment during hours 820–860, it is questionable why EnergyPLAN did not curtail CHP. However, the EnergyPLAN tool seeks to balance electricity, heat and gas demand as well as production and storage over the entire year. For this reason, short periods such as these are tolerable given a greater time horizon.

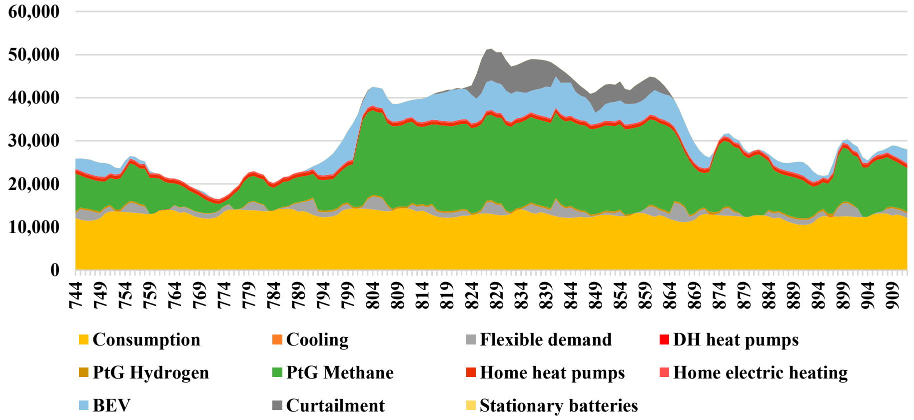

Figure 3. Electricity demand (MW_e): 1–7 February (Hours 744–912). Flexible demand and PtG utilised during all noon peaks of solar photovoltaic (PV) production.

In the second study period (see Figures 6–8), which involves both the highest solar PV production around the summer solstice (15,508 MW_e during Hour 4236) and lowest electricity consumption (5431 MW_e during Hour 4204) as annual summer holidays begin, all batteries become fully charged during periods of excess electricity. However, there is still a minor period of curtailment towards the end of the week. This period of high solar PV production is also a time of relatively low wind and hydro production, indicating that variability of supply is partly smoothed by seasonality. During this time, thermal storage is full and excess heat from industrial processes is condensed. At the beginning of the week, stationary batteries are not used at all for daily storage of electricity, a trend that can also be noted for much of the year. In this regard, stationary batteries seem to be the storage option that is selected last by EnergyPLAN as well as being the storage option that is chosen first for discharge. This is seen as SOC begins the week at 0% and then quickly shoots up to 100% at midweek. Over the year, stationary batteries spend a vast majority of time either being fully charged or fully discharged, with just 5 full load cycles annually, which merits further investigation as other results clearly show about 200–300 full load cycles annually [41,42]. The daily function of electricity storage appears to be allocated to V2G batteries, with 159 full load cycles annually. At the beginning of the second study period, a typical period of charging during the day and discharging in the evening occurs over the first three days. These cycles of charging correspond directly to solar PV production peaks around midday. As electricity storage fills towards the end of the week, other storage options are considered by EnergyPLAN. Towards the end of the week, gas storage begins to fill as the PtG process utilises excess electricity when wind production increases.

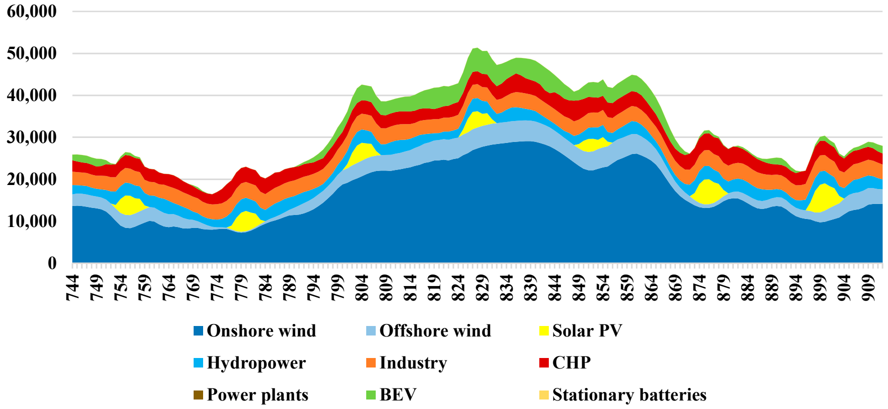

Figure 4. Electricity supply (MW$_e$): 1–7 February (Hours 744–912). Solar PV production occurs in the few hours surrounding the noon peak during study period. Winter months show relatively higher amounts of wind power and Combined Heat and Power (CHP) production.

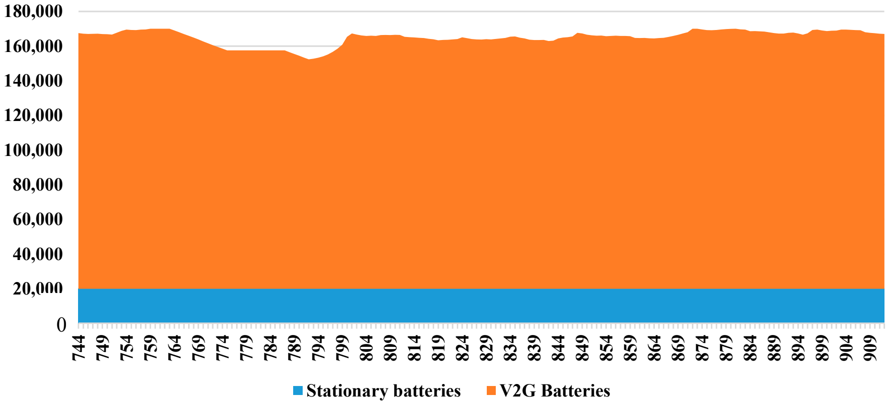

Figure 5. Electricity storage (MWh$_e$): 1–7 February (Hours 744–912). Maximum storage is 170,000 MWh$_e$. Electric storage levels are maintained throughout the study period due to relatively high wind power and CHP production. Stationary batteries are not used, while Vehicle-to-Grid (V2G) batteries serve a minor role in regulating daily power. This is most prominent at the beginning of the study period.

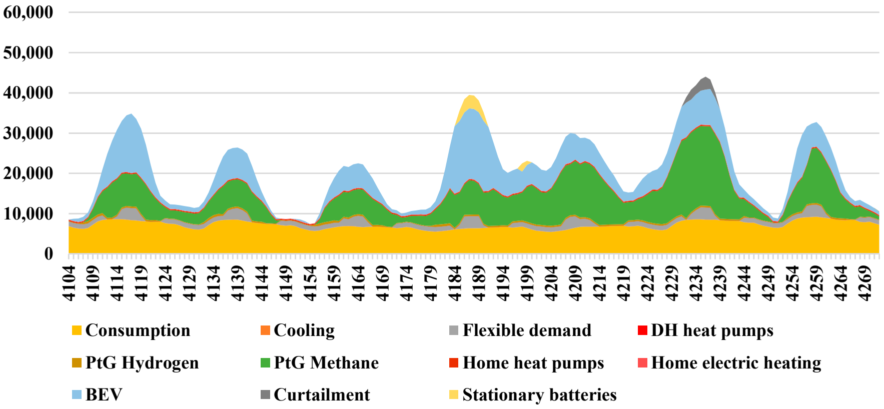

Figure 6. Electricity demand (MW$_e$): 20–26 June (Hours 4104–4272). Overall end-user demand for electricity is relatively low during the study period. Flexible demand and PtG production are utilised during peaks in solar PV production around noon of each day of the study period. Flexible demand by battery electric vehicles (BEVs) is also noticeable.

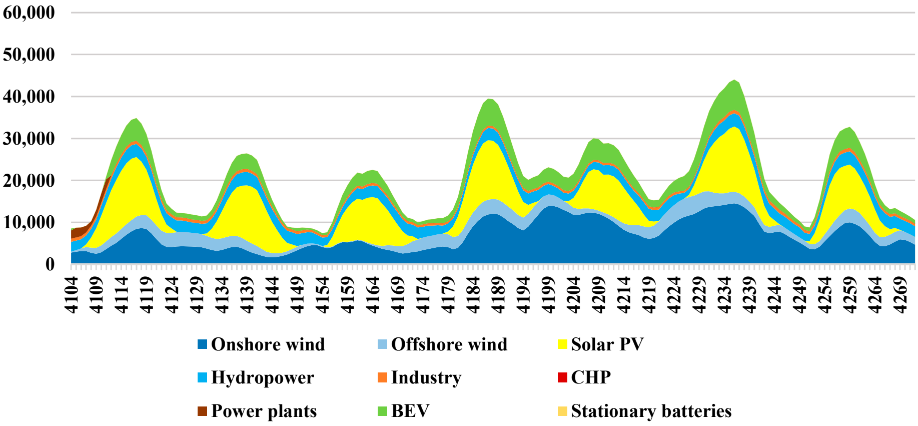

Figure 7. Electricity supply (MW$_e$): 20–26 June (Hours 4104–4272). Supply from solar PV production is high during the study period that encompasses the summer solstice. Solar PV power provides more than 100% of end-user demand during the noon peak on all days but the last of the study period. Solar PV power production represents 35–53% of total electricity generation during noon peaks.

The role of solar PV in this study period encompassing the summer solstice merits further comment. As can be seen from Figure 9, solar PV production exceeds 100% of noon demand in all but the final day of the week. During this week it can also be seen that flexible demand measures are being utilised during noon solar PV peaks to their maximum of 3000 MW$_e$ in a given hour, assisting in higher direct utilisation of solar PV electricity. The share of solar PV in total electricity generation is shown in Figure 10. Values range from 35–53% during noon peaks.

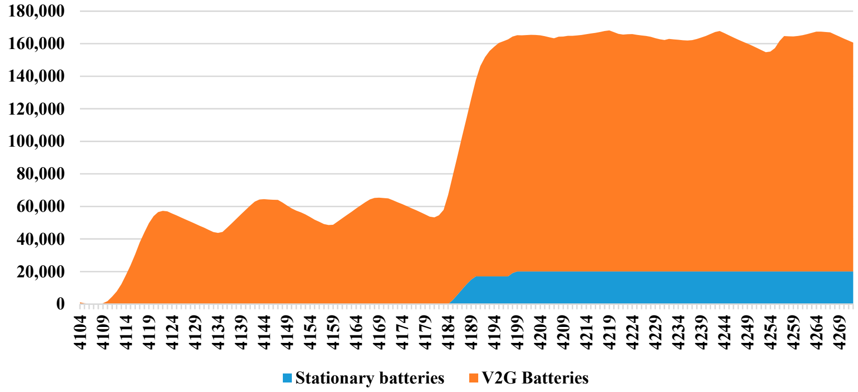

Figure 8. Electricity storage (MWh$_e$): 20–26 June (Hours 4104–4272). Maximum storage is 170,000 MWhe. V2G batteries are charged during the day and discharged at night, showing a strong relationship with solar PV production. Relatively higher winds and reduced demand near the end of the study period result in stationary and V2G batteries being fully charged.

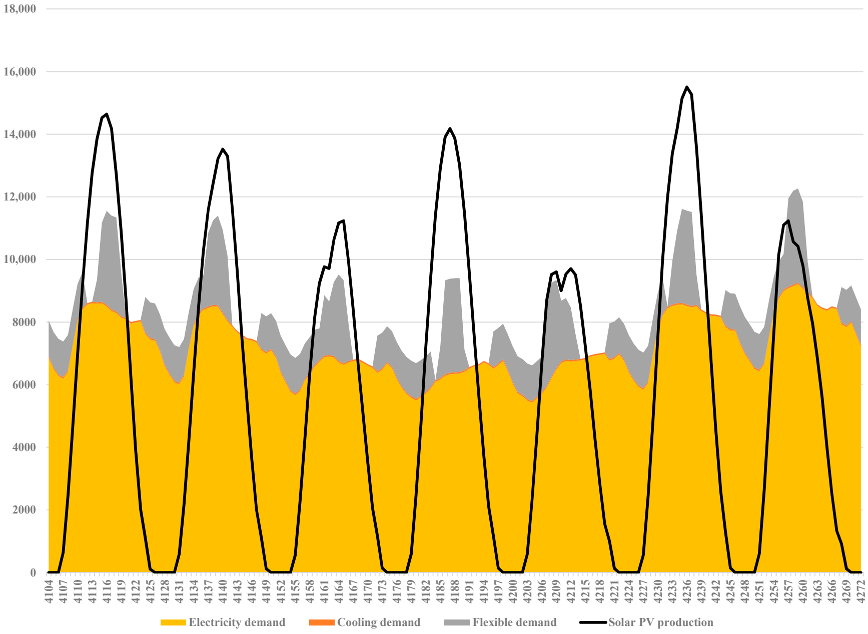

Figure 9. End-user consumption of electricity and solar PV power generation (MW$_e$) during the second study period (Hours 4104–4272). Solar PV production exceeds 100% of noon demand in all but the final day of the week. Flexible demand is used to its full potential during noon peaks of production during this period in order to facilitate higher direct utilisation of solar PV power

The third study period (see Figures 11–13) provides an interesting case. During the first part of the week, cold temperatures result in quite a high demand for electricity. At the same time, the pre-Christmas holiday period generally sees relatively high levels of individual electrical consumption. As levels of all categories of RE production are quite low at the beginning of the week, power plants provide a large share of production, partly due to the fact that batteries have been depleted. This situation changes as both milder temperatures and higher winds are present towards the end of the week. Enough electricity excess exists to begin charging V2G battery storage. Heat storage is also increased as CHP plants shift from condensing mode in the early part of week to backpressure mode later in the week. Hydro production is consistent and relatively high due to hydro reservoirs being at their fullest at this time of year. Also of interest is that grid gas is supplied through biomass gasification in the early part of the week and then by PtG after wind power increases towards the end of the week. The role of solar PV is minor during this week of lowest irradiation. However, this low generation is complemented by both wind power and generation from CHP plants utilising both biomass and stored synthetic grid gas.

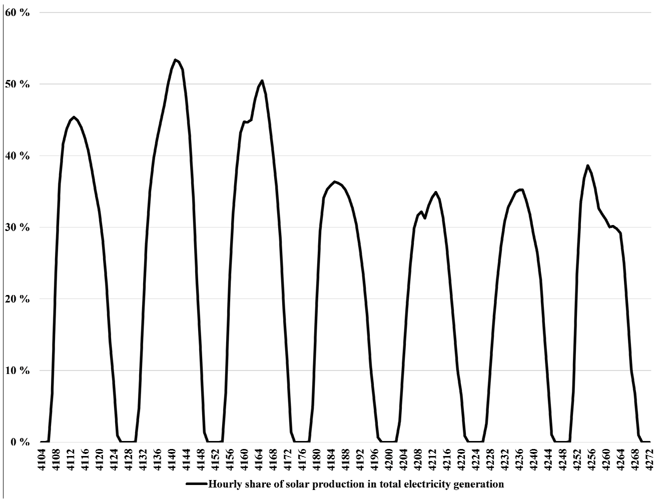

Figure 10. Share of solar PV (%) in total electricity generation during second study period (Hours 4104–4272). Values range from 35–53% during noon peaks of production.

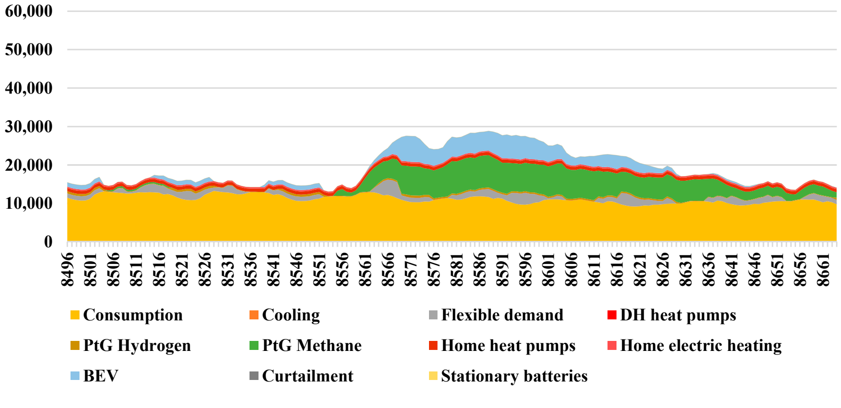

Figure 11. Electricity demand ($\mathrm{MW_e}$): 20–26 December (Hours 8469–8664). Relatively high electricity demand during the winter solstice and during Christmas holidays. PtG methane production corresponds to higher levels of wind power production during the middle of the study period.

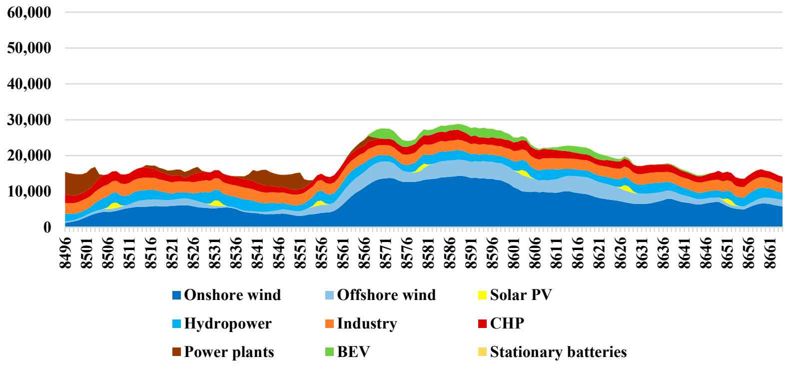

Figure 12. Electricity supply (MW_e): 20–26 December (Hours 8469–8664). Solar PV power production is at its lowest for the year during this study period. This necessitates the use of production from thermal power plants.

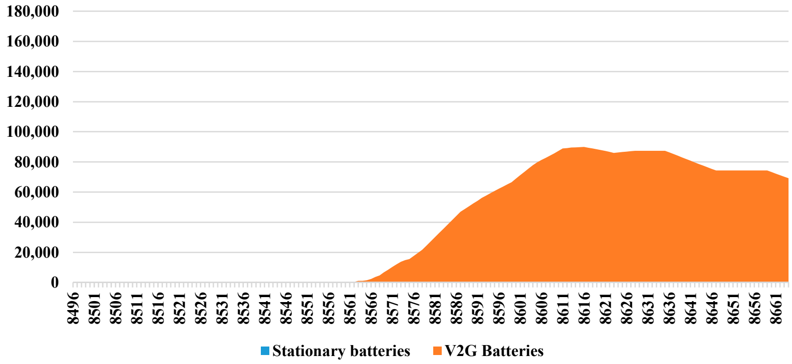

Figure 13. Electricity storage (MWh_e): 20–26 December (Hours 8469–8664). Maximum storage is 170,000 MWhe. Electricity storage is at its lowest levels for the year, causing maximum production of power from thermal plants early in the week. Storage is replenished somewhat after a period of high wind power production during the middle of the study period.

With both the second and third study periods, the weeks are divided into two fundamentally different parts. At the same time, the energy system makes a fundamental change in response, showing rapid adaptation through the use of various flexibility measures. This flexibility appears to come from both storage and generation technologies.

Figures 14 and 15 show how CHP and solar PV production complement each other seasonally. In general, CHP production is lowest when solar PV production is highest, and vice-versa. A noticeable seasonal complement also appears to exist between solar PV and onshore wind generation (Figures 15 and 16). While each is highly intermittent, solar PV generation appears higher at times of low wind and wind generation seems higher in the winter months when solar PV generation is at a minimum. Such a complementary effect of solar PV and wind energy has also been described for other places in Europe [43,44]. Offshore wind (Figure 17) is also intermittent, with a somewhat weaker generation phase during times of high solar PV generation. At the same time, overall generation is lower in magnitude than onshore wind. Electricity consumption (Figure 18) also has a seasonal pattern, with higher consumption during the colder months (November–April). In addition, there is still a significant level of base load demand for electricity even in the summer.

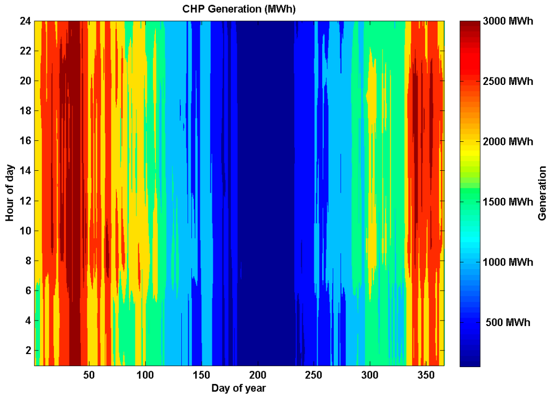

Figure 14. Hourly CHP electricity production (MWh_e). CHP can be used variably both seasonally and daily to correspond to peaks in demand or lower levels of solar PV production.

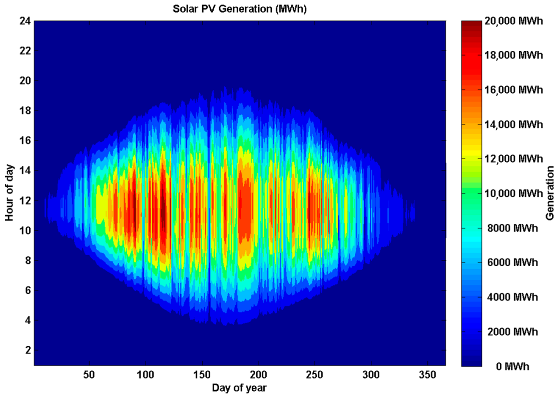

Figure 15. Hourly solar PV electricity production (MWh_e). The seasonality and diurnal nature of solar PV production is offset by variable CHP production.

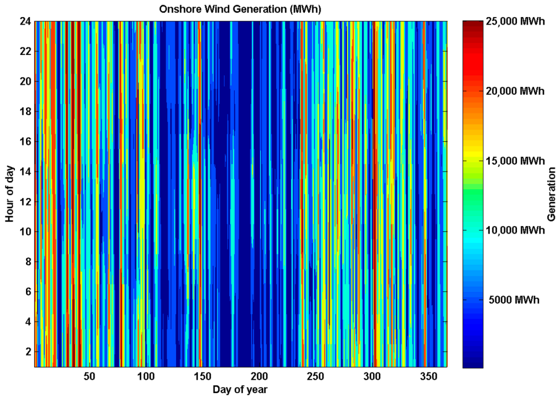

Figure 16. Hourly onshore wind electricity production (MWh_e).

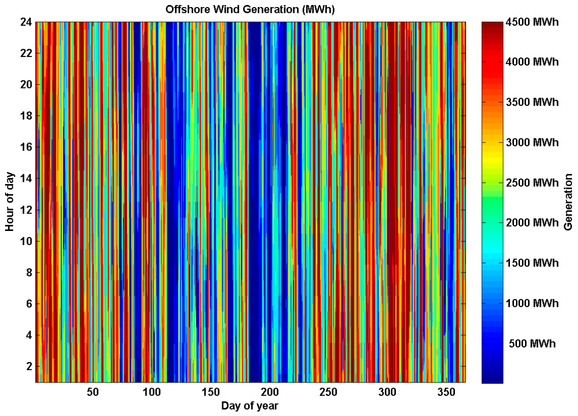

Figure 17. Hourly offshore wind electricity production (MWh_e).

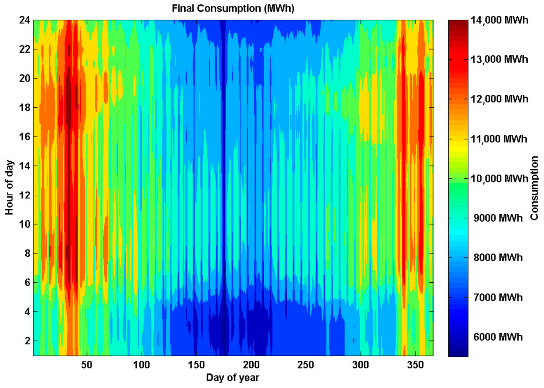

Figure 18. Hourly electricity consumption (MWh_e).

3.2. Barriers and Solutions

Results for the reinvestigation of barriers to the implementation of high shares of solar PV in Finland and their possible solutions are summarised in Table 4. A more in-depth analysis occurs in the following sections.

3.2.1. Technological Issues

Perhaps the biggest technological barrier in Finland has been the lack of energy storage systems [29]. Nevertheless, high growth of newly introduced storage solutions in Germany shows very fast progress. E.ON announced that a third of their newly sold PV systems are already sold with battery storage solutions [45]. It appears rather likely that solutions of front-running markets will be introduced finally also in Finland, which leads to the fact that the problem is no longer a technological one, but rather a problem of inefficient markets.

Table 4. Barriers and possible solutions to increased capacities of solar PV in Finland.

	Barriers	Possible Solutions
Technological	• Lack of energy storage solutions in Finland • Grid and grid monopoly	• Lessons to be learned from solutions available in Germany, R&D allocated to storage solutions • Sufficient and efficient grid, easier to access for small-scale producers, compensation for the producers
Economic	• Competitiveness • Module prices • Price of the electricity in the Nord Pool Area • A need for new electricity markets and rules • Inefficient markets of storage systems • Support and high subsidies for conventional energy system	• Solar has reached grid parity in some market segments and will become more competitive on its own in the future • Module prices are falling continuously • Storage solutions are available at least in Germany—a need to export solutions • As long as electricity prices are lower in Finland than in other countries, solar will not be as popular as elsewhere • Ideally there should be no support systems in the long run distorting markets • Subsidies for harmful emissions from conventional energy need to be eliminated • New business models
Institutional and political	• Current energy regime based on nuclear power, fossil fuels and bio energy • Vested interests • Path dependency • Lock-in • Incumbent electricity companies • Lack of support policy • Lack of powerful advocacy coalitions • Fossil fuels lobbying • Failure to overcome existing subsidies	• A possibility to build a more distributed energy regime • New business models • Some support policy seems to be needed in the beginning phase but type is less significant • More established and powerful solar energy advocacy coalition
Behavioural	• General attitudes • Psychological resistance • Political will	• More information and practical examples of successful installations provided

Grids and grid monopoly have most often been mentioned as technological problems [28,29]. There are concerns about possible impacts of distributed power on the electrical grid, the lack of standard procedures for grid connections, and issues with metering [29]. Grids also need to be made easier for small-scale producers to connect to and producers also should receive better compensation, for instance an hourly based net metering. At the moment, utilities still have to manage the costs of connecting solar households to the grid and make sure the grid is reliable and working efficiently. Respectively, the utilities usually pay for the electricity they buy from small-scale producers for less than the market price and take a monthly fee as compensation for the work done. More advanced utilities, however, already pay better prices and think of it as a sensible thing to do because at the same time they are able to maintain good customer relations with producers and prosumers.

3.2.2. Economic Issues

Cost comparisons with the conventional energy system and competitiveness are no doubt among the biggest barriers overall in Finland, both for utilities and for consumers [28,29]. From the perspective of utilities, the incumbent energy companies feel that an energy system that is based on higher shares of renewables is too expensive; without a well-functioning energy storage system intermittent renewables are expected to need a back-up system and incumbent energy companies still expect that they have to maintain that infrastructure and manage the costs. Eventually, the incumbents might also receive compensation for maintaining the old base load capacity if necessary.

However, instead of looking back to the way things were in the past, the incumbent utilities could treat solar as a gateway into a new market: utilities could sell solar modules, provide financing and grid connections, and build a service relationship [46]. Solar is anticipated to become the largest source of energy in the world by 2050 [47] and that means that there is also a vast market across borders as well. Well-functioning home markets would enhance the possibilities for firms to enter these attractive markets. To sum up, there is a need for new kinds of electricity markets and rules but also new business models.

From the perspective of consumers and prosumers, module prices have been higher in Finland than in other countries due to sales channel inefficiencies and very low market volumes in Finland, but module prices are falling continuously and will be competitive on their own in the future in a wider range of market segments [18,21,48,49]. Installation costs have been relatively high in Finland due to expensive labour and comparably less experienced installers in Finland. However, once the domestic market grows, installation costs will become cheaper as well. This could also be facilitated by training and certification of solar PV installers at a national level. Also, the fact that electricity has been quite cheap in Finland and the Nordpool area compared to other countries has provided little motivation for people to produce their own electricity [28,29]. This might change if electricity prices went up.

Historically, the conventional energy system has received subsidies in different forms and has been able to grow and stabilise its position in the markets. In Finland, solar PV has not received practically any subsidies and this has further supported the conventional energy system. Ideally, there should be no support systems in the long run distorting markets. However, conventional energy technologies receive substantial subsidies due to no or considerable less pricing for harmful emissions [50]. Renewable and conventional energy technologies do not have a level playing field due to these unfair market inefficiencies. This distorts markets as well.

3.2.3. Institutional and Political Issues

There are also conflicting wishes and expectations of society that constitute vested interests [28]. Incumbent energy companies are likely to maintain the status quo as there are enormous investments in the old system. This creates path dependence and lock-in, as stated earlier. At the same time, there are new forms of energy generation that try to break the lock-in and this clashes with the current energy regime based on nuclear power and fossil fuels that exploit economies of scale to achieve profitability. Resistance from utilities or industry can be sensed in the context of path dependence and lock-in, and in the undermining of renewable sources of energy.

Despite the fact that there is hardly any support policy for solar PV in Finland, there has been a growing interest among citizens related to solar energy. In 2016, 88 per cent (or almost nine out of ten people) responding to a survey by Finnish Energy Industries felt that solar energy should be increased [51]. There are a range of different kinds of support instruments in use in other countries, such as feed-in tariffs, green certificates with quota systems, investment and tax incentives, and bids on quota systems, which have proven to create growing home markets in their respective countries. Even a coal-rich country, such as Poland, recently showed more progress than Finland, after a solar PV feed-in tariff was introduced in 2015 [52]. Lund [53] raises the important point that dynamic support structures for a range of new energy technologies can aid in increasing their market penetration. A period of high subsidy may be particularly important to establish early growth in market share, but should be followed by adjustments in subsidies to prevent markets from growing too quickly. At the same time, Ref. [29] reminds that support must go beyond financial measures to be sustainable. Furthermore, some forms of support are seen as preferable for a wide range of distributed generation technologies. Ref. [30] found that one-off investment support or tax rebates were preferable to feed-in tariffs, as they were deemed more cost efficient and were likely to instil greater confidence in Finnish investors.

Lobbying for the conventional energy system has been strong and, as powerful advocacy coalitions in favour of solar PV have been missing, there have not been many disagreements in public debate and decision-making [28]. During the past few years, though, new associations have been established and advocacy coalitions promoting solar energy have started to take shape and actively participate in promoting solar energy in Finland. This may change the current way of thinking as overall energy discourse becomes more representative of a wider range of opinions.

3.2.4. Behavioural Issues

Still, the main obstacles and challenges seem to be the general attitudes toward solar energy in Finland. According to the study by Haukkala [28], there is said to be an attitude problem, a resistance to change, toward new ways of doing things which is in line with Sovacool's [40] behavioural barriers that include public apathy, misunderstanding and psychological resistance. There is a strong belief that the sun does not shine in Finland and the political will has been missing to challenge this myth. In addition, there is a common misunderstanding that rare earth metals will limit the ability to produce solar PV modules in the future, and that modules will ultimately consume more energy than they produce. Despite the fact that research dispels such myths [54,55], the misunderstanding persists.

In order to integrate higher shares of solar PV, the existing barriers need to be overcome. As Painuly suggests [31], policy approaches can either eliminate barriers or promote conditions whereby the market is enabled to ignore the barriers. Solutions suggested are not difficult; some of them will happen on their own, for instance module prices are constantly falling and leading to higher shares of installations. Some solutions concern political decisions: whether to allocate research and development funds for energy storage systems or to introduce some support policy in the beginning phase for solar PV. The energy sector needs to be restructured and new business models should be promoted. Also, providing more information and correcting misunderstandings is just as important. Barriers can be overcome: solutions just need to be implemented or developed further. All this is relevant in countries other than Finland as well.

4. Drivers for Solar PV

Climate change has brought a global need to reduce greenhouse gas emissions. Solar PV offers no direct carbon emissions. According to [56], together with other renewable energy resources, solar PV is currently the leading economically viable and environmentally sound option to reduce CO_2 emissions and meet growing energy needs as long as and unless there are no technological and safety breakthroughs with other low emission technologies, such as nuclear power and carbon capture and storage (CCS). For a growing number of PV applications and regions in the world, one can observe financial CO_2 emission reduction benefits, i.e., no cost anymore, as a consequence of the rapidly increasing competitiveness of PV [57]. It also provides energy security and diversification of production. Further, there are new "green" jobs created in conjunction with installations in the domestic markets and growth opportunities in high tech business exports, for instance with technical equipment needed in panel manufacturing and installation. Lastly, solar PV can provide more access to electricity in rural areas, reduce the number of outages and hence lower economic losses in the future [56].

The drivers for solar PV are mostly technological improvements, cost reductions and government policies. For the first, solar energy has experienced a major technological shift from small-scale photovoltaic installations to large-scale PV systems that feed into electricity grids [33]. Secondly, the costs have dropped over the last 30 years and are expected to continue on this trajectory [21]. Thirdly, solar energy benefits from fiscal and regulatory incentives that have led to a rapid expansion of the solar energy market [33]. While the declining support policy for PV is reducing the European market and even increasing the PV electricity cost by increasing the risk and thus the cost of capital, the implementation of new feed-in tariff policies has led to an increase in markets in, for instance, China and Japan [58].

Río and Unruh [34] have identified barriers and drivers to PV energy in Spain. Surprisingly, the barriers do not differ much from those in Finland despite the fact that Spain has the best solar resources in Europe. Therefore, solar insolation cannot be the only explanatory factor. The barriers in Spain are high initial costs, lack of an accurate legal framework and insufficient support, administrative barriers, financial barriers, companies in the conventional electricity sector, training and skills of equipment installers, lack of information, connection to the grid and integration in buildings. In terms of policy, the authors [34] note a number of key drivers similar to the solutions suggested in this work that would aid in overcoming such barriers, including: expanding the solar PV market to promote scale and learning effects, supporting R&D, expanding financial support measures, mandating solar PV installations in new buildings, establishing minimum competencies for PV installers, and raising awareness of the many benefits of solar PV as well as the steps needed to begin enjoying them. Further, they suggest awareness campaigns targeted at individuals, professional groups, and architects. As pointed out by [21], an unclear public PV policy directly or indirectly increases the risk for PV investments and represents a major cost driver, as the cost of capital reflects the level of investment risk in a country. Therefore, a sound PV policy has to aim at reducing the risk for PV investors to reduce the overall cost of PV electricity generation, since cost of capital can represent an even higher cost fraction than the initial investment cost as emphasised by [21].

A recent study of the role and future of distributed energy generation in Finland suggests that there has been a general lack of understanding about which factors will promote its growth and the actual barriers which need to be overcome or removed [29]. However, the authors suggest that a comprehensive approach to the removal of barriers should go beyond promoting only one form of energy production and include all forms of distributed generation of heat and electricity. This "more profound process of transformation" must promote institutional change as well as the engagement of a wide variety of stakeholders and key actors throughout the energy sector. Investment support should be seen as only one part of a sustainable approach.

The same study [29], based partially on previous work [30] identifies four business models for distribution system operators (DSO) and other energy companies that are suited to small-scale renewable energy generation in Finland. The first is the one that currently dominates the landscape—a company or DSO as intermediator/facilitator. In this concept, the surplus electricity generated by prosumers is purchased and passed along to other areas of the grid for a modest profit to the facilitator. In general, prosumers earn very little from this sold electricity and so design their systems to maximise self-consumption. However, as interest in solar PV has grown in Finland, new models have begun to emerge. The second is the turn-key (energy optimisation) model, whereby utilities or large companies provide full-service solutions, from generation to possible sales of energy. Important features of this model is the ease for customers and the ability for utilities to optimise customer consumption. The third is the centralised solar PV concept. Accordingly, a company will plan, build and operate a large-scale solar PV plant, but individual investors share in the ownership and become indirect prosumers. These investors are generally viewed as having a high awareness of sustainability issues in general, and quite importantly, may have a higher ability to pay for sustainable energy. The fourth is a joint purchase model, whereby demand for small-scale generation is driven by groups that organise themselves as grassroots movements. Joint purchases can be performed as a collection of individuals, established purchase groups or large networks. Working together results in an ability to achieve discounts related to scale and learning effects. Each of these models are already present in Finland, and have allowed a greater number of individuals and groups access to a low-cost form of electricity. This may empower many to determine their own pathway towards long-term sustainability on more than economic terms.

Full empowerment of stakeholders can only be achieved through careful consideration of stakeholder needs and goals. Therefore, Goldstein [59] reminds that regular input from and engagement with stakeholders must be essential elements of the research process. In doing so, one can then "facilitate realism and traction" of the process so that momentum is generated. To accomplish this, stakeholders must have an honest accounting of the risks and rewards related to proposed choices. These risks and rewards, as well as what drives them, must also be accounted within the different realms of sustainability (economic, environmental and social) and for different groups within a society. In particular, raising awareness of the benefits of solar PV may be the most important step for stakeholders to be enabled to enjoy such benefits.

5. Discussion

A reliable energy system based on 100% RE seems technically feasible for Finland in 2050. PtG and energy storage solutions contribute significantly to the energy system by offering flexibility and integration of the electricity, heating/cooling and mobility sectors. Moreover, flexibility of the energy system is harnessed at times of lower RE resource availability through the use of methane storage over the long term, and battery storage over the short term.

In this study, solar PV makes a roughly 10% contribution to final energy consumption and is 16% of the total electricity generation, but that contribution is concentrated in approximately seven months of the year. In addition, that contribution is at times concentrated even more during daylight hours, necessitating daily and seasonal storage. On a daily basis, V2G batteries seem to have a much greater role than stationary batteries, although this may be due to how the model prioritises storage solutions. One could expect more use of stationary batteries in reality, especially on a daily basis.

Other studies have suggested a strong complement between solar PV and batteries [22–25]. This current study also shows such a complementary relationship, albeit to a lesser extent. At the same time, the way the EnergyPLAN tool allocates energy to the stationary batteries in the scenario under study appears to be the main limitation. This function will need to be considered in more detail in further studies.

On a seasonal basis, PtG technology bridges the gaps between demand and supply at times when generation is most intermittent. At the same time, these technologies are available to provide base loads of electricity, heating, cooling and mobility when they are needed. These results are in line with those for Germany [60,61]. What is more, PtX (Gas, Liquids, Chemicals) technologies are already showing promise of profitability in niche applications in Finland [62] and the role of PtX may expand outside of the energy sector [61].

Interestingly, there is no time when the sun does not shine and the wind does not blow. Indeed, other studies are also confirming the feasibility of solar PV systems in Nordic conditions [63]. The seasonal complement of solar PV and wind power production in Finland appears obvious, despite the intermittent nature of each. This intermittency appears manageable by the storage technologies utilised in this study. In addition, the ability of distribution networks in Finland to host large capacities of distributed rooftop PV generation appears not to be a technical impediment [64]. One must also remember the important role of hydro power in Finland. Up to 20% of end-user electricity consumption can be supplied by hydro. This study also does not fully explore the full potential of hydro storage available in Finland. Indeed, a full accounting of the potential of hydro storage in Finland is lacking. Should there be further potential flexibility in hydropower production as expected, this could lessen the need for other storage capacity, such as batteries or PtG production, or power plant capacity, and may in turn result in a decrease in overall costs.

The integration of high shares of renewable energy sources in future energy systems will require a variety of complementary storage solutions. It has been previously determined that electricity storage devices will be needed once 50% of power demand is met with variable RE, and that seasonal storage devices will be needed once more than 80% of electricity demand is met by RE [44,65]. Currently, there is a long list of energy system flexibility measures available to support high levels of intermittent RE [66]. Developing a 100% RE scenario for a nation requires careful consideration of the right mix of these measures for each context. In turn, these measures should be suited to and complemented by the energy generation technologies that make up the energy system. Such is the case for solar PV and the energy storage technologies investigated in this work. Solar PV and energy storage solutions can play a significant role in a future energy system for Finland based on high levels of renewable energy generation. This conclusion is in line with other such analyses of the Finnish energy system [5,7,8,67]. As well, the role of EV batteries in mitigating the negative effects associated with the intermittency of some forms of renewable energy has been documented in studies performed on a broader context [68,69].

Other studies of the Finnish energy system have provided a wide range of projections for future solar PV installed capacities. In the most pessimistic assessment [9], solar power in Finland was described as "...not expected to be a profitable production method if connected to the grid in Finland" and would only be "...utilised to meet the increasing electricity consumption in holiday and second homes". Even the optimistic Greenpeace [70] offers only a conservative 4 GW_p of installed solar PV capacity in Finland by 2050. More recent analyses have taken into account the increasing role of solar PV in global energy systems as a low cost or possible breakthrough technology for the future. In turn, the most recent scenario models for Finland suggest much higher amounts of installed capacities or energy production. Ref. [71] suggests that approximately 7.2 GW_p would be technically possible for Finland in the future (5.6 TWh_e/a). In their Technological Breakthrough Scenario, Ref. [72] suggests that approximately 7.5 GW of distributed generation (primarily solar PV) would be possible, totalling roughly 10 TWh_e. Lastly, in their Change Scenario, Ref. [1] estimate that approximately 18 TWh_e could be generated from solar PV (about 20 GW_p installed capacity). The 100% RE scenario considered in this analysis suggests that 30 GW_p of installed capacity would generate approximately 29 TWh_e of power in 2050, or 16% of final electricity consumption.

There are several reasons for the differences between the current results and those of others. These can be divided into two main groups: scenario design and key assumptions. In terms of scenario design, the main aims of [5] included designing an energy system that had virtually no carbon emissions and that accomplished total energy independence (no imports of electricity, gas or other fuel). In addition, a wider range of flexibility mechanisms in the form of energy storage and energy sector integration were utilised that supported higher installed capacities of solar PV and other forms of variable RE. Furthermore, a least cost solution for the energy system requires solar PV for balancing the relative lack of wind in the summer months. Importantly, only one of the previously mentioned studies were based on such high shares of renewable energy, and almost all reported high shares of electricity import. In terms of basic assumptions, by utilizing a learning curve approach, this work assumes that solar PV will continue its exponential growth, resulting in lower prices for modules and the balance of the system components, as well as higher efficiencies of modules over time [21]. It is not surprising, then, that this study reports very different installed capacities than other studies.

6. Conclusions

This article has discussed the prospects of reaching an energy system based on 100% renewable resources by 2050 in Finland. To achieve such high installed capacities of solar PV, significant changes must occur in the Finnish energy sector. Most noticeably, storage solutions and other elements of flexibility, such as flexible demand and smart charging of electric vehicles, will need to balance the intermittent nature of electricity generation in an energy system based on high shares of wind energy and solar PV. Batteries will play a key role in providing short-term storage on a daily or multi-day scale, while PtG will provide storage on a seasonal level. An important complement between solar PV and battery storage, seen in several other studies, was also seen in this investigation. In the end, a technically feasible and economically competitive solution for Finland based on 100% renewable energy and high shares of solar PV is demonstrated in detail to reveal how such a system could work.

Such a future energy system represents a complete transformation away from what currently exists, and will by no means be easy or quick to achieve. A variety of technical, economic, institutional, political and behavioural barriers currently exist that prevent further solar PV capacity increase. However, these barriers can be overcome with new policy, regulation and understanding. The aim of this study was not to direct policy in any one particular direction, but to suggest several options available. Ultimately, the optimal mix of technological solutions and the policy measures that facilitate them will be determined based on how well they enable the achievement of a wide range of societal, economic and environmental goals. It is hoped that many of these suggestions could also be applied to other emerging RE technologies and could be very applicable in other northern countries as well.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/8/1358/s1, Table S1: Installed capacities of energy technologies for the 100% RE scenario for Finland in 2050; Table S2: Main scenario input parameters; Table S3. Storage parameters; Table S4: Technology efficiencies; Table S5: Main cost parameters for 2050 Finland. Figure S1: DH demand (MW_{th}): 1–7 February; Figure S2: DH supply (MW_{th}): 1–7 February; Figure S3: DH storage (MWh_{th}): 1–7 February; Figure S4: Grid gas demand (MW_{gas}): 1–7 February; Figure S5: Grid gas supply (MW_{gas}): 1–7 February; Figure S6: Grid gas storage (MWh_{gas}): 1–7 February; Figure S7: DH demand (MW_{th}): 20–26 June; Figure S8: DH supply (MW_{th}): 20–26 June; Figure S9: DH storage (MWh_{th}): 20–26 June; Figure S10: Grid gas demand (MW_{gas}): 20–26 June; Figure S11: Grid gas supply (MW_{gas}): 20–26 June; Figure S12: Grid gas storage (MWh_{gas}): 20–26 June; Figure S13: DH demand (MW_{th}): 20–26 December; Figure S14: DH supply (MW_{th}): 20–26 December; Figure S15: DH storage (MWh_{th}): 20–26 December; Figure S16: Grid gas demand (MW_{gas}): 20–26 December; Figure S17: Grid gas supply (MW_{gas}): 20–26 December; Figure S18: Grid gas storage (MWh_{gas}): 20–26 December. Figure S19: State of charge of stationary batteries; Figure S20: State of charge of V2G batteries; Figure S21: State of charge of DH storage; Figure S22: State of charge of grid gas storage.

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Abbreviations

BAU	Business as usual
BEV	Battery electric vehicle
CCS	Carbon capture and storage
CHP	Combined heat and power
DH	District heating
DSO	Distribution system operator
GHG	Greenhouse gas
LCOE	Levelised cost of electricity
NG	Natural gas
PtG	Power-to-gas
PtL	Power-to-liquid
PtX	Power-to-chemicals
PV	Photovoltaic
RE	Renewable energy
RET	Renewable energy technology
SOEC	Solid oxide electrolysis cell
SOC	State of charge
TES	Thermal energy storage
V2G	Vehicle-to-grid
WACC	Weighted average cost of capital
$_{e}$	Electric units
$_{gas}$	Gas units
$_{th}$	Thermal units
$_{p}$	Nominal or peak capacity

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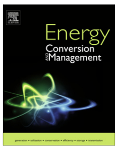

Scenarios for a sustainable energy system in the Åland Islands in 2030

Michael Child [a,*], Alexander Nordling [b], Christian Breyer [a]

[a] Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland
[b] Åbo Akademi, Tuomiokirkontori 3, 20500 Turku, Finland

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ABSTRACT

A fully sustainable energy system for the Åland islands is possible by 2030 based on the assumptions in this study. Several scenarios were constructed for the future energy system based on various combinations of domestic production of wind and solar photovoltaic power, expanded domestic energy storage solutions, electrified transport, and strategic energy carrier trade. Hourly analysis of scenarios using the EnergyPLAN tool shows that annualised costs of operating a future sustainable energy system for the year 2030 range between 225 and 247 M€/a compared to 229 M€/a for the business as usual case. However, this result is highly dependent on how vehicle and battery costs are accounted. A scenario featuring a highly electrified transport sector, including a wide range of terrestrial and aquatic forms of mobility, was among the most cost competitive solutions due to high levels of flexibility and electric storage harnessed in the energy system. In this scenario cost reductions were achieved as high capacities of electric vehicle battery storage resulted in less need for seasonal storage and synthetic fuel production in the form of Power-to-Gas technologies and offshore wind power capacity. Results also indicate that 100% renewable energy-based domestic energy production can be achieved in Åland, with or without reliance on imported energy carriers, such as sustainable biofuels or electricity. A demonstration of a highly electrified transport sector may also offer Åland society several benefits outside of the boundaries of the energy system. New job creation related to renewable energy production on Åland could total between at least 3100 and 3900 job-years during manufacturing, construction and installation, and between 45 and 59 more permanent jobs related to operations and maintenance, depending on the scenario.

1. Introduction

Islands and regions of archipelago represent interesting case studies on sustainable energy systems. Firstly, they tend to be compact geographic areas with homogeneous populations. Secondly, components of the energy system tend to be less complex and are more easily documented than larger continental systems. Thirdly, islands are generally associated with significant imports of expensive fossil fuels from [1] or power interconnections with continental energy suppliers. Further, eliminating dependency on imported energy through expanded use of domestic renewable resources and storage solutions has been suggested as an alternative for islands around the globe [2]. Importantly, islands may offer blueprints for sustainable energy system transitions that will occur on a larger scale with continental systems.

Several studies describe the benefits of Renewable Energy (RE) based energy systems on islands. Kaldellis et al. [3] propose that RE and Energy Storage Solutions (ESS) can encourage a shift away from oil dependence while promoting environmental benefits and financial advantages. In addition, Franzen et al. [4] demonstrate that optimized renewable energy system configurations up to 100% RE can "generate substantial savings" and eliminate the need for diesel generators on islands while still guaranteeing grid stability and reaching ecological as well as economic goals. The authors also point out that island energy systems may encounter shares of RE beyond 50% much sooner in the future than mainland grids, highlighting further relevance of the study of island energy systems. Further, Hlusiak et al. [5] outline how integration of electric vehicle batteries can add to island grid stability while reducing overall emissions associated with diesel generators. Of interest is the fact that the simulated island energy system demands on electric vehicle batteries did not pose significant restrictions on vehicle range, suggesting potential benefits of coupling RE and electrified mobility. To this extent, Blechinger et al. [2] claim that islands may not only represent a blueprint for future mainland systems, but represent an attractive new business field which can serve as showcases of the "attractiveness of reducing fossil fuel based power generation and GHG emissions".

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[*] Corresponding author.
E-mail address: Michael.Child@lut.fi (M. Child).

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Nomenclature

RE	renewable energy
ESS	energy storage solutions
PV	photovoltaic
DC	direct current
AC	alternating current
BEV	battery electric vehicle
V2G	vehicle-to-grid
BAU	business as usual
e	electric units
th	thermal units
gas	gas units
p	nominal or peak capacity
PtG	power-to-gas
Capex	capital expenditures
Opex	operating and maintenance expenditures
O&M	operations and maintenance
MCI	manufacturing, construction and installation
SE	Sweden
FI	Finland

The archipelago of Åland is located in the Gulf of Bothnia of the Baltic Sea (Fig. 1) between Sweden in the east and Finland, of which Åland is an autonomous region, in the west. The Government of Åland has recently established a development and growth plan aimed at achieving sustainability throughout all spheres of life by 2051 [6]. In addition, local stakeholders have begun to envision how an energy system could enable the delivery of reliable, affordable, quality energy services which are free of fossil fuels to local end users [7]. Fundamental to a vision of a future Åland energy system is the consideration of optimal energy flows between Åland, the rest of Finland, and neighbouring Sweden, the latter of which has long been a significant supplier of power to Åland due to its geographic proximity. An 80 MW high voltage AC connection with Sweden is expected remain an important part of the energy system, and a link with Finland was expanded in January 2016 to a 100 MW high voltage DC cable. For these reasons, a transition to a different kind of energy market design is likely to occur in the decades to come. At the same time, local stakeholders would like to determine the optimal balance of the entire energy system (electricity, heat and transport sectors) in order to achieve security of supply, reasonable levels of self-sufficiency, competitiveness of society, and mitigation of climate change. A summary of key Åland facts is presented in Table 1.

The electrification of much of Åland's transport seems interesting in light of a seeming local willingness to adopt to new, efficient technologies. Already, another area of the Nordic region, Norway, is considering high levels of future transport electrification by making conditions unfavourable for non-electric vehicles by 2025

Table 1
Key Åland statistics.

Åland facts 2014	Unit	Value
Capital		Mariehamn
Population in 2014		28,983
Population expected by 2030		33,000
Number of islands		6757
Number of inhabited island		60
Total electricity supply	GW h_e	288.4
Domestic electricity production	GW h_e	70.1
From oil	GW h_e	11.7
From bioenergy	GW h_e	1
From wind	GW h_e	57.4
From Sweden	GW h_e	200.7
From Finland	GW h_e	17.6
Total heat supply to district heating	GW h_{th}	115
From oil	GW h_{th}	15
From biomass	GW h_{th}	100
Share of district heating in total heat supply		40%
Length of district heating network	km	66.4
Biomass use in households (estimated)	GW h_{th}	20
Total transport demand	GW h_{th}	227
Gasoline demand	GW h_{th}	129
Diesel demand	GW h_{th}	98
Number of cars and vans		26,636
Number of lorries and buses		841
Number of motorcycles, mopeds and tractors		7625
Total road transport demand (estimated)[a]	Million pkm	250
Number of large marine vessels		112
Number of recreational watercraft		~7000

[a] Based on usage of transport fuels stated above and an assumed conversion of 1.5 km/kW h_{th} of fuels (6.7 L/100 km of diesel and 7.4 L/100 km of petrol).

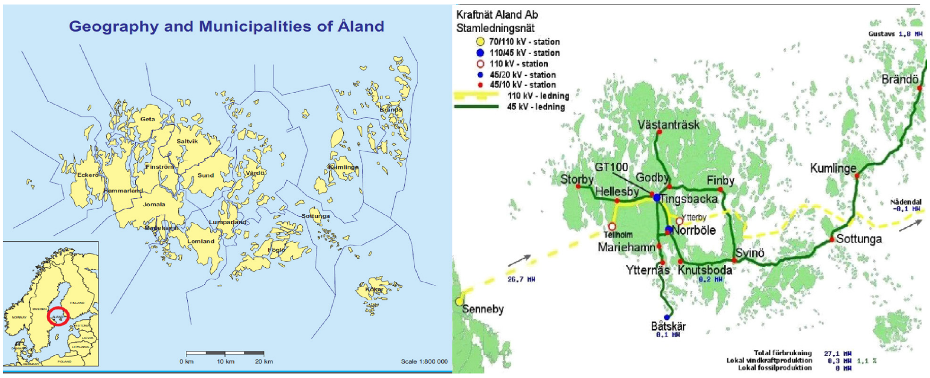


Fig. 1. Location of Åland and interconnections with Sweden and mainland Finland. Source: [8] (left), [9] (right).

[10]. And given the small area and relatively homogeneous population of Åland, a fast roll-out of such a technology as Battery Electric Vehicles (BEVs) seems possible. In addition, the electrification of boating, shipping and biking offers further possibilities. The long-term environmental and economic benefits of the electrification of marine transport was recently discussed in [11] for marine power systems either retro-fitted or newly built with Li-ion battery capacity. This leads to the question of how potentially large transport battery capacities can add flexibility to future energy systems based on high shares of intermittent renewable energy generation. However, not all future transport needs will be suitable for electrification, especially heavy transport. For this reason, biofuels offer a solution, but the feasibility of sustainable, domestic production compared with imports has not been studied for Åland, and represents a significant gap in knowledge. Further, should electrification be extended to a wider range of transport, particularly the large number of boats, ferries and bikes that are operated in the warmer months but sit idle for long periods during winter, the potential for transport-based electric storage seems promising and may extend beyond typical scenarios that involve only road vehicle-to-grid connections. This aspect of storage needs investigation in further detail to determine if such flexibility can be harnessed in a future energy system.

The effects of widespread use of electric vehicles on transmission grids remains an area of concern. Sadri et al. [12] observe that BEVs can result in higher peak demand, and may result in intensified line congestion at times of high demand. However, when charging occurred at off-peak times, between the hours of 1:30 a.m. and 9:00 a.m., a valley-filling effect was noticed during morning hours that normally saw low demand. Similar issues were mentioned in [13], who studied the effects of BEVs on the power system of the island of Flores in the Azores archipelago. The study showed that the issues of low voltage profiles and very high peak loads could be easily resolved by a smart charging scheme. The studied concluded that the current, robust grid on the island of Flores was already prepared for the arrival of BEVs, and that as penetration of BEVs increases, smart charging would be required to manage the network within its technical limitations. There were, however, noticeable limitations in how both studies represented BEV batteries. For one, neither study represented an ability of BEVs to provide electricity back to the grid. For another, the storage capacity of batteries, only 9 kW h in [12] and both 12 and 24 kW h in [13], are far short of the current 60 kW h battery for Nissan Leaf [14] and 100 kW h battery for Tesla Model S [15]. Therefore, the flexibility offered by BEVs to electricity networks remains somewhat underrepresented.

Recently, Child and Breyer [16,17] described the role of ESS in the Finnish energy system as a whole, and observed that Power-to-Gas (PtG) was a complement to wind energy production, while battery storage coupled well with solar PV production in Finland. It seems reasonable to investigate whether the same would hold true for Åland in particular, where both wind and solar resources are measurably better than those on mainland Finland.

In the past Åland has relied heavily on imported electricity from Sweden, and currently seems poised to benefit from greater trade with mainland Finland. Creating a new market design that optimises domestic production and trade with neighbouring countries will be necessary in the future, but the exact dynamics of such a new market currently remain unknown. Before a new market can be designed, several different energy futures should be explored that account for a variety of production and trade possibilities. Due to electrical interconnections and the relatively ease at which energy carriers can be traded, Åland has the ability to decide how much of an 'island' it wishes to be, at least in energetic terms. From the results of such analysis, stakeholders can weigh options in terms of their overall sustainability within the specific socio-economic context.

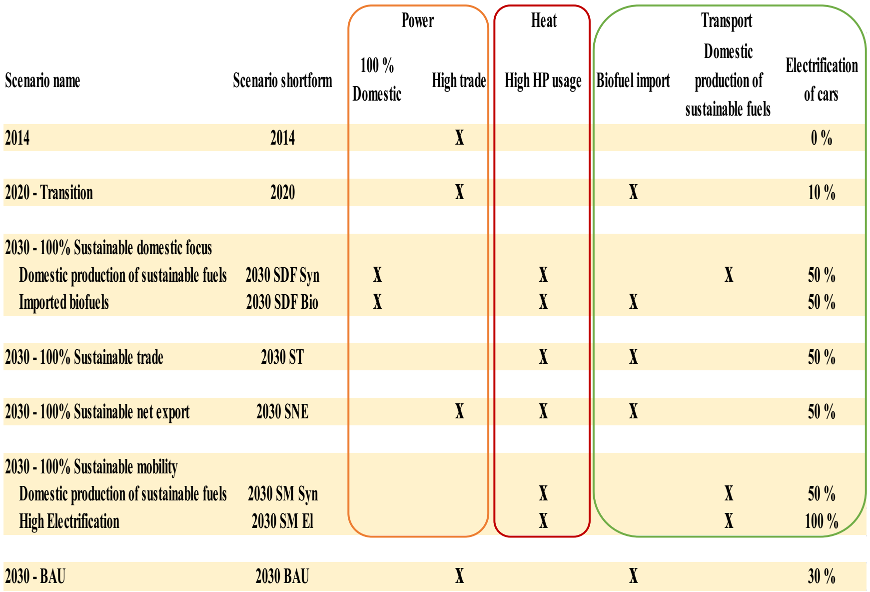
The purpose of the current study, therefore, is to perform and initial investigation of future energy system scenarios for Åland in order to facilitate planning and decision making by the Åland Smart Energy Platform and guide future research into possible energy market design. Specific research questions of interest are:

1. Can a 100% sustainable energy system be achieved by 2030 for Åland?
2. What is the least cost scenario that can result in a fully functional, reliable, 100% sustainable energy system for Åland in 2030?
3. What are the roles of Power-to-Gas, Vehicle-to-Grid and other energy storage solutions in future energy system for Åland?
4. What would be the optimal roles of domestic production of energy carriers and imports?

2. Methods

The methodology of this study is divided into four main sections. A short description of the EnergyPLAN advanced energy system analysis computer model [18] will be followed by a description of scenario construction. A visual representation of the main scenario design parameters is found in Fig. 2. To some extent, binary features were used to define aspects of the power, heat and transport sectors whereby a characteristic was either present (marked by an X in Fig. 2) or not. The power sector involved either 100% domestic production of power, or use of current interconnections. Further, in scenarios marked as high trade, total annual net electricity import or export was greater than 50 GW h_e. Otherwise, net imports or exports of electricity were restricted by scenario design to less than 25 GW h_e. In scenarios marked 100% domestic, no trade of electricity was allowed and all excess domestic electricity production was considered curtailed. Control of levels of import and export was accomplished in two ways. First, the EnergyPLAN tool allows for allocation of critical excess electricity production (CEEP) through the use of specific strategies. In test scenarios, excess electricity was used to increase PtG production, reduce CHP production by replacement with boiler (heat) only production, and to replace boiler production with electric heating (Strategies 8, 3, and 5, respectively). Second, the authors manually controlled acceptable levels of export through specific choices of technologies and their capacities so as to minimise excess production. In 100% domestic scenarios, transmission line capacity was artificially designated as 0 within the EnergyPLAN tool in order to simulate island mode. However, costs were still assigned for the known interconnections. In this regard, the interconnections would represent an emergency back-up in extraordinary circumstances.

The heat sector was classified as having a high level of installed heat pump capacity (greater than 1 MW_e), or not. In general this was related to how the domestic market could handle excess electricity available from the power sector. Otherwise, the parameters of the heat sector remained constant, with future values changing mostly with respect to population change. The transport sector was classified in three main ways: first, according to whether imports of biofuels were allowed or not; second, according to whether the scenario involved domestic production of transport fuels or imports; third, according to the level of electrification of cars (in %). At the same time, electrification of transport was extended to a greater range of the transport sector (boats, ferries, bikes, etc.) in one scenario. Lastly, main cost assumptions are presented, with more detailed assumptions related to costs and inputs to EnergyPLAN listed in the Supplementary material (Tables A5–



Scenario name	Scenario shortform	Power		Heat	Transport		
		100 % Domestic	High trade	High HP usage	Biofuel import	Domestic production of sustainable fuels	Electrification of cars
2014	2014		X				0 %
2020 - Transition	2020		X		X		10 %
2030 - 100% Sustainable domestic focus							
Domestic production of sustainable fuels	2030 SDF Syn	X		X		X	50 %
Imported biofuels	2030 SDF Bio	X		X	X		50 %
2030 - 100% Sustainable trade	2030 ST			X	X		50 %
2030 - 100% Sustainable net export	2030 SNE		X	X	X		50 %
2030 - 100% Sustainable mobility							
Domestic production of sustainable fuels	2030 SM Syn			X		X	50 %
High Electrification	2030 SM El			X		X	100 %
2030 - BAU	2030 BAU		X		X		30 %

Fig. 2. Main scenario design parameters for the power, heating and transport sectors.

A12). Finally, modelling results are compiled and analysed. A flow chart of the simulation is found in Fig. 3.

2.1. The EnergyPLAN tool

The EnergyPLAN advanced energy system analysis tool is a deterministic, input/output computer model that can assist in the design of energy systems on a regional, national or multinational level. The tool has been continuously developed since 1999 at Aalborg University in Denmark and the version used (12.3) was released in June 2015. A full description of the tool and its advantages can be found at [18]. Several studies of future Finnish energy systems with high shares of renewables have utilized the EnergyPLAN tool in recent years [16,19–21], the first of which included a thorough description of its limitations in the Finnish context. Of highest relevance to the current study of Åland is that EnergyPLAN can only simulate a single external electricity market. Moreover, the user must define a single interconnection capacity and hourly electricity market price for the system, and this interconnection is used one way in any given hour. Therefore, the complexity of the future Åland energy system may not be fully represented as interconnection is to two separate price areas within the Nordpool market.

2.2. Scenario descriptions

In total nine different scenarios were analysed in this work, and main scenario inputs are summarised in Tables 2–5. All scenarios were designated as Technical Simulations using the EnergyPLAN tool, in which both heat and electricity demands were balanced (Technical Simulation Strategy 3) and individual heat pumps and electric boilers sought to utilize only critical excess electricity production (Individual Heat Pump Simulation 2). These strategies were chosen to best reduce excess energy production. The first scenario was a reference scenario for 2014 based on known and estimated energy system parameters. One purpose of the reference scenario was to determine the accuracy of the EnergyPLAN model in representing the Åland energy system. However, it was known in advance that this representation would be troublesome to a degree, as a long disruption in the interconnection between Sweden and Åland occurred between November 26 and December 8, 2014. As such a disruption is not accurately modelled with EnergyPLAN, the reference scenario was not expected to reflect what actually occurred in the energy system. At the same time, results derived from this analysis could still serve as a reasonable representation of the current energy system, especially with relation to overall annualised costs. Reference scenarios constructed for 2012 Finland in [19] and [16] both showed that EnergyPLAN provided a suitable representation of the Finnish energy system.

To build the Åland reference model, input data was based on information for the year 2014 available from [8] unless otherwise stated. The goal was to simulate the current energy system of Åland as closely as possible in order to calibrate the EnergyPLAN model and to provide comparison to other scenarios. Assumptions for various elements of energy system infrastructure were made for the Åland built environment, district heating system, gas distribution infrastructure, modes of transportation, and energy storage systems based on changes to population structure between 2014 and 2030. In some cases, these assumptions were direct inputs to EnergyPLAN. In others, values were used to calculate overall costs. All assumptions and inputs to EnergyPLAN assumptions have been summarised in Tables A1–A3, A11 and A12 of the Supplementary material.

The second scenario was a transition scenario constructed for the year 2020. The main goal of this scenario was to obtain an annual energy balance that was 100% sustainable. As such, only

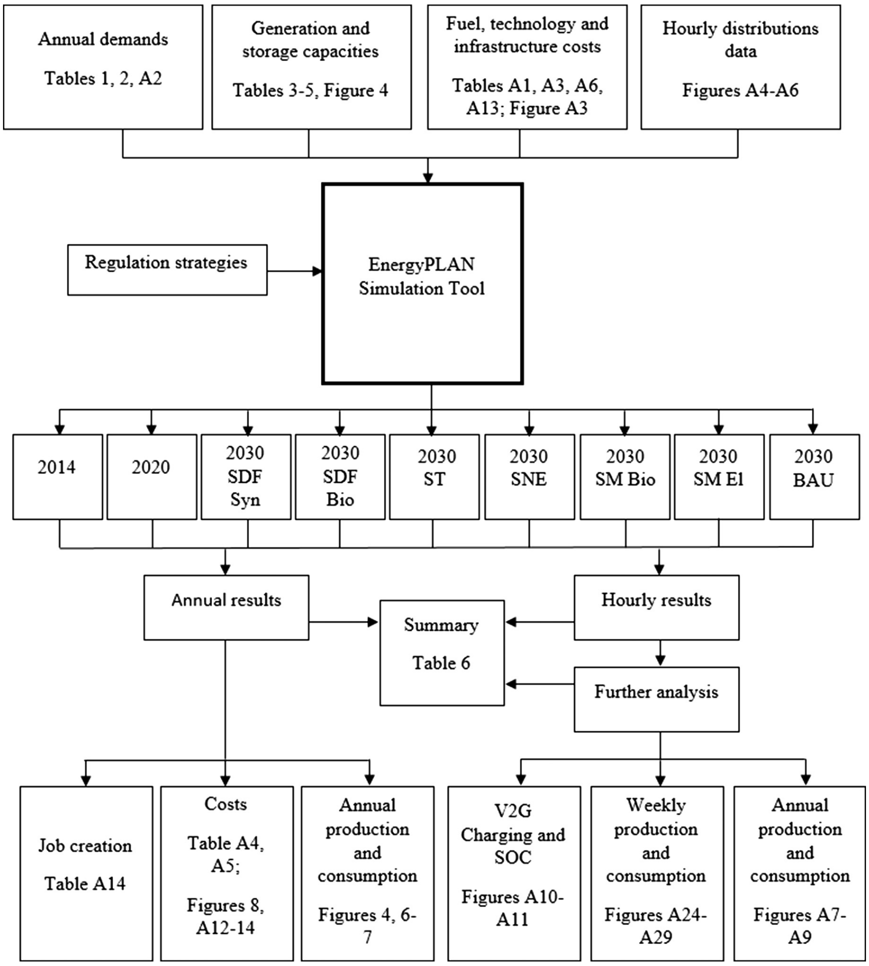


Fig. 3. Flow chart of general procedure developed in this study. SOC - state of charge.

Table 2
Main cost parameters for 2030 Åland.

Technology	Capex [€/kW]	Opex fix [% of capex]	Opex var [€/kW h]	Lifetime [a]
Wind onshore	1000	2.5	0	25
Wind offshore	2100	3.4	0	25
PV ground mounted	550	1	0	35
PV rooftop	700	1	0	35
Biomass gasification	320	7	0	25
Biodiesel plant	2530	3	0	20
PtG plant (electrolysis and methanation)	600	3	0	15
Condensing power plant	980	3.16	2.636	27
CHP plant	1200	3.75	2.7	25
CHP boiler	800	3.7	0.15	29
CHP heat pump	3250	2	0.27	25
Interconnection	1200	1	0	40
Thermal storage	3	0.7	0	20
Gas storage	0.08	1	0	50

Table 3
RES capacity parameters for all scenarios.

		Scenario								
RES Capacities	Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM El	2030 BAU
Wind onshore	MW_e	22.185	70	70	70	70	70	70	70	70
Wind offshore	MW_e	0	0	100	80	40	100	100	55	0
Solar PV - Rooftop	MW_e	0	10	28	28	28	28	28	28	15
Solar PV - Ground mounted	MW_e	0	0	55	50	50	50	50	55	0

Table 4
Thermal power plant capacity and efficiency parameters for all scenarios.

		Scenario									
Thermal plant capacities and efficiencies	Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM El	2030 BAU	Conversion efficiencies (%)
Condensing PP	MW_e	30	0	27	29	10	10	10	10	0	45%
CHP	MW_e	26.6	10	40	40	20	20	20	20	20	$40\%_e$, $50\%_{th}$
DH Boilers	MW_{th}	30.8	18	14	13	15	18	13.5	15.3	20	90%
DH Heat pumps	MW_e	0	1	5	5	5	5	5	5	0	300%

Table 5
Storage capacity parameters for all scenarios.

		Scenario								
Storage capacities	Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM El	2030 BAU
Heat storage	$MW\,h_{th}$	0	500	1500	2100	1000	1200	700	1100	0
V2G Electric storage	$MW\,h_e$	0	0	1200	1200	1200	1200	1200	2750	0
Methane storage	$MW\,h_{th}$	0	0	11000	24000	0	0	9000	1200	0
Electrolysers	MW_e	0	0	54.3	36.2	0	0	57.5	6.1	0
Methanation	$MW\,h_{gas}$	0	0	34.5	23	0	0	36.5	3.9	0

sustainable electricity for import and export was assumed (i.e., not derived from nuclear or fossil fuels). In terms of the EnergyPLAN tool, there is no way to achieve such an assurance of sustainable trade, and so this designation is rather arbitrary. In reality, achieving 100% sustainable trade would be much more complex economically and politically. The purpose of this designation is only to demonstrate that sustainability could theoretically be achieved even during the transition towards more domestic production of energy.

The third and fourth scenarios can be described as 100% sustainable scenarios with a domestic focus. In these scenarios, the import of electricity was not allowed. Excess electricity was considered available for export, but kept low due to the fact that it could also be considered curtailment in the case that export was not possible, thereby simulating a true island mode. The third scenario (2030 SDF Syn) involves sustainable domestic production of all fuels, while the fourth (2030 SDF Bio) differs only by allowing imported biofuels for transport. In the transport sector, electrification of 50% of cars is assumed, 25% of these as a so-called dump charge (one-way with no vehicle-to-grid (V2G) connections) and 75% as so-called smart charge (with V2G connection). This proportion of dump/smart charge was used in all future scenarios.

The fifth scenario (2030 ST) is one that involves sustainable trade of all energy carriers. For electricity trade, the overall volume was purposely kept low (below 25 GW h_e). In all other respects it is similar to the 2030 SDF Bio scenario.

The sixth scenario (2030 SNE) is one that has a focus on high domestic production of electricity along with high net export of electricity. The intention of this scenario was to find a least cost solution for the energy system with no restrictions on electricity trade. In designing this scenario, it was not the intention to aim for high net export, but rather unlimited exchange. Therefore, the use of net export in the name of the scenario reflects the result rather than the intention. In all other respects it is similar to the 2030 ST scenario.

The seventh and eighth scenario involve a special focus on the mobility sector, which utilizes only domestically produced sustainable fuels. These scenarios differ in whether electrification of cars was set at 50% (2030 SM Syn) or 100% (2030 SM El). In addition, and extra 350 MW h_e of V2G battery capacity was included in the 2030 SM El scenario to represent marine transport batteries that are assumed to be available for V2G services. In all other respects these scenarios are similar to the 2030 ST scenario.

The final scenario was defined as a Business As Usual scenario (2030 BAU). This scenario reflected the demand changes described for the other 2030 scenarios as well as maintained the high level of imports seen in the 2014 and 2020 scenarios. In addition, since there was much less domestic production of electricity, lower capacities of heat pumps are assumed. In the transport sector, electrification of 30% of cars is assumed as a so-called dump charge (one-way with no V2G connections). In all other respects this scenario is similar to the 2030 SDF Bio scenario.

Next, the roles of various forms of storage in the energy system for 2030 scenarios (excluding 2030 BAU) were summarised according to the same method as [17]. This was deemed necessary in order to provide an overview of storage for the scenarios and to more easily compare the influence of the various storage solutions. Accordingly, the proportions of storage discharges to respective consumptions (total, electric, thermal, gas) were determined as well as the proportion of V2G discharge to total electricity storage discharge. Results were tabulated for comparison.

2.3. Cost assumptions

Registered users of EnergyPLAN have access to a cost database for almost all elements of the energy system [22]. This database was last updated in January 2015, and was deemed acceptable by the Åland Smart Energy Platform as a starting point for future cost assumptions. Costs for 2020 applied to the reference scenario (2014) and 2020 scenario. For all other scenarios, 2030 costs were applied. A full disclosure of the cost assumptions used in this analysis is found in Tables A5–A12 of the Supplementary material. In all scenarios, a weighted average cost of capital of 7% is used.

2.4. Job creation

IRENA [23] reports that on average in OECD countries 8.6, 18.1, and 17.9 full time equivalent (FTE) manufacturing, construction, and installation (MCI) job-years are created for each MW of installed capacity of onshore wind, offshore wind, and solar PV, respectively. A further 0.2, 0.2, and 0.3 more permanent jobs are generated from ongoing operations and maintenance (O&M) over the lifetime of each plant for each category, respectively. For some system components, such as PtG and V2G, job creation estimates do not currently exist. However, one could expect increases in both MCI and O&M job-years in scenarios that feature these technologies. In addition, no accounting has been made for jobs related to decommissioning. Therefore, the IRENA estimates could be seen as lower limits for job creation. A total number of job years was calculated for each scenario based on IRENA estimates. Results were compared.

3. Results

Tables 3–5 show the installed capacities of major technologies that resulted in least cost solutions for each scenario after iteration. In addition, simplified flows of annual energy from fuel consumption to end-user demand for each scenario are found in the form of Sankey diagrams in Figs. A15–A23 of the Supplementary material.

Annual fuel consumption for each scenario is shown in Fig. 4. Each future scenario, with the exception of 2030 BAU, represents 100% renewable energy generation, with strong roles for biomass, wind energy, and solar PV production. Annual fuel consumption is lower in scenarios that allow import of electricity, with the exception of 2030 SNE, which allows both imported electricity and biofuels, but seeks a net export of electricity over the year. The scenario with the highest level of electrified transport (2030 SM El) has the lowest overall fuel consumption, which is a consequence of the high efficiency of BEVs.

Total installed capacity of electricity generation is shown in Fig. 5 and total electricity production in all scenarios is presented in Fig. 6. In all but the 2030 SNE scenario, exports of electricity were purposely kept low, as the ability of export may not be assured due to unknown demands of neighbouring countries. In such cases, net export may represent curtailment. In all future scenarios there is a strong role of wind energy and solar PV. Thermal power plants are generally used to provide balance to the intermittent nature of the main energy resources. Electricity consumption is shown in Fig. 7.

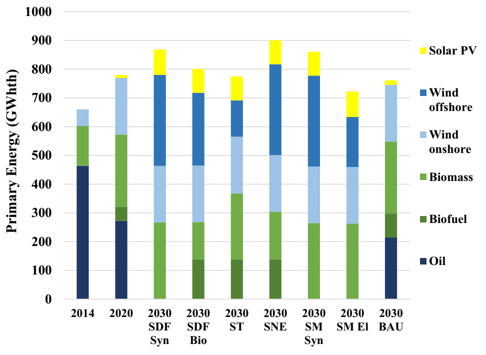


Fig. 4. Total annual fuel consumption for all scenarios.

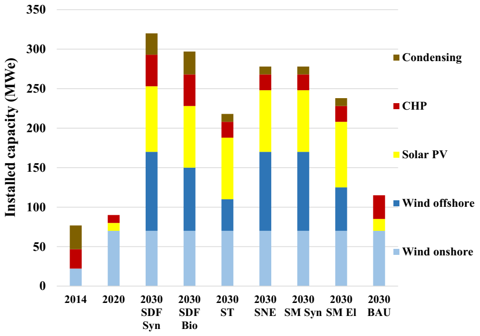


Fig. 5. Installed generation capacity for all scenarios. For the 2014 scenario, interconnection capacity of 80 MW_e was assumed to represent interconnection with Sweden. For all other scenarios, this value was 180 MW_e to reflect an additional interconnection with Finland.

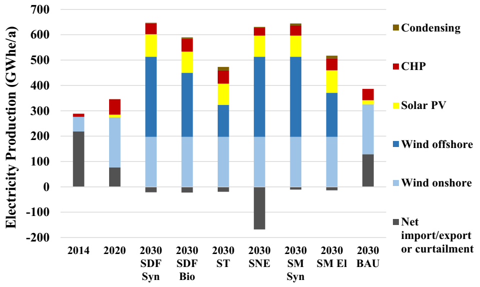


Fig. 6. Electricity production for all scenarios.

The total annualised costs of operating the energy system for each scenario is shown in Fig. 8. Values range from the current 225 M€ annually to 247 M€ annually. The scenarios with the

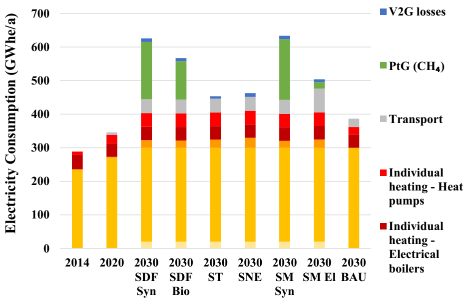


Fig. 7. Electricity consumption for all scenarios.

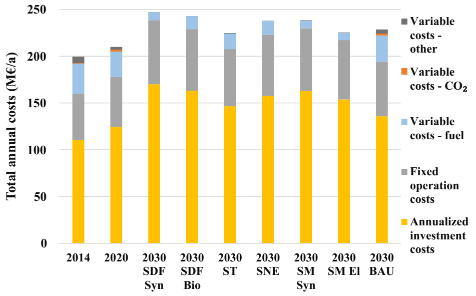


Fig. 8. Total annualised costs of operating the energy system for each scenario.

lowest calculated cost are the 2030 ST and SM El scenarios (225 M€/a), the latter of which involves high electrification of transport, compared to the 2030 BAU (229 M€). The nature of scenario costs also appear quite different, with scenarios that include imported fossil fuels (2012, 2020 and 2030 BAU) having relatively higher variable costs (fuel, CO_2 and other), while other scenarios showed relatively higher investment costs. Fuel costs were highest in scenarios that involved the import of biofuels: 2030 SDF Bio, 2030 ST, 2030 SNE and 2030 BAU. The highest and lowest annual cost future scenarios differed by 22 M€/a, or about 10%. A breakdown of all annualised investment costs (excluding the costs of vehicles) is found in the Supplementary material (Fig. A12 and Table A4).

The role of energy storage solutions is summarised in Table 6. Thermal storage discharge in the DH system was relatively low for all scenarios, with values ranging from 2% to 10% of end-user consumption. Electric storage was noticeable in all scenarios, with values ranging from 16% to 26% of end-user consumption. V2G discharge represents a large proportion of electric storage in all 2030 test scenarios, with values ranging from 78% in the 2030 SDF Bio scenario to 97% in the 2030 SDF Syn scenario, and to 100% in all others. Electricity was generated from stored gas was generated in both 2030 SDF scenarios, which had a focus on domestic production of energy. Gas storage was not present in the 2030 ST or SNE scenarios due to a focus on trade of electricity, but was notable (29–34% of grid gas consumption) in both 2030 SM scenarios and the 2030 SDF Syn scenario. The role of gas storage was highest in the 2030 SDF Bio scenario, supplying 87% of grid gas consumption. Total energy storage discharge range from 9% to 18% of total end-user energy consumption in the 2030 test scenarios.

Job creation estimates for all 2030 scenarios can be found in Table A14 of the Supplementary material. The scenario with the highest installed capacities of wind and solar PV is 2030 SDF Syn. The total MCI job-years would therefore be 3898, and a further 59 jobs (1722 FTE job-years) would result from O&M. This is based on 25-year lifetimes for offshore and onshore wind turbines and 35-year lifetime for solar PV systems in 2030. For the 2030 SM El scenario, this would correspond to 3083 MCI job-years and 50 O&M jobs (1669 FTE job-years). For the 2030 BAU scenario, the corresponding totals would be 871 job-years and 19 jobs (508 job-years) for MCI and O&M, respectively. For the lowest cost scenarios (2030 ST and 2030 SM El), job creation was 4091 and 4580 FTE job-years, respectively.

4. Discussion

A reliable energy system based on high sustainability criteria seems technically feasible for Åland in 2030. Through the integration of the power, heat and transport sectors, as well as through the flexibility offered by energy storage solutions, the Åland energy system can accommodate high levels of domestic, intermittent renewable energy production in a variety of scenarios.

The 2030 SM El scenario, with high levels of electrification of the transport sector, and the 2030 ST scenario, with high levels of electricity trade, have emerged as the least cost solutions, based on the assumption made in this analysis. This result is similar to [24] and [25], [26], which found that future scenarios for Denmark and Ireland, respectively, based on high shares of domestic, intermittent renewable energy need not be significantly more expensive than energy systems based on high shares of fossil fuels. Further, [16] found that 2050 scenarios based on 100% renewable energy for Finland as a whole were slightly lower in cost and substantially lower in financial risks than scenarios that utilized fossil and nuclear fuels. In addition, [16] found that these scenarios could offer a high degree of energy independence.

The competitive cost of the 2030 SM El scenario appears driven by the flexibility offered by the high electrification of transport demands in addition to storage offered through V2G connections and other energy storage solutions. These result in both lower fuel costs and lower overall investment costs. These lower investment costs in production technologies seem to be linked to strategic use of interconnections and power import. Similar low investment costs occur in the 2030 ST and 2030 BAU scenarios for the same reason. Therefore, these scenarios carry the risk of offering lower relative energy independence. However, since Åland has had good relations with its energy trade partners in the past, and now has expanded interconnection with mainland Finland, there seems to be little chance that the risk of lack of import supply would become a great threat to energy security. At the same time, it must be kept in mind that the energy systems of neighbouring countries may themselves also contain high shares of intermittent renewables in the future. While intermittency is generally lower when these resources are seen over wider geographic areas, there is a small, unlikely chance that the sun may not shine and the wind may not blow in all three areas at the same time for some extended period of time. Fortunately, future incorporation of energy storage solutions and hydropower availability in Finland, Sweden and Norway can offer further flexibility and security.

In terms of annualised energy system costs, the low difference between the lowest and highest cost scenarios is not large, suggesting that other impacts of the scenarios should be considered in more detail in order to arrive at the most preferred option for Åland. While it is outside the scope of this study to examine full lifecycle costs and a wider range of economic impacts of the technologies utilized, some comment is necessary. For scenarios with higher levels of domestic investment costs, a fuller analysis of broader economic impacts and job creation could result in these scenarios becoming more favourable.

Child and Breyer [16] showed that investment costs in wind power and biomass-based energy generation are 60% domestic and that operations and maintenance costs are 50% domestic. Further, the same study and others confirm a link between renewable energy production and job creation [24,26,27]. Lastly, the World Bank [28] claims that “Greening growth is necessary, efficient, and affordable” as well as essential to achieving sustainable development, and that “fears of job losses are misplaced” as there is “surely potential to create green jobs” around the world. Highest job creation is seen in the 2030 SDF Syn scenario, which features a high amount of domestic, synthetic fuel production. In general, scenarios with higher annualised costs have higher job creation, suggesting a potential benefit in exchange for higher domestic investment. The two least cost scenarios see lower job creation, but the higher number of FTE jobs in the 2030 SM El scenario should be considered when determining the overall preference of

Table 6
Summary of calculations related to ratios of storage discharge to consumption.

Parameter	Unit	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM El
Electricity consumption	GW h_e	422	422	422	422	422	452
Heat consumption	GW h_{th}	375	375	375	375	375	375
Total energy consumption	GW h	797	797	797	797	797	827
V2G discharge	GW h_e	99	85	66	104	97	78
Electricity from stored gas	GW h_e	3	25	0	0	0	0
Heat from stored gas	GW h_{th}	0	25	0	0	0	0
DH storage discharge	GW h_{th}	11	13	7	7	6	7
PV & wind directly consumed	GW h_e	288	281	261	298	288	273
as % of PV & wind production		53%	58%	72%	51%	53%	67%
as % of all electricity production		45 %	48%	55%	47%	45%	53%
as % of electricity consumption		68%	67%	62%	71%	68%	60%
PV & wind to electric storage	GW h_e	238	182	74	112	245	115
as % of PV & wind production		44%	38%	20%	19%	45%	28%
PV & wind to curtailment	GW h_e	22	23	28	171	15	20
as % of PV & wind production		4%	5%	0%[a]	0%[a]	3%	5%
Total storage discharge	GW h	113	147	73	111	103	85
as % of total consumption		14%	18%	9%	14%	13%	10%
Electricity storage discharge	GW h_e	102	109	66	104	97	78
as % of electricity consumption		24%	26%	16%	25%	23%	17%
V2 G discharge	GW h_e	99	85	66	104	97	78
as % of electric storage discharge		97%	78%	100%	100%	100%	100%
Thermal storage discharge	GW h_{th}	11	37	7	7	6	7
as % of heat consumption		3%	10%	2%	2%	2%	2%
Gas storage discharge	GW h_{gas}	43	60	0	0	35	4
as % of grid gas consumption		34%	87%	0%	0%	29%	31%

[a] In the 2030 ST and SNE scenarios, the amount of curtailment is assumed to be 0%, while export of PV and wind production are 8% and 29%, respectively. EnergyPLAN did not distinguish between export and curtailment, but had a single category of critical excess electricity production (CEEP).

these two scenarios. There is negligible difference in the overall annualised costs of the scenarios, but the SM El scenario has approximately 10% more job creation. Due to a lack of information concerning total job creation throughout the energy system, it is not possible to make definitive conclusions, but this remains an area of interest which merits further study.

Fig. 8 shows the total annualised costs of operating the energy system for each scenario. Further examination of the category of annualised investment costs shows the high impact of vehicle capital expenditures on overall costs. When vehicle costs are excluded, the scenario with the lowest capital expenditures is the 2030 BAU scenario (40.8 M€/year), followed by the 2030 ST scenario (53.2 M€/year) and the 2030 SM El scenario (59.8 M€/year). These costs can be compared to those for the 2014 scenario (28.9 M€/year) and the 2020 scenario (39.1 M€/year). The nature of this difference between the costs of operating the entire energy system and the investment costs is also a key issue that will need to be part of the overall discourse on the future of Åland. What is clear is that the scenario with the lowest capital expenditures is not the scenario with the lowest overall cost to society. Optimal capital investment may not necessarily be lowest capital investment, as different scenarios bring different costs and benefits for different stakeholders. For example, the electrification of transport will come at great expense to citizens worldwide. At the same time, EVs will be purchased due to their overall cost effectiveness in the long run. On top of this will be the services that EV batteries (and those from electrified marine transport) can bring to the energy system as a synergetic, additional benefit.

The role of energy storage solutions appears significant in each of the future scenarios. On a seasonal basis, PtG technology can bridge the gaps between demand and supply at times when generation is most intermittent. These results are in line with those for Germany [29], [30]. This occurs in the 2030 SDF Syn, 2030 SDF Bio and 2030 SM Syn scenarios. In the SDF 2030 Bio scenario, PtG played a significant role in providing electricity and to end-users over a seasonal time frame. In total, 60 GW h_{gas} was discharged from storage, representing 87% of all grid gas demand. Ultimately, much of this went to creating electricity (25 GW h_e) and heat (25 GW h_{th}) that could be used when needed. This was also seen to a lesser extent in the 2030 SDF Syn scenario, with the bulk of grid gas going to synthetic liquid fuel production and satisfied transport demand.

In the 2030 SM scenarios, synthetic liquid fuel production provided all of the grid gas demand. This leads to an interesting limitation of EnergyPLAN with regards to the distinction of PtG and Power-to-Liquids. As such, EnergyPLAN users must first produce synthetic grid gas and then convert that to a synthetic liquid fuel in a Power-to-Gas-to-Liquid process. However, direct conversion of electricity into liquids in a Power-to-Liquid process such as Fischer-Tropsch synthesis is efficient and less expensive [31,32] thereby making scenarios with synthetic fuel production more attractive.

In other scenarios, the need for seasonal storage is eliminated by dependence on imported electricity. On a shorter term basis, V2G batteries play a large role in providing balance between supply and demand of electricity, and also have a key role in providing grid stability on an hourly basis. In many ways, the role of V2G batteries resembles that of power plants in providing a flexible and stable power in the absence of solar PV or wind production. Interestingly, V2G discharging was lower in the 2030 SM El scenario than the SM Syn scenario, despite a 350 GW h_e increase in V2G batteries. This would suggest that there would be no benefit to higher participation in V2G services by marine vessels and other watercraft. This was also observed by [33], who found that the marginal benefits of higher penetration of plug-in hybrid electric vehicles decreased with higher participation in V2G services due to limited demands for power system reserves and system flexibility.

However, closer analysis of these results reveals something different. In the 2030 SM El scenario, the amount of intermittent RE being used directly is much higher (67% of PV and wind generation) compared to the 2030 SM Syn scenario (53%). Likewise, the discharge of electricity from V2G connections to the grid is much lower (17% of electricity consumption compared to 23%, respectively). In both scenarios the charging of V2G batteries is similar (139 GW h_e and 138 GW h_e for the 2030 SM El and Syn scenarios, respectively). However, the former scenario sees a much higher (51

GW h_e vs 30 GW h_e) consumption of stored electricity by the larger number of vehicles and watercraft. The key point is that stored electricity need not only be considered as storage for future use by the grid, but V2G batteries can provide a buffer between generation of intermittent RE and its use by end-users. Direct consumption of intermittent renewable energy reduces the need for seasonal storage and generation capacities. In comparing the 2030 SM scenarios, it can be observed that the higher participation in V2G (2750 vs 1200 GW h_e) for the El and Syn scenarios, respectively, results in less need for gas storage (1.2 vs 9 GW h_{th}), electrolyser capacity (6.1 vs 57.5 MW_e), methanation capacity (3.9 vs 36.5 MW h_{gas}) and offshore wind power capacity (55 MW_e vs 100 MW_e). As a result, total annualised costs were lower (225 M€/a vs 239 M€/a). The influence of V2G connections on seasonal storage and synthetic fuel production is an interesting result for a relatively cold, northern geographic area. Further research is needed to determine if such an effect may be more noticeable in more temperate regions of the world.

As strategic import of electricity helped reduce overall system costs in a number of scenarios, so too did the choice to import liquid biofuels. In most scenarios, utilization rates of the interconnection abroad were low (1–2%). The exception was the 2030 SNE scenario, where utilization of the interconnection was higher (11%) when net export was encouraged. In the 2030 BAU scenario, utilization of the interconnection was approximately 10% and was comprised mostly of import (Fig. 6). A comparison of the two 2030 SDF scenarios (Syn and Bio) highlights the lower cost of importing biofuels, all else being equal. Further, importing biofuels from either mainland Finland or Sweden serves also to reduce the complexity of the energy system. However, overall costs of the energy system were not substantially different (a difference of 4 M€/a), and the expense to the energy system is only one element to consider. In a wider social and economic context, local energy independence and job creation would be higher in scenarios with local production.

The 2030 SM El scenario offers another perspective on the question of whether to import biofuels or not. As this scenario resulted in the lowest annualised costs, perhaps the debate should not surround whether to import biofuels or not. Instead, the results point to the fact that the electrification of transport should be maximised, thereby precluding the need for large amounts of liquid biofuels, independent of their origin. One reason for this is that the efficiency of electrified transport (5 km/kW h_e) is much higher than that for transport based on internal combustion engines (1.5 km/kW h_{th}) [18]. High electrification of transport results in less need for biofuels, less need for PtG, lower installed power generation capacity, and lower overall annualised costs.

The integration of high shares of renewable energy sources will require careful planning to ensure its success, as future energy systems will require a variety of complementary storage solutions. Refs. [34,35] found that electricity storage devices will be needed once 50% of power demand is met with intermittent RE, and that seasonal storage devices will be needed once more than 80% of electricity demand is met by RE. Fortunately, there are many flexibility measures available to support high levels of intermittent RE [36], and these have been used in each future scenario to provide a reliable technical solution.

An interesting correlation was detected between RE energy production and V2G battery charging. Results suggest that V2G batteries will not place a significant burden on the energy system, but will actually function as one of the flexibility measures that support intermittent RE. This result is similar to [37], which showed that effective interactions between electric vehicle owners, distribution system operators and aggregator entities can result in flattened load profiles facilitated by effective scheduling of vehicle charge and discharge times. The new business opportunities of BEV aggregator entities in day-ahead, real-time, and reserve markets, as well as their ability to optimise vehicle owners' revenue has been described in [38].

A further investigation into the nature of V2G charging revealed that, V2G battery charging was almost entirely (97% or more) achieved by wind and solar PV production. This suggests that V2G battery charging need not be an electricity demand which adds significantly to overall end-user electricity demand if it is done wisely. This is in line with conclusions of Lassila et al. [39,40], who describe how charging optimization of electric vehicles need not result in either significant burdens for electricity distribution companies, nor extra costs for the electricity distribution system. This result is confirmed by [41], who propose an efficient management methodology for vehicle charging and discharging, and conclude that the additional storage from high BEV penetration can be beneficial to high shares of intermittent RE. Further, key challenges related to the integration of electric vehicles into low voltage grids, and possible methods of overcoming such challenges are discussed in [42]. Similarly, [43] demonstrated that line loss and cost of grid operation could be reduced through strategic energy management with modern grid interactive electric vehicles. With the exception of the 2030 BAU scenario, each of the 2030 scenarios for Åland assumed a 75% participation of cars in V2G services, and the 2030 SM El scenario assumed a wider range of transport options being included in the provision of V2G services.

Key to the success of such services is optimization of charging. Incentives may be needed to induce participation in V2G services, but a lack of participation may result in greater costs for EV owners. Such incentives will no doubt include those that are financial in nature. Kiviluoma [33] suggests that smart charging of electric vehicles can aid in reducing power system costs by 227 €/vehicle/year, whereas a scenario with no V2G services showed decreased system benefits for EVs. The author also points out that smart charging is actually "more important than V2G" in reducing system costs. It seems only fair that if smart charging and V2G services result in such significant cost saving in the energy system, then BEV owners and V2G participants should share in the financial windfall with other power market participants accordingly. Zhang et al. [44] show how individual electric vehicle owners can be encouraged to individually optimize charging by responding to an electricity pricing scheme known a day in advance, resulting in lower overall costs for both vehicle owners and grid operators.

There were some notable limitations of this study that should be reiterated. First, only one hourly electricity price could be represented by the EnergyPLAN tool, in this case the SE3 price region of the Nordpool market. In reality, however, the Åland energy system is connected to two price regions (SE3 and FI) that may have different prices. This fact could influence overall future decision making on economic viability. Second, the EnergyPLAN tool allows for hourly analysis of the energy system. Therefore, grid stability and network management issues that are on a finer resolution were not within the scope of this study. That being stated, one must note that the Åland power system is considerably smaller than the two to which it is connected. Therefore, use of the interconnections for grid stability and network management should not represent an unreasonable burden for either the SE3 or FI regions, nor should it result in significant cost for Åland.

5. Conclusions

This study concludes that a fully sustainable energy system for Åland can be achieved by 2030. Expanded roles of solar PV and wind power generation capacities through domestic investment can effectively replace reliance on imported energy carriers, promote sustainable growth, and eliminate the need for fossil fuels in the energy system. The role of V2G connections and other energy storage solutions, such as PtG, increase the flexibility of the energy system required when levels of variable renewable energy generation are high. Expanding participation in V2G services to include more road vehicles and other vehicle types, such as boats, can result in less need for other energy storage solutions and reduced offshore wind power generation capacity, resulting in lower annualised energy system costs. V2G connections serve a strong role in accepting energy produced by solar PV and wind power generation in times of excess, and a much less noticeable role as a provider of electricity back to the grid. In this study, V2G batteries provided up to 100% of the electric storage in the energy system, depending on the scenario, and seem associated with a greatly reduced need to import electricity from abroad, for less need of seasonal storage and synthetic fuel production in the form of PtG technologies, and for lower offshore wind installed capacity. Finally, the movement towards sustainability for Åland by 2030 can result in several potential benefits outside of the boundaries of the energy system, such as promotion of employment and international partnerships.

There can be many pathways towards achieving 100% sustainable energy futures for Åland by 2030. At the same time, each pathway involves significant change away from the current energy system, and each would involve some level of urgency if full sustainability is to be achieved by 2030. Perhaps the most urgent matter for the Åland Smart Energy Platform is to inform a wide range of actors and stakeholders of the possible options, and invite feedback. The least cost scenario investigated in this study could also be one that involves a high level of public participation and public acceptance. Determining if this public participation is an opportunity or an unwanted burden can only be achieved through open discourse. The relevance of each option for the people of Åland should, likewise, be best established by the people in question. The purpose of this study was to provide several unique options which can each, in their own way, contribute to the full sustainability of the Åland energy system. The best option will be the one that the people of Åland choose through informed discourse.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enconman.2017.01.039. Refs. [45-64] are cited in the Supplementary material.

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Culture, values, lifestyles, and power in energy futures: A critical peer-to-peer vision for renewable energy

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Culture, values, lifestyles, and power in energy futures: A critical peer-to-peer vision for renewable energy

Juho Ruotsalainen*, Joni Karjalainen, Michael Child, Sirkka Heinonen

Finland Futures Research Centre, Korkeavuorenkatu 25 A 2, 00130 Helsinki, Finland

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ABSTRACT

Energy is not solely a techno-economic question, but has implications for the whole of society – its culture, values, lifestyles, and power structures. Changes in energy systems affect societies over decades, and long-term social and cultural processes in turn affect energy systems. Thus, energy systems should be studied from socio-cultural and futures-oriented perspectives. The purpose of this article is to describe the relationship between energy transitions and social change, and to offer one plausible socio-cultural vision of the era of renewable energy. The article addresses one of the emerging topical areas of energy research – that of rhetoric and sociotechnical imaginaries of energy transitions — surrounding emerging energy systems. Through a literature review, the article first deals with how energy transitions and societal change are related, and then maps out connections between energy and communication technology transitions. It proposes a decentralised peer-to-peer society as an emancipatory and transformative socio-cultural vision of the era of renewable energy systems. Opening up energy futures allows possible and desirable societal futures to be pursued. However, future visions need not be utopian. In order to deal with the possible contradictions of a peer-to-peer future, a critical stance is taken by using the concept of postnormality.

1. Introduction

Every human culture is dependent on its sources of energy — ancient Greek and Roman societies depended on the energy of slaves, and modern industrial societies are dependent on fossil fuels [1]. Despite its fundamental role in human societies, energy has occupied a relatively marginal place in sociological and historical research, and in social sciences in general [2,3]. Especially the relation between energy transitions and social change has been neglected. Social sciences have had a role in the analysis of public opinion and examination of the acceptability of new energy technologies and systems, but wider societal investigation – such as examining the relationship between energy transitions and cultural, social and lifestyle-related changes – is often omitted [4,5,2].

Analyses of societal changes related to new energy systems tend to be historical (see e.g. [6]), or assume a fairly narrow scope, such as conceptualizing the automobile as an emblem of mobility, individualism, and progress [7]. Relatively little is known about social consequences that transpire from energy projects and how energy contributes to specific human development outcomes [8,9]. In energy policy analyses, energy transitions have been viewed narrowly as a change in fuels and associated technologies. These narrow views exclude other transitions, such as the switch from centralised to decentralised energy production, turning energy consumers to energy producers, and the widespread availability of energy resources to all social classes [4,8,9]. Some research takes socio-cultural aspects into account in anticipating societal energy futures, but the focus is still on the futures of energy systems, not on the futures of societies per se [9–11].

In other words, there is a research gap in envisioning societal futures for the current transition towards renewable energy. This article responds to such a call. Assuming a perspective of futures research [12], it examines the relationship between energy transitions and social change and offers a societal vision, as a possible future, of the era of renewable energy. As an essay, the article is a conceptual, theoretical and anticipatory analysis based on literature from different fields. Therefore, it does not display a specific method or empirical data. As a loose analytical framework, the article draws insights from science and technology studies (Section 2.1), which see human and technological development as inseparably intertwined [13].

By providing an energy vision, the article addresses one of the emerging topical areas that could deepen and broaden energy research, proposed by Sovacool [3] – that of the rhetoric of energy transitions as sociotechnical imaginaries surrounding emerging energy systems. How

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* Corresponding author.
E-mail address: juho.ruotsalainen@utu.fi (J. Ruotsalainen).

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people imagine energy technologies and their futures are critical social facets of energy transitions, as they play significantly to the desirability and acceptability of new energy systems [7]. Decisions about energy are a mix of rational reasoning, communal hope, future visions, business ambition, and national pride. Energy visions seek to give a broad, holistic meaning and purpose to energy transitions by providing a narrative about how a future society will be powerfully and positively different from the present [7]. Mapping out possibilities for a future society, and especially for one based on renewable energy, is currently important as the global energy sector is argued to be at a historic crossroads, with differing imaginations of the world and of the place of humanity in it [14].

1.1. Outlining the vision

The future society anticipated by this article is in large part organised around peer-to-peer models, enabled by more decentralised renewable energy – mainly solar photovoltaics (PV), wind, and energy storage, supplemented by other emerging technologies, e.g. geothermal energy (see Ref. [15]). Peer-to-peer refers to individuals and groups who act and self-organise outside traditional organisations, or establish peer-networks within traditional organisations [16,17]. A decentralised energy system, in turn, can be based both on independent energy prosumers (consumers who are also producers) [18], utilities with decentralised energy harvesting, and public authorities who ensure functionality and reliability. The vision presented in this article does not imply a total upheaval of the energy sector, as utilities would still have a central role alongside prosumers. However, the more energy producers there are, the more efficiently the potentials of renewable energy sources are harvested, and thus the role of prosumers is assumed to grow.

The vision relies on four assumptions and requirements regarding the energy system: 1) the energy system will be more distributed, and consumers will become energy producers as well (prosumers), 2) the average marginal costs of energy will fall [19], and consequently so will the costs of production and living, 3) the amount of available energy will increase [15], and 4) an efficient circular economy [20] will emerge so that the system is sustainable and does not violate material constraints.

In addition to the renewable-based, distributed, and prosumeristic energy system, the article regards current production and especially communication technologies as central to the organisation and culture of societies. As prices decline, different technologies are becoming increasingly affordable for citizens [21]. These affordable technologies create a “habitat” that sustains a grassroots, peer-to-peer organisation of society (on energy ‘habitats’ see Refs. [8,9]; on media ‘habitats’ see Ref. [22]). Furthermore, if renewable energy enables highly developed automation and artificial intelligences (AI), the role of work in society can change. Toffler [23] anticipated already in the 1980’s a future where people work half of the time as paid labour and the other half for themselves and their peers. If more and more tasks are automated, enabled by robots that are powered by renewable energy, this seems an increasingly plausible future.

Based on these assumptions and requirements, the article proposes the following societal vision of the era of renewable energy. This possible future is set in the year 2050, which was chosen because it is often the farthest year (before 2100) in energy and climate scenarios and roadmaps (see e.g. Ref. [24]). The year 2050 is also far enough in the future for many of the social, cultural and technological changes described in this article to have taken place. For instance, according to Frey and Osborne [25], 40% of all jobs in the US are at risk of being lost to computers in the next two decades. The purpose of the vision is not to make an exact forecast, but to offer one desirable future for discussion and debate about energy transitions and their implications:

> *Humanity has been able to meet the demand of 130 000 TWh of renewable energy per year. The goal has been achieved through ubiquitous and distributed harvesting and storage of renewable energy, especially solar and wind. On top of energy production, energy efficiency has increased significantly. With the new surplus energy, production is mostly automated and artificial intelligence is embedded everywhere, making society function very efficiently. Thanks to a significant increase in productivity, working hours are halved, and the resulting free time is used for hobbies and other voluntary, productive activities. With effective peer-to-peer communication, citizens are able to self-organise as prosumers. People use their free time for their own and community projects, producing use value for the rest of society as well.*

At the core of the vision is peer-to-peer society, which can be conceived as desirable for many because of its emancipatory nature. The core principles of peer-to-peer society are manifested in the French Revolution and its goals of liberty, equality and fraternity [26]. Under different socio-material conditions, the ideals of peer-to-peer were in use already in the early 20th century to promote the electrification of the United States [27]. A more current argument for the desirability of a peer-to-peer society can be found from internet culture. Its values of prosumerism, openness, interactivity, new communality, and individualism [28,29] may become established and prevail in society at large. Individual freedom and social equality are, for many social theorists, the foundations of human organisation [30,31,32]. The vision seeks to place renewable energy systems in a wider cultural context that make them more socially and culturally embedded. Finally, besides desirability the vision has to be plausible; otherwise, it would be useless.

In the following sections the article argues how such a future could come to be. The second and the third sections outline the relationship of energy with social change and communications technologies. The vision for renewable energy and a peer-to-peer society is then opened up and elaborated upon theoretically in sections four through six elements: lowering marginal costs of production, constraints on peer-to-peer society related to high shares of renewable energy generation, motivations to engage in peer-to-peer, the possible future role of companies, the significance to both economic development and decision-making, and the critical notion of postnormality. These are followed by conclusions.

2. Energy transitions and social change

The more energy humans are able to harness, the more complex societies are enabled. Human history can be seen as the mastery of new sources of energy [33], whereas societal collapse is often associated with an inability to harvest energy in an efficient manner [34]. Increase in the energy input of society correlates with a higher level of organisation and complexity in social structure, which can in general terms be called “development” or “progress” [35,36]. Societal complexity can be defined as differentiation in social structure (i.e. more parts and more types of parts in a system), variation in organisation, ranges of behaviour, and higher subsystem integration in social structures [37,35,38].

It is often assumed that the transition towards renewable energy systems requires reducing energy consumption, and that the energy abundance provided by oil has come to an end [39]. This paper takes an opposite stance: that a 100% renewable energy system can meet increasing energy demands [15,40], and possibly lead to a world of sustainable abundance [1]. If humanity could capture 0.1% of the solar energy irradiating the Earth, there would be roughly six times the energy consumed today [41]. If the promise of abundance in renewables is realised, higher levels of organisation and complexity of societies can be achieved, and society would thus be transformed further.

However, energy technologies do not determine social and societal development. In order to get a balanced perspective on the social transformations related to the renewable energy transition, concepts related to science and technology studies (STS), and the connections between the cultural and the technological, are helpful.

2.1. Energy as a general purpose technology, sociotechnical systems, and actor-networks

From the perspective of the history of technology, energy technologies can be seen as prime movers in society [42]. In other words, they are the most fundamental general purpose technologies (GPTs). GPTs – such as the steam engine and the internet – can be applied to almost everything [43], and thus impact the economy, society and culture thoroughly. A related, but less deterministic, concept to the GPTs is that of sociotechnical systems, which refers to large-scale technologies such as electricity networks, telecommunications, and railroads. These systems weave together technical artifacts, organisations, institutional rule systems, and cultural values [44,3]. To realise the socio-cultural embeddedness of energy, one only has to think about the changes enabled by electrification in lifestyles, urban infrastructure, and industrial production.

A third conceptual framework that allows the embedding of energy within varied social systems and with other technologies is the Actor-Network Theory (ANT). ANT describes social reality as networks consisting of both human and technological "actors", and sees these human and non-human actors as equal in importance [13]. ANT is concerned with networks that encompass the technological, the social, the economic, and the political [45]. Within these networks all actors affect each other in complex ways.

ANT helps in placing emerging energy systems within very broad sociotechnical settings that highlight the complex interactions of their elements. From the point of view of ANT, the aspiration for democratic, emancipatory and interactional social formations can be seen as among the core motivations to develop modern information and communication technologies, i.e. the personal computer and the internet [29], which were possible in the first place due to the use of electricity. These technologies, in turn, laid the basis for a network society [46] and a breakthrough of peer-to-peer practices [17]. Decentralised renewable energy systems may become part of this socio-technical Actor Network. Renewable energy technologies can be claimed to have cultural desirability because they fit so well in the networked, emancipatory and decentralised ethos of the current era. At the same time, they advance this ethos by offering one more building block for the possibly emerging peer-to-peer society.

A concept through which to map the Actor Network of energy systems and their relation to social change in more concrete terms is technology affordance [47]. The concept refers to the possible ways that humans can make use of specific technologies. Seeing technologies as affordances highlights the fact that technologies do not determine human development, but they "afford" certain uses and practices through their properties. How and if these properties are applied in practice is up to human actors. Some core technology affordances of renewable energy, especially solar PV, are those already mentioned in the introduction: decentralisation, relative ease of use, low marginal costs, and potential abundance. These affordances are realised in broad Actor Networks, in which communication technologies play a central role.

3. Energy and communications technologies

Another research area for energy and social research proposed by Sovacool [3] considers communications, and one of the research questions he suggests is, "how do particular energy technologies alter or enhance practices of communication?". Although energy, media and communications seem to have little in common, they actually are closely related in terms of social transformations. If a renewable energy system promotes a decentralised peer-to-peer society, it is because modern communication technologies have already laid the groundwork [29]. On the other hand, a more developed peer-to-peer society would perhaps be impossible without a new energy system. Organising such society would in turn require highly developed, decentralised communications infrastructure.

3.1. Energy and communications in social transformations

All industrial revolutions have emerged from developments in both energy and communication technologies [6]. For instance, the second industrial revolution of the early 20th century was powered by electricity and organised with electric communications such as the telephone and the telegraph. New energy regimes provide the material basis of production, whereas new communication technologies are used as a means to organise and manage increasingly complex temporal and spatial dynamics of production and social organisation [35,6]. An increase in the energy input of society correlates with a higher level of organisation and complexity in social structure, which in turn requires new, more advanced technologies of communication [35]. Together new energy and communication technologies increase the efficiency of production, help in creating fundamental shifts in social structures and modes of production, and hence shape societies.

Last [35] goes further than Rifkin [6] by suggesting that all − not only industrial – social, economic and organisational transformations in human history are facilitated by the combination of new energy sources and new means of communication. According to Last [35], the first great transition in human history, the rise of hunter-gatherer societies, was facilitated by the exploitation of biomass (plants and cooked animal meat). The extra energy made possible the first forms of a division of labour with unprecedented levels of varieties of skills. The development of spoken language allowed earlier humans to organise parties and groups into bands and tribes. The second transition, the agricultural revolution, was facilitated by the domestication of plants and animals. Written language allowed human ancestors to create chiefdoms, kingdoms, city-states, empires, and nation-states. The third transition, the industrial revolution, was catalysed by the steam engine and later by the exploitation of fossil fuels. The printing press, already invented in the 15th century but expanding its use during the industrial revolution, allowed people to organise larger nation-states and multi-continental empires. This was followed later by international and global organisations with the aid of pre-internet electric communications [35].

From these historical transitions it can be seen that social "evolution" has been a story of higher levels of organisation and coordination. Similar to Rifkin [6], Last [35] anticipates that the next transition and leap in social complexity will be caused by the combination of renewable energy and the internet. In future, the internet may transform into a social "nervous system" or a "global brain" – a global, interactive and simultaneous network of collective intelligence. According to Last [35], solar energy would be needed to provide energy for such a complex communication system and the social organisation it would enable. Organisations and individual lives will be increasingly mediatized [48] – possibly in different virtual realities.

3.2. Communal energy visions and energy technologies as "habitats"

Media ecology sees media technologies not only as conduits of information, but "environments" in which people live and which shape culture through their distinct characteristics and properties [22]. In a similar vein, Miller et al. [8,9] conceive energy systems as habitats that shape societies and socio-economic relations: "[P]eople today literally inhabit energy systems. They live with, in, around, and through energy […]. Energy shapes—and is shaped by—people's economies, workplaces, identities, environments, technologies, landscapes, politics, and mental maps of the world."

Together media and energy technologies may create new kinds of habitats. Rifkin [6] anticipates an "updated" version of pre-industrial, local communities and workshops to emerge along with new energy and communication technologies. Such a communal vision of the future is not uncommon. Media ecologists often conceive electronic media as ushering a revival of pre-industrial communities. For instance, the concept of the Global Village by McLuhan [49] depicts a future in which electronic media bring about culture and social relations that resemble pre-industrial times. Public and private spheres – such as work and leisure –would not be separate any more, as they are in the industrial society, but would merge together. This vision has become reality with the internet, which merges private and public communication, and enables individuals to communicate with each other regardless of institutional, temporal, and spatial barriers. As a result, previously separate social spaces and spheres are reconnecting [46,50,51].

The same dualities of public–private and modern–pre-modern are often assigned also to energy technologies. In the mid-1930s, gasoline-powered car travel was marketed as the reappearance of pre-modern experiences, drivers becoming independent actors in contrast to the standardisation and centralisation of rail travel and industrialised society [7]. The electrification of the United States from the late 19th to mid-20th century was, in turn, seen as an opportunity to return to the "wholeness" and grass-roots organisation of the pre-modern society, as unprecedented amounts of energy could be transmitted virtually everywhere [27]. It was envisioned that "electric power could serve to create 'industrial villages' where handicrafts, manufacturers, agriculture, and scientific investigation could be combined in small-scale regional economies" [27].

That such transition did not eventually take place may be because of the lack of proper communication technologies. The age of electrification was defined by the top-down mass media, and together these promoted a centralised society. A prominent media ecologist, Innis [52], disputed the idea that electricity would bring about decentralisation and grassroots democracy, due to the centralised mass media of the time. With the ubiquitous and mobile internet, there is now a medium that enables decentralised, oral-like communications. This is a technological step closer to a "utopian" dream of a bottom-up, peer-to-peer society. If the internet creates a habitat of grassroots communication and culture, a more decentralised renewable energy environment could empower peer communities by providing them with cheap and clean energy.

4. Vision for the renewable energy system: peer-to-peer society

This section will elaborate upon the societal, peer-to-peer vision of the era of renewables as presented in the introduction, and provide theoretical justification for it. A peer-to-peer society is enabled by the declining costs of information, material production, and energy. It is driven by the logics of immaterial economy, intrinsic motivations, and technological developments. In the immaterial economy peer-to-peer practices have already proved effective [17], and people increasingly seek activities they find intrinsically meaningful [53]. If automation replaces jobs or reduces working hours, different peer-to-peer projects could at least partially replace them [54]. For the purposes of focus, this article concentrates mainly on production, general organisation and culture in a peer-to-peer society. In practice peer-to-peer would concern every sector of society – such as education, agriculture and healthcare.

In general, a peer-to-peer society [55] can be defined as one which is structured around self-organising citizens with the help of digital information and communication technologies, which enable low transaction, coordination and communication costs. This does not imply that traditional organisations and institutions cease to exist, but that their relative significance and authority decrease. Peer-to-peer production, in turn, can be defined as a distributed network of free participation of equal partners, who are engaged in the production of common resources without monetary compensation as the key motivating factors. Participants are instead driven mainly by intrinsic and social motivations, and they contribute to "modular tasks" according to their interest and skills, in the same way as in editing a Wikipedia article. Peer-to-peer production relies on social relations rather than pricing mechanisms or managerial commands to allocate tasks and resources. It is governed by the community of producers themselves. It makes use value freely accessible, through new common property regimes [56,16].

Open-source programming projects are often used as examples of peer-to-peer organisations, but peer-to-peer can be applied also to the physical realm as demonstrated by "hackerspaces" [57], Wikispeed, an energy efficient and modular car made in micro-factories at a fraction of the price of a conventional car, and locally-adapted and sustainable farming systems with "open source" seed-sharing [55]. In the energy sector there are also examples that follow the principles of peer-to-peer and localisation. New business models for distributed solar PV have been identified [58,59], ones that include a so-called joint purchase model. In this regard, demand for small-scale distributed generation of solar PV is driven by groups that organise themselves as grassroots movements. In East Africa, mobile-enabled subscription schemes to solar energy rely on peer-to-peer ideals (although they are currently mainly provided by centralised companies). In the future, especially in low- and middle-income countries, peer-to-peer innovation could be increasingly recognised as a part of the informal sector economy [60].

Peer-to-peer models consider also culture and values. In a peer society a change should be expected from "mass" culture to culture that stems more from the life-worlds of individuals and communities. Peer-to-peer production often strives for originality and authenticity [61], which implies that products are not aimed at the mass market but for smaller audiences that share common tastes and values with the producer community [62]. Budhathoki and Haythornthwaite [63] describe a shared "unique ethos" of distinguished ideals, values, beliefs, and sentiments, along with individualistic motivations such as self-expression and fun, in open collaboration projects as among the key motivations of participation.

Renewable energy fits this picture if it too is in part produced by prosumers. If energy prosumerism becomes widespread, it too could have broad cultural implications and advance peer-to-peer society. Lord [1] suggests a culture of stewardship – an active, eco-conscious citizenship – as the culture of the era of renewable energy, reflecting prosumers as independent actors instead of passive objects [64]. If consumers become energy producers, they may develop a more active and "intimate" relationship with energy than when they only consumed it and paid the bills [65,66]. Producing their own energy could also bind communities together and enhance their sense of togetherness [66].

This active and responsible stance toward energy production may then broaden as a more active stance towards life and society in general. Prosumerism urges us to see citizens as whole, interconnected personalities instead of divided into work and leisure roles and separate self-interested individuals – the *homo economicus* [23]. Similarly to peer-to-peer production, prosumerism emphasises use value and "artisanal" originality over exchange value. If production and consumption are to reunite, not only in the energy sector but also in other spheres of life, the life of individuals may return back to intimate and holistic settings akin to the pre-industrial era. Prosumerism and prosumeristic values thus fit well into the communal, "pre-industrial" energy and media visions depicted in Section 3.

4.1. Declining costs as a driver of peer-to-peer

Core drivers towards a possible peer-to-peer society are the decreasing marginal costs of information, material production, and energy. Lowering marginal costs in these three areas are pivotal, as they enable ordinary citizens to access and do things that were unattainable in the past. Marginal costs refer to those of producing an additional good or service. The marginal costs of information have been close to zero for a while already [17]. Producing a music album, for instance, still involves fixed costs, but its digital reproduction and distribution (marginal costs) are almost free. As physical production is being automated, the marginal costs of physical production are also decreasing [67]. Renewable energies, in their part, have low marginal costs for end-users, as the cost of energy for household solar PV systems is virtually zero once the costs of the panels, related equipment and their installation have been covered [68].

Goods for which the marginal costs are near zero are often treated as publicly available goods, as commons. The concept of commons refers to shared, free-to-use resources – free to utilise, distribute, improve, and change within community-defined rules, not free as in "without cost" – as well as products that can be used as resources for new end products. Commons rely on social relations rather than pricing mechanisms or managerial commands in allocation. They are non-scarce, and their consumption does not prevent others from consuming them. Therefore, they are non-rivalry [69,56]. Peer-to-peer projects create and are based on commons, goods that have been developed and maintained by a community [70]. If the potential of renewable energy can be harnessed, energy too may become a commons.

The maximum societal benefits of commons are gained only if they can be freely (but sustainably) used – otherwise they will be left underutilised [69]. As commons are non-scarce and non-rivalry, the more they are used, the more social benefits they should entail. Creative labour and immaterial goods are based on previous work done by others. Thus, the more information and creative work are freely available, the more efficient production is [17]. In terms of energy, a prosumeristic energy system should in principle be more equal and prosperous than a system in which citizens' access to a solar economy is restricted.

4.2. Constraints on a peer-to-peer society based on renewable energy generation

High shares of renewable energy, particularly solar PV, in the future will mean that the global energy system after a transition will be very unlike the current one. The plausibility of such a future vision must therefore be established on multiple levels in order to elevate beyond speculative fantasy. Furthermore, the roles of various actors and infrastructure must be described not only in terms of the final vision, but so that the transition towards a final state makes sense. Important issues related to material constraints, the roles of new and incumbent energy actors, and energy system infrastructure, particularly electricity grids, cannot merely be assumed. The peer-to-peer vision under examination cannot be overly simplified, but must be robust enough to encompass a range of plausible energy futures.

The question of whether material resources will be sufficient to support high shares of renewable energy technologies is highly relevant. Should a lack of adequate flows of key materials form barriers or bottlenecks in supply, certain technological changes could either not happen within the 2050 time frame of this vision, or not at all. Grandell et al. [71] examined the dependence of renewable energy scenarios presented by the IPCC Fifth Assessment report on the availability of various metals needed for a range of renewable energy technologies. No serious long-term material constraints were identified for almost all technologies, but possible shortages of silver, tellurium, indium and ruthenium could lead to higher costs for solar PV modules unless significant recycling and material substitution efforts are achieved. Likewise, Davidsson and Höök [72] determined that material availability could be problematic during a rapid energy transition unless overall material intensities are decreased, especially for silver. To this end, they suggest that decreasing or eliminating silver requirements of solar PV modules would be a sound strategy "to enable continued fast growth of PV, as well as sustained decreasing costs of PV technology" [72].

At the same time, solar PV technologies fall under several categories, each of which have different material needs. It is beyond the scope of this research to discuss these different categories, but so-called thin film solar PV technology may be more sensitive to material constraints and related increased cost effects than the currently dominant silicon-based technology [101]. In a separate study, Jacobson and Delucchi [73] conclude that "costs of recycling and replacement [of materials] are unlikely to noticeably affect economics in some cases", but that cost impacts could be expected in others, particularly with lithium ion batteries.

The relevance of these batteries is that they will support both the future electrification of mobility on a very large scale, and provide balance to the intermittent nature of solar PV energy generation. Kushnir and Sandén [74] propose that "recent debate seems to have concluded that there is 'sufficient' lithium available". However, they remind that it is not merely a question of quantity. This point must also apply to other emerging technologies. While material scarcity can be avoided through recycling and other efforts, policy support for such efforts must be in place in time to avoid such scarcity or adverse economic effects. In essence, timing matters. Efforts will need to involve the coordination of a wide range of actors, including individuals, small companies, and large corporations in order to establish and maintain necessary resources and knowledge that will enable an energy transition and a peer-to-peer society. Inevitably, these efforts will have costs, but the full extent of these costs is currently unknown.

This raises a natural limit to the decentralised nature of a peer-to-peer society. It is clear that such a society must have some centralised institutions, public authorities and large companies to facilitate the transition and maintain a functional energy system (transmission, distribution, balancing, frequency control, etc.). What is more, incumbents in the current energy system tend to be large, multi-national companies with vast human, knowledge and capital resources, and it is unlikely they will just disappear overnight. However, as will be shown in Section 4.3, larger, more traditional companies will co-exist along with networks of individuals. These larger, more centralised actors will be essential to providing reliable energy infrastructure (e.g. electricity grids), energy markets, energy security, and energy justice at regional, national and global levels. In addition, prosumerism will be seen on residential, commercial, and industrial scales. Therefore, prosumerism will not entirely replace, but supplement, more traditional utility scale energy generation.

4.3. Motivations for peer-to-peer

Although peer-to-peer and prosumer projects are already quite common [75], the question remains whether masses of people would be motivated enough to engage in them. Regarding energy prosumerism, Biggs [65] lists as motivations for prosumer solar PV: 1) falling costs and rising retail electricity prices, 2) concern for climate change, and 3) greater control, autonomy and independence over energy costs and energy supply. Van der Schoor and Scholtens [66] add the strengthening of social cohesion and the investment of revenues in the local community as motivations for local community energy projects. These motivations seem general enough to attract a critical mass of people, especially if solar panels are leased and installed by energy companies.

In terms of broader peer-to-peer activities the questions of motivation and scalability become somewhat trickier. Wikipedia – the usually mentioned example of a successful peer project – has 70 000 people[1] who contribute actively. Although the figure is only about 0.002% of registered users, it equates to the number of employees in a large, global company. Contributors do not get any concrete benefits such as monetary compensation and cost-savings, which suggests they are driven by inner and social motivations. Intrinsic motivations are often stronger than extrinsic, and people are willing to do many things without payment if they find them personally meaningful [53].

Widespread willingness to participate in media content production is well documented [28]. Media technologies, services and applications are so well-developed, inexpensive and easy that ordinary people are

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[1] https://en.wikipedia.org/wiki/Wikipedia:About.

able to use them proficiently. Motivations for media prosumerism are self-expression and reputation [63]. From these premises one can extrapolate a continuing and widening trend. Taking into account the strengthening of self-expression values [76], people's aspiration for self-governing groups [77], and the decreasing costs of technologies [21,68], it is hard to see why prosumeristic peer-to-peer production and self-organising would not have a more prominent role in 2050 than today, also in sectors other than media and the internet.

4.4. Companies in a peer-to-peer society

The current economy is already a hybrid of market and social relations, open sharing, and private profits. Production is increasingly cooperative, and companies utilise the vast reservoir of commons generated by the "general intellect" of citizens [78]. Knowledge capital is not obtained exclusively through market transactions but is partly available as a commons. Businesses use free and non-scarce information to produce scarcities, such as services and experiences. The Linux operating system is free, but the company monetises services around the operating system. Platforms such as Facebook and YouTube enable and empower sharing, and sell aggregated attention, which is a scarcity, to advertisers [78]. The electric car manufacturer Tesla gave away all its patents in the spirit of "open source" in order to spur the electric car industry [79].

This trend towards a hybrid economy can be expected to strengthen as there is further movement towards a knowledge and information economy, and as many jobs are being automated [25]. The trend is strengthened by a renewable energy system also, as the surplus of clean energy would enable more automated processes and ubiquitous artificial intelligence. The human energy freed from necessary labour would then be used for new purposes. In such a future, production could transfer into global (global & local) workshops, and among other grassroots organisations [55].

However, it is crucial to highlight that traditional organisations, such as global enterprises, would still have a central role in a peer-to-peer society. Moving to peer-models does not mean that citizens would do everything by themselves or that professionals would be replaced altogether by prosumers. Big companies would still have access to unparalleled financial, social and cultural capital, and know-how. Furthermore they, too, would benefit from the decreasing costs of energy and technologies, and thus increase their capabilities. It might be so that innovations and products dependent on high capital costs would be produced mainly within such firms. Otherwise peer-to-peer networks would have a significant role [80]. The dynamics, interaction and power struggles between traditional organisations and peer-to-peer networks could be one of the core dualities in future societies.

It may also well be that peer-to-peer production becomes prevailing in "traditional" companies as well. They could be organised around "centralised" peer-to-peer models. Such companies would allow their workers to self-organise, and would cooperate and exchange non-vital information openly with other corporations. Benkler [80] argues that firms benefit from peer-to-peer practices as they increasingly need a) the ability to harness and combine diverse motivations of talented individuals, b) to manage the delicate balance between intrinsic and prosocial motivations and material interests, and c) to heighten social integrity—offering shared knowledge, identity and social meaning that keeps teams working well together and gives the firm a distinct advantage over ad hoc networks. Examples of such models already abound throughout industries [81]. The World Economic Forum sees open collaboration as central in the "Fourth Industrial Revolution" [82]. Kurki and Wilenius [77], in turn, have studied workers' self-organisation in two middle-sized companies: the Finnish ICT consultancy firm Reaktor, and the Dutch home care enterprise Buurtzorg. In both cases, self-organisation was beneficial for both the firms' bottom lines, worker satisfaction and well-being in the workplace.

By extrapolating these business trends, and heightening social and ecological consciousness into the future, it may be that profit maximisation will not be the only goal of businesses. Collaboration and cooperation may replace economic competition to a larger extent than today. This would be so because of the peculiarities of the information and the creative economy: innovation is a collective, not individual process [80] and the creation of non-monetary value is exponential whereas the monetisation of such value is linear [78]. Only a fraction of value created by humans can be captured in market relations, but the more non-monetary value is created and shared, the easier it is to turn it into profit [83]. Thus, alongside money making, companies would concentrate on the production of use value and social value – shared meanings, social relations, well-functioning technologies and applications [18] – in order to find ways to monetize them later on.

4.5. Implications for social equality, economic development and policy-making

Energy visions tend to outline optimistic views of the future [7], and the one presented in this article is also for the most part positive. Peer-to-peer envisions self-regulation, self-steering and self-guiding systems over central organisation, hierarchical rule, command and discipline [32]. On the surface, peer-to-peer and prosumerism seems inherently democratic and involves equality. But wealth cannot automatically be expected to be distributed equitably – even in peer-to-peer models. Whereby liberal capitalist techno-utopian approaches typically have treated technology as class-neutral and a positive-sum, they have ignored the class agenda embodied in technology and technological change (Carson, 2016; [84]).

Peer-to-peer would not materialise by itself. Historically speaking, energy policy has favoured centralised actors. This makes the emancipatory character [14] of the peer-to-peer vision important; questions on what is to be transformed attract political and economic interest [85]. Peer-to-peer, as a transformative vision across regimes [86,87] would benefit from an enabling environment, with supportive legislative and policy changes, and incentives across geographies and sectors. A locally-driven transformation can be supported by the state as a transition partner to the civic sphere, as a "wiki-state" that takes the character of a support platform to citizens' peer-to-peer ethos ([67,78]; Carson, 2016). A peer-to-peer vision opens up discussion not only on incremental change, but transition policies that can be radically transformative (Schot and Steinmüller, 2016) and complement each other [88] – constructing the emerging regime and disrupting the old [89].

If peer-to-peer can play a part in providing local well-being, rights and freedoms (Sen, 1999) as the ingredients of "progress" [90], this could support the aim of achieving a "deep" societal transition [87]. In a disruption of economy, culture and social relations, peer-to-peer could actually help overcome one challenge in the "creative destruction" of capitalism [91, namely social exclusion in innovation (Arocena and Sutz, 2012). An increasingly citizen-driven technological transformation could be harnessed with the growing expertise and learning of expert citizens or 'citizen scientists' (Wildschut, 2017). Peer-to-peer would rely on the processes of inclusive and networked innovation to ensure local benefits, legitimacy and ownership of technology. In turn, this could even help radical innovations to diffuse faster than before [92,93].

4.6. Postnormal world

New, smart, innovative and socially conscious policies are needed as there is movement towards a decentralised grassroots society. However, new policies would probably not be enough. Even if there could be reach material abundance, innovation of a way out of ecological crisis, and even distribution of wealth, immaterial factors could place citizens in unequal positions. In an immaterial, creative, and partly post-money economy, cultural and social capital could increasingly define social classes. Further, on an even deeper level, a peer-to-peer society would be more complex, uncertain and unpredictable than the society of today.

Sardar [94] calls current times postnormal: a time of uncertainty, rapid change, realignment of power, upheaval and chaotic behaviour – characterised by complexity, chaos and contradictions. Sardar does not conceive normality as a normative concept, but as a sense of continuity: that the economy grows steadily, people live in coherent and cohesive communities, living is purposeful and meaningful, and that the future is more or less secure.

Sardar does not discuss it, but the transition to a fully renewable energy system is a crucial factor in postnormal times. This is because more and cheap energy means faster and deeper changes [35,36]. A peer-to-peer society, enabled in part by decentralised energy production, also plays straight into postnormality, as it fragments power and creates numerous new power centres. These changes would add to complexity, chaos, and contradictions in societies.

One can argue that humans have throughout history lived in postnormal times as they have always faced sudden, dramatic and unpredictable changes. Then again, historical periods have in general been relatively stable, predictable and stagnant – guided by traditions. Perhaps, then, postnormality characterises especially the modern world (including the postmodern or “late modern” era of the 1970s onwards), which Marx and Engels [95] famously described as a period when “all that is solid melts into air”. With the advent of new transformative technologies, such as artificial intelligence, solar PV, and the ubiquitous internet, this modern postnormality is only accelerating. Core modern institutions, such as the nation state, and stable occupations are deteriorating, and few new institutions have emerged to replace them.

The transition towards new, renewable energy systems can also be seen as a part of postnormality. The old energy regime is being questioned, but at the same time a new energy regime with related culture and lifestyles has not been established, and the futures of energy are largely uncertain. In this vein, Tainter et al. [96] state that “A transition from fossil to renewable fuels would be likely to involve post-normal science, which is science constrained by uncertainty, urgency, high stakes, and public values.” At the same time, it must be realised that all large technical systems have momentum [86]. Centralised energy systems are planned decades in advance, and “become embedded in society, resulting in many linkages between firms, regulatory bodies, departments in educational institutions, and research laboratories” [86]. Therefore, the transition towards a new energy regime may be generally slower and the period of postnormality inherently longer.

However, peer-to-peer models also offer one possible route out of postnormality by providing an embryo for new institutions and meaningful communities [62]. Sardar [94] states that “plurality, diversity and multiple perspectives are essential for understanding and steering through postnormal conditions”. Analysing postnormal times, Montuori and Donnelly [97] write that “Leadership and creativity are shifting from a Heroic, Great Man view to a more relational, distributed, everyone/everywhere/everyday process”, and that leadership is increasingly viewed as based on aptitude for a particular context, task, and situation. The new leaders in a postnormal world are likely to arise from those who are on the margins of the current energy system regime – “outsider groups” who have occupied a niche role in the sociotechnical landscape [86]. The outsiders generally include societal pressure groups, outside professional scientists or engineers, and outsider firms and entrepreneurs [98].

Society organised around networked peer-to-peer communities would be one of plurality, diversity and multiple perspectives. Cubitt et al. [99] claim that in postnormal times, “networks are emerging as major powers alongside the nation and the market”. Peer-to-peer networks may even supersede nations as the main source of identification, loyalty, and the sense of purpose provided by the sensation of being a part of something bigger than ourselves [99]. Personal identities could thus obtain a new and more solid basis compared to modern institutions such as factories, which are instrumental and hierarchical in nature [97].

5. Conclusions

This article has outlined a peer-to-peer vision for a 2050 society powered by a partly prosumerist renewable energy system. By doing so it contributes to bridging the research gap of the lack of energy research with holistic societal perspectives on energy transitions. The article argues that a transition towards a new energy system and sustainability is better understood – and advanced – as a combination of economic, technological, political, institutional, and socio-cultural changes. Most importantly, the offered vision – desirable for some, undesirable for others – contributes to debate on which kinds of (energy) futures to pursue and how. Therefore, future energy system planning can be better understood as different options for a long-term social contract [100].

At the core of the vision are self-organising citizens who have been empowered by automation, ubiquitous digital communications, and the declining costs of energy, living and production. These, in turn, have been enabled in part by a more distributed renewable energy system. Different peer communities, and their networks, have become central actors and institutions in society. Increased complexity in social structures has made societies vibrant, pluralistic, innovative, and resilient. Values of self-expression and creativity prevail in the mode of production of peer-to-peer prosumerism. The renewable-powered peer society has realised the democracy and grassroots aspirations inherent in many of the energy visions of the past [7,27].

As a critical remark on the vision, the article presented the concept of postnormality [94]. What are often viewed as positive developments – further democratisation, grassroots emancipation, locality, decentralised renewable energy – increase complexity in societies and are problematic precisely because of that complexity. Complex societies tend to be more chaotic, contradictory, and unpredictable – i.e. “postnormal”. In the research of the social and societal aspects of renewable energy systems, especially these and other critical questions should be addressed in more detail.

It has to be noted that 2050 is probably too near a future for a full-blown peer-to-peer society to be realised. It is still plausible to anticipate that many aspects of peer-to-peer will have developed by then as much more sophisticated than today. More research is needed to outline in more detail how such a society and its energy system could work in practice, to what degree societies could be arranged around peer-to-peer models in the future, and what emerging and surprising technological and social developments may promote or hinder peer-to-peer.

By focusing only on the past and the present, one chooses to overlook emerging social and technological forces that can – or already are changing society. If socio-cultural and political considerations are analysed to understand how energy systems are changing, futures research enables discussion on the possibility and desirability of different alternatives. It stimulates holistic discussions as a pretext for concrete policies, social aspirations or industrial change. It is useful to recognise historical accounts of how change can take place, but it should not be assumed that history must be repeated. To attain desirable futures, deliberation, technological development, active planning, and socio-political action are all required. Therefore, it is hoped that this work can serve as a possible guardrail for future energy system planning that more holistically considers the precursors and effects of large-scale change.

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