Alena Lohrmann

THE WATER FOOTPRINT OF THE GLOBAL POWER SECTOR: STATUS QUO, CHALLENGES, AND OPPORTUNITIES FOR TACKLING THE GLOBAL WATER CRISIS

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Abstract

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Freshwater resources are becoming increasingly unavailable, and the competition for water resources among different sectors of the economy is worsening in many parts of the world. For instance, in the energy sector, the technologies currently used for electricity generation rely heavily on water availability. Examples of these technologies include hydropower plants that utilise the natural flow of moving water to generate electricity, thermal power plants (coal, gas, oil and nuclear) that require water for cooling purposes, and solar PV power plants in which water is deployed for cleaning of the PV modules. However, statistical data regarding water use in power plants is still scarce, since power plant operators do not usually disclose the amount of water needed during the power generation process.

This lack of statistical data impedes the assessment of water use in the global power sector and, consequently, limits the analysis of potential water use reduction. The aim of this research is to address this data gap by focusing on the global water demand of thermal power plants. By applying several energy system transition pathways, the water demand of the global power sector is estimated for the period 2015 to 2050 in five-year time intervals. The results of the study revealed that the global power sector currently consumes about 88 cubic kilometres of water annually, of which about 20 cubic kilometres of water evaporate due to the cooling of thermal power plants. It is demonstrated that the gradual decommissioning of a thermal power plant fleet during the energy system transition can annually ‘save’ about 98% of this cooling water, which will allow it to be allocated for other purposes—for instance, food production.

Subsequently, this analysis was expanded by applying energy transition pathways to 353 main global rivers. The results demonstrated that all water withdrawals from the main global rivers associated with thermal power generation can be fully mitigated by 2050. In addition, using the global cobalt supply chain as an example case, the study explored how the water demand of the power sector affects the water footprint of different products and services. The results revealed that the power system-related water demand represents about 90% of the total water footprint, allowing for a considerable water use reduction through the transition towards an energy system based on low water-demanding renewable energy technologies.

Present literature on water is focused on tackling rising water demand and reducing global water stress. To enhance this discussion, the water consumption criticality matrix was introduced, which draws attention to geographical areas that are potentially critical from the perspective of the availability of freshwater resources for current and future energy-related water consumption.

Overall, this research sheds light on the use of water in the global energy sector and will contribute to the discussion of a sustainable energy transition from the perspective of energy-related water demand.

Keywords: water–energy nexus, thermal power plants, energy transition, water footprint, water consumption, water withdrawal

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My sincerest thanks to my family. To my parents Irina and Victor, and my grandmother Elena for always encouraging and believing in me. To my husband Christoph, who has been my source of strength and optimism (and of endless amount of wordplay jokes) through the years. Without you and your support, I would not be here today.

With love and gratitude,
Alena Lohrmann
October 2023
Helsinki, Finland

To my parents, Irina and Victor
To my husband, Christoph

Researcher is drinking coffee

Researcher: “Coffee, you’re my only friend”

Coffee: “Research is a sh***y career”

Researcher: “Hmm, too dark”

* Researcher adds more milk into the coffee*

Coffee: “Research is hard but also satisfying”

Researcher: “Perfect”

© *High Impact PhD memes*

“Everything is peer reviewed if your friends are judgemental enough.”
© *yournerdyfriend*

Contents

List of publications

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

I. Lohrmann A., Farfan J., Caldera U., Lohrmann C., and Breyer C. (2019). Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nature Energy,* 4(12), pp. 1040–1048. doi.org/10.1038/s41560-019-0501-4. **Publication Forum JUFO Level: 3.**

II. Lohrmann A., Child M., and Breyer C. (2021). Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system. *Energy*, 233, p. 121098. doi.org/10.1016/j.energy.2021.121098. **Publication Forum JUFO Level: 3.**

III. Lohrmann A., Farfan J., Lohrmann C., Kölbel J., and Pettersson F. (2023). Troubled waters: Estimating the role of the power sector in future water scarcity crises. *Energy*, 282, p. 128820. doi.org/10.1016/j.energy.2023.128820. **Publication Forum JUFO Level: 3.**

IV. Rahimpour Golroudbary S., Farfan J., Lohrmann A., and Kraslawski A. (2022) Environmental benefits of circular economy approach to use of cobalt. *Global Environmental Change*, 76, p. 102568. doi.org/10.1016/j.gloenvcha.2022.102568. **Publication Forum JUFO Level: 3.**

These publications are numbered throughout the research thesis using Roman numerals.

Author's contribution

Alena Lohrmann is the principal author and investigator in **Publications I–III**.

Publication I: Alena Lohrmann carried out research, collected cooling technology data, analysed and visualised the results, and drafted the manuscript. Francisco Javier Farfan Orozco provided the initial power plant data, helped develop the methodology and assisted in the analysis of the results. Upeksha Caldera also helped in the methodology and assisted in the literature review. Christoph Lohrmann contributed to the development of the sensitivity analysis and assisted in writing the article. Prof. Christian Breyer supervised the work and reviewed the article.

Publication II: Alena Lohrmann authored the idea, designed the study, performed the analysis and drafted the manuscript. Prof. Michael Child developed scenarios for the energy transition and provided support for the paper writing. Prof. Christian Breyer reviewed the work.

Publication III: Alena Lohrmann authored the idea, designed the study, carried out the analysis and wrote the article. Francisco Javier Farfan Orozco assisted with the methodology development and data collection for the energy transition scenarios. Christoph Lohrmann designed the machine learning algorithm for the cooling system identification of future power plants, assisted with the sensitivity analysis and assisted in the paper writing. Prof. Julian Fritz Kölbel collected data on announced power plants globally and reviewed the article. Frank Pettersson contributed to the discussion of the results and reviewed the article.

Publication IV: Saeed Rahimpour Golroudbary carried out the research, including the development of the model, analysis of the results and writing of the manuscript. Francisco Javier Farfan Orozco created projections for cobalt production until 2050, and Alena Lohrmann contributed a section on water demand analysis and assisted in writing the article. Prof. Andrzej Kraslawski reviewed the work.

The list of all research articles published over the course of this research is provided in Appendix.

Nomenclature

CAP	Active capacity of an individual power plant
CCS	Carbon capture and storage
CSP	Concentrated solar thermal power
EEA	European Environment Agency
EIA	United States Energy Information Administration
EPRI	California Energy Commission and Electric Power Research Institute
ESG	Environmental, social, and corporate governance
FAO	Food and Agriculture Organization of the United Nations
FLH	Full load hours
GEO	Global Energy Observatory
GIS	Geographic Information System
GHG	Greenhouse gas
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography Database
GW	Gigawatt
HDI	Human Development Index
IEA	International Energy Agency
IGES	Institute for Global Environmental Strategies
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
KNN	K-Nearest Neighbour
LCA	Life Cycle Assessment
MENA	Middle East and North Africa
MW	Megawatt
MWh	Megawatt-hour
OECD	Organisation for Economic Co-operation and Development
PA	Probability of assignment
PV	Photovoltaic
SWC	Specific water consumption of power generation, in cubic meters of water per MWh of generated electricity
STWD	Specific total water demand (consumption) for the production of cobalt, in cubic meters of water 1 kg of cobalt
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations International Children's Emergency Fund

USGS	United States Geological Survey
WCC	Water consumption criticality
WEF	World Economic Forum
WF	Water footprint of an individual power plant
WFC	Water footprint of the power sector
WHO	World Health Organization
WRI	Water Resource Institute
WRM	Water resource management
WUI	Water use intensity factor

1 Introduction

The technologies currently used for electricity generation (especially fossil fuel power plants) are known to have a considerable environmental impact: air pollution, climate change, thermal pollution and solid waste disposal are acknowledged to be directly linked to the energy generation process (European Environment Agency (EEA), 2004). In addition, it is associated with a considerable water footprint, which indicates the amount of water used and/or polluted during the electricity generation process (Water Footprint Network, 2022). In light of an unfolding water crisis (United Nations Educational Scientific and Cultural Organization (UNESCO), 2022), consideration of the actual water footprint of current and future energy systems is important. To address this call, the present study evaluates the current water footprint of the global power sector and estimates its development until 2050. It also investigates how the water footprint of the global power sector affects the water footprint of the global cobalt supply chain.

This section briefly presents the context of this study, its focus, motivation, aims and scope, and summarises its main contributions.

1.1 Water—our most precious resource

Water is the lifeblood of our planet and is necessary for all life on Earth. The ability to acquire clean water is essential for human survival, and water resources have played an important role in the expansion and development of human culture and civilisation. For instance, the first great civilisations were born on the banks of large rivers: the Ancient Egyptians settled on the Nile, the Mesopotamians—on the Tigris and Euphrates rivers, the Ancient Chinese were based on the Yellow River, and the Ancient Indian civilisations were formed in the valley of the Indus River (Wang and Guohua He, 2022). For these civilisations, rivers were sources of a steady supply of water and became a foundational element for the development of agriculture, trade, transportation and even a defence against enemies (Hosseiny, Bozorg-Haddad and Bocchiola, 2021).

Today, our reliance on water resources is as high as ever. Water is essential for the development of all sectors of the economy, and it is a critical part of the global ecosystem. According to some estimates, agriculture is currently responsible for about 69% of global freshwater extractions, which are mostly used for the irrigation of crops (UNESCO, 2022). In some developing countries (for example, in Viet Nam), this share can be as high as 95% (Institute for Global Environmental Strategies (IGES), 2015). Globally, the industrial sector, including the energy sector, is associated with about 19% of total freshwater use, and the municipal sector accounts for 12% (UNESCO, 2022).

Overall, water is currently the world's most extracted natural resource by volume (Green Initiatives, 2021). It has been estimated that since the 1980s, global freshwater use has increased at a rate of roughly 1% per year, driven by the growth of the global population, economic development, and changes in water use patterns (UNESCO, 2019). While the use of freshwater in the world has increased sixfold over the past one hundred years (Zhongming et al., 2021), the share of the global population suffering from water resource deficits has increased from 14% to 58% (Kummu et al., 2016).

We live on a blue planet; however, freshwater resources are very limited and distributed unevenly across the world. The estimated total amount of water resources on the planet is about 1.4 billion km^3, the volume of freshwater resources is approximately 35 million km^3, which corresponds to about 2.5% of the total volume. Of these freshwater resources, about 68.9% is stored in the form of ice in glaciers and as permanent snow cover in the Arctic and Antarctic regions, and on mountains; and about 30.8% is groundwater, found in shallow and deep groundwater basins, soil moisture, permafrost and swamp water. Approximately 0.3% of the world's freshwater resources are surface water found in rivers and lakes. In fact, only about 200,000 km^3 (which is less than 1% of the total freshwater resources and just 0.01% of the total amount of water resources on the planet) are directly available for consumption for life on Earth. (United Nations Environment Programme (UNEP), 2002)

The current global water demand is estimated at the level of 4,600 km^3 per year (Boretti and Rosa, 2019) and is expected to increase by about 20-30% by the year 2050 (Burek et al., 2016). According to the projections of Boretti and Rosa (2019) this increase in water demand will not be distributed equally around the world. In particular, the highest growth (up to 300%) is expected in Africa and Asia, which will be mostly driven by population growth (Boretti and Rosa, 2019). According to UNEP, by 2030, 40% of the world's total demand for freshwater would not be met by the global water supply (UNEP, 2015). The extensive use of water coupled with the limited availability of freshwater resources, often worsened by the consequences of the ongoing climate change, has already resulted in water shortages that can already be witnessed in many parts of the world and that can be considered a water crisis (UNESCO, 2022).

1.2 Water scarcity, water stress and water risk

To describe water resource availability in different geographical regions, the scientific literature commonly uses the terms 'water scarcity', 'water stress' and 'water risk'. Figure 1.1 demonstrates the main differences between these terms.

The term '*water scarcity*' refers to the volumetric availability or lack of freshwater resources within a given area (Schulte and Morrison, 2014). In contrast to the word 'arid', which refers to regions that severely lack available freshwater due to climate conditions (e.g., regions that receive low precipitation), the term 'scarcity', in this context, also indicates the anthropogenic footprint (i.e., originating from human activity). Furthermore, water scarcity is calculated as the ratio of anthropogenic water consumption to available freshwater resources within a given area (Schulte and Morrison, 2014). Therefore, a dry region/area with little availability of water, but no anthropogenic water consumption, is here referred to as 'arid', but not 'water-scarce'. Also, water scarcity refers to the physical availability of water, regardless of its suitability for use or accessibility (see Figure 1.1).

In this regard, a region may have abundant water resources, but may have very limited accessibility to them (e.g., groundwater resources); hence, this region will not be considered water-scarce. According to current estimations, four billion people reside in areas that experience severe water scarcity for at least one month every year (Mekonnen and Hoekstra, 2016).

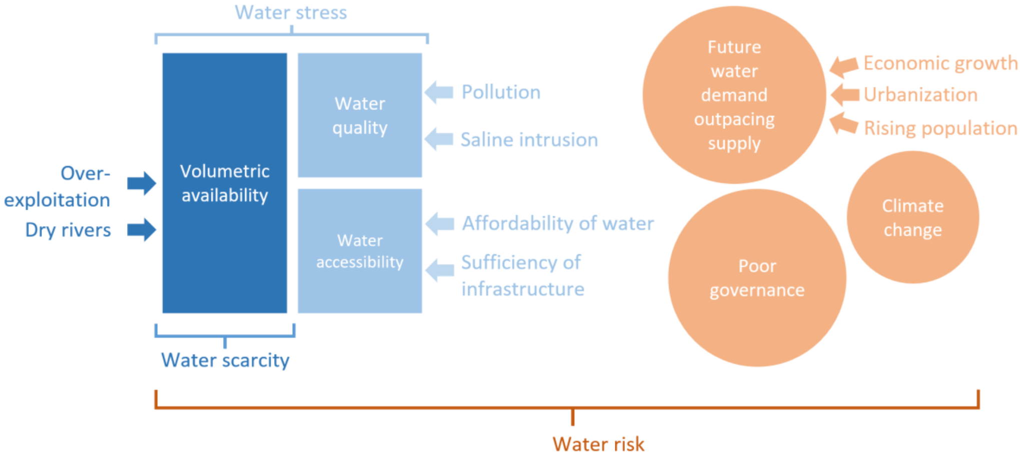

Figure 1.1 Water scarcity, water stress and water risk, and examples of factors that influence them, modified from Schulte and Morrison (2014)

Compared to 'water scarcity', the term '*water stress*' is a broader construct. It takes into account such aspects as volumetric availability of freshwater resources, water quality and its accessibility (Schulte and Morrison, 2014). Water accessibility, among other factors, considers the affordability of water and the sufficiency of the water supply infrastructure. 'Water stress' refers to water availability to meet the human demand for freshwater in a given area/region (Schulte and Morrison, 2014). Hence, water stress occurs when demand for freshwater exceeds the available amount of freshwater during a given period of time or when the poor quality of freshwater resources restricts the use of water (EEA, 1991).

In contrast to the term 'water scarcity', 'water stress' includes subjective elements; hence, the existence and/or level of water stress may be assessed and perceived differently by different actors. One example of this issue is the different thresholds for the water quality of drinking water by set by governments in different countries (World Health Organization (WHO), 2018). To address this, the Water Resources Institute (WRI) investigates the levels of water stress globally through a unified methodology and provides projections of future water stress for each country—as demonstrated in Figure 1.2. According to this methodology, a country/region is reported to suffer from high water stress if the total water withdrawal in that country/region is more than 40% of the available freshwater resources. If the country/region withdraws are more than 80% of the available freshwater resources, it is classified as having extremely high water stress (Hofste, Reig and Schleifer, 2019). In total, 44 countries are characterised by high and extremely high water stress, according to this classification (Hofste, Reig and Schleifer, 2019). In Europe alone, about 142 million people are currently living in areas that experience high and extremely high water stress, according to the WRI (2021).

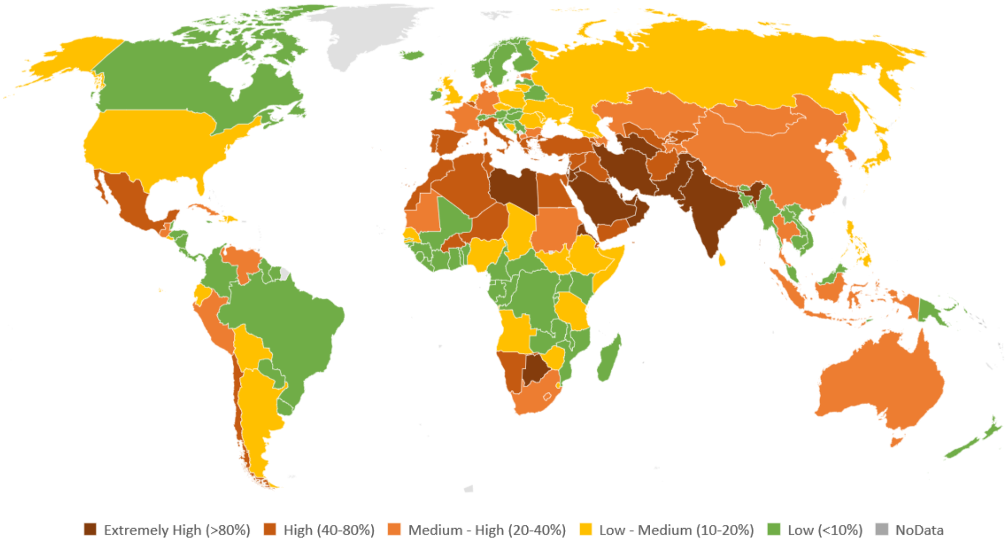

Figure 1.2 Water stress per country, based on the data provided by the Water Resources Institute for 2019 (WRI, 2021)

Understanding the level of water stress is crucial because higher water stress levels indicate that there is most likely competition for the available freshwater resources among the different sectors of an economy (such as agriculture, food production and the energy sector) and the population (Food and Agriculture Organization of the United Nations (FAO) and UN-Water, 2018). Moreover, high water stress levels may have severe consequences for the environment, as many natural ecosystems rely on a steady water supply (Hofste et al., 2019).

Finally, the term '*water risk*' refers to the possibility that an entity (a country, a sector of the economy, a company, etc.) experiences a harmful water-related event (Schulte and Morrison, 2014). The Organisation for Economic Co-operation and Development (OECD) identifies water risk events as insufficiency or oversupply of freshwater, or water pollution and disruption of the water supply (OECD, 2021). In this regard, water risk is a function of the probability of an event and the severity of its impact (Schulte and Morrison, 2014).

Since 2012, the World Economic Forum (WEF) has consistently included water crisis in the top five global risks in terms of impact (WEF, 2020). Numerous water-related issues, including freshwater scarcity, water pollution, poor governance, insufficient infrastructure and climate change events, have imperilled economic activities. In addition, the growing population and an increasing demand for water from the agricultural, industrial and domestic sectors (including the energy sector) have already intensified water risks in many parts of the world (Boretti and Rosa, 2019). Water risks often compound across many sectors of the economy, although the severity of the impact depends on the intensity of the water risk event and the vulnerability of the entity. To address this risk, the World Wide Fund for Nature (WWF) has developed a WWF Water Risk Filter (WWF, 2023) – an online tool for companies and businesses to better understand the water risks across their operations and to provide guidance for risk mitigation.

It is important to understand the issues related to water scarcity, water stress, and water risk from the point of view of the involved stakeholders (us all) and for different industries specifically. This thesis specifically focuses on how the water and energy generation industries are related and on understanding the potential water risks for the industry.

1.3 Water–energy nexus

Water and energy are closely linked. On the one hand, coal mining, extracting oil and growing crops for biofuels use considerable amounts of water. Electricity generation at power plants often requires a large amount of water. On the other hand, extracting, treating and purifying water consumes energy. This dependency between water and energy, also known as the 'water–energy nexus', has been increasingly discussed in many scientific studies (IEA (International Energy Agency), 2016; Behrens et al., 2017; Ganguli, Kumar and Ganguly, 2017). The extensive use of water by the energy sector is increasingly becoming a concern of many scholars (Helerea, Calin and Musuroi, 2023) and is also the subject of this study. It has been estimated that about 88% of the water used in the energy sector is associated with the water required for electricity generation at power plants (IEA, 2016). A large share of this water is used in thermal power plants (facilities that burn coal, gas, oil, biomass or fission atoms—to generate electricity): thermal power plants currently account for about 70% of the global power plant capacity (IEA, 2016).

Currently, industrialised countries withdraw a considerable amount of water for thermal electricity generation. In the United States, freshwater withdrawals for thermal power plants account for 40% of all freshwater withdrawal (Maupin et al., 2014). The power sector of the European Union accounts for about 55% of the total annual amount of water withdrawn (Eurostat, 2014). This extensive use of water by thermal power generation leads to a high use of water resources, which may be critical in regions that suffer severely from water resource scarcity (Schleifer and Luo, 2018).

From another viewpoint, the currently used technology of electricity generation relies heavily on the availability of water resources. Water scarcity, which is increasingly common due to climate change, directly influences the reliability of thermal power generation and already has numerous reported cases of negative impacts on the operation of power plants around the world. In many countries worldwide, droughts caused by amplified water temperatures and reduced river flow have compromised power generation during the summer of 2022 (Cuff, 2022; IEA, 2022; Jones et al., 2023). Furthermore, a limited electricity supply, together with rising generation costs, has already led to an upsurge in prices for electricity in many parts of the world (Azevedo Rocha and Mathis, 2022; IEA, 2023).

Hence, the power sector contributes to and directly suffers from water resource scarcity and water stress. These complex interdependencies between water and energy present policy makers with challenges in ensuring a secure and sustainable supply of energy and water in the future.

The water demand of the power sector is a critical constraint that is often overlooked in planning decisions regarding future energy systems. Furthermore, statistical data on water use by specific power plants is not available. The scarcity of data complicates the assessment of water use in the power generation sector. In this regard, the most crucial steps of research should involve (1) the development of methodologies to assess the water demand in power plants when the data on the actual water use is limited and (2) the collection of data on the water use (current and projected in the future) on a power plant level.

1.4 Focus of research

The main focus of the study is the assessment of the water footprint of the power sector, conducted from the perspective of the amount of water used in power plants. Specific attention is paid to the water demand estimation for cooling in thermal power plants (see Figure 1.3).

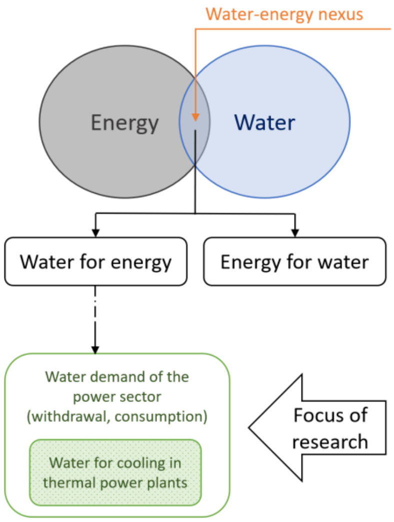

Figure 1.3 Focus of the research

In this study, the assessment of the water demand of power plants is performed from the viewpoint of water consumption and water withdrawal. Water withdrawal represents the total quantity of water that was extracted from the water source (river, lake, sea, etc.) during the power generation process. Opposed to that, water consumption defines the amount of water lost during the power generation process, usually by means of evaporation (Kenny et al., 2009). In other words, water consumption shows the quantitative difference between water withdrawals and the amount of water returned to the water source. In this research, the main emphasis was on water consumption because it reflects the direct impact of power generation on water resource availability.

1.5 Motivation and aims of this research

The initial motivation for starting this research was the observation made about the limited availability of data concerning the quantity of water used in the power generation sector. Most countries do not require that power plants disclose their water use, despite the fact that the power sector is the biggest industrial water user (Schleifer and Luo, 2018). Power plant operators do not usually report on the amount of water use associated with their operations (Luo, Krishnaswami and Li, 2018). Although inventories containing the water demand of individual power plants exist, they typically include thermal power plants located (only) in one specific region/ country—for example, for the United States (EIA, 2015b). To the best of the author’s knowledge, no such database has previously been available at a global level. This represents a large information gap and considerably complicates the assessment of global water use in the power sector. This research is intended to create a holistic understanding of water use in the power generation sector.

One way to overcome this data limitation in the attempt to gather holistic data is to use the information regarding the types of cooling systems that are installed in individual thermal power plants. In general, the type of cooling system installed in a thermal power plant determines the amount of water used for cooling in the power generation process (Macknick et al., 2012). Thus, knowledge of the cooling technology of specific power plants enables the assessment of water used for cooling when other (better) information is not available. However, in many widely used power plant databases and inventories of electricity generation, the information concerning the installed cooling systems in individual thermal power plants is either very limited or completely unavailable (Larsen et al., 2019). To address this information gap, the *first aim (A#1)* of this study was to collect cooling technology data for the global thermal power plant fleet, to compile a database containing this data and to make the information contained in the database freely available to researchers and practitioners.

To overcome the limited availability of cooling technology data, previous studies on the water–energy nexus have applied various estimation techniques for their water demand calculations. As demonstrated in the work of Lohrmann, Lohrmann and Luukka (2021), the accuracy of these approaches seems to be rather low—about 35% for a setting with the five common cooling technology types (the five-class problem) for thermal power plants. The low accuracy for the assignment of cooling technologies that can differ considerably in their water demand may severely impede the ability to determine a realistic and accurate estimate of the water footprint of the thermal power sector. Building on this observation, the *second aim (A#2)* of the study is to develop a bottom-up approach to estimate the water demand of the power sector in a high spatial resolution (starting from individual power plants), which is aimed at increasing the accuracy of water demand estimates, compared to previous studies. This also allowed us to aggregate the water demand estimates on different levels of aggregation (i.e. at the river, region, country and global levels).

The *third aim (A#3)* of this study is to estimate the current water demand of the thermal power sector and of the entire electricity sector using the collected cooling technology data and the developed estimation approach.

In addition to investigating the current water demand of the power sector, the next step in this research has been to project this demand to the future. Usually, energy transition scenarios are focused on mitigation strategies for carbon emissions in the energy sector and the electrification of all economic sectors (Khalili and Breyer, 2022). WRI's projections clearly demonstrate that water resource availability is expected to worsen considerably in most countries of the world in the following decades (WRI, 2021). However, the water demand of the future power sector in particular is typically overlooked (Terrapon-Pfaff et al., 2020). Therefore, the *fourth aim (A#4)* of this research is to explore whether the energy transition scenarios selected for this study actually lead to a decrease of water used in the power system.

The next step in the discussion regarding the development of the future energy system is to identify countries and regions, where due to the use of water-intensive technologies in the power generation mix, the water demand is projected to increase in the future. This analysis should go hand in hand with the consideration of the water resource availability in each specific country/region. Hence, the *fifth aim (A#5)* of this study is to connect the estimated water demand with the country-specific water stress score reported by WRI (2021) to highlight geographic areas that are potentially critical in terms of the limited availability of water resources for energy-related water demands.

A large current and future water footprint of the power generation sector will indirectly influence the water footprint of many services and products that require electricity for their manufacturing. To address this concern, the *sixth aim (A#6)* of this research is to explore how the water demand of power generation may affect the current and future water footprint of products and services, for example, global cobalt production.

The connection between the aims of this research and the enclosed publications is depicted in Figure 1.4, which also depicts the publication-specific focus of the research.

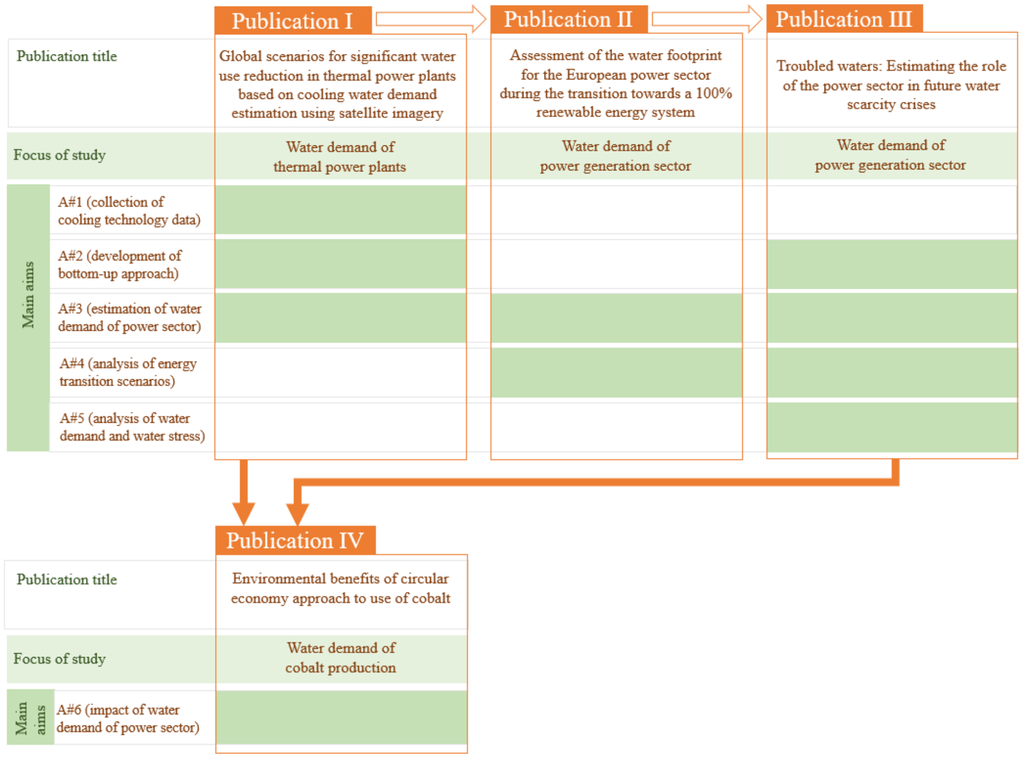

Figure 1.4 Aims of this research and how the enclosed publications are related to them

It is crucial to mention that Figure 1.4 only depicts the aims in relation to the water footprint analysis. The main aim of **Publication IV** was to evaluate the environmental impact of the cobalt supply chain, and the analysis of the water footprint of cobalt production formed only one part of this study.

The orange lines in the figure represent the connections between the enclosed publications: The analysis in **Publication IV** was built on the data obtained in **Publication I** and the methods introduced in **Publication III**.

1.6 Geographical, temporal and technological scope

Figure 1.5 depicts the geographical, temporal and technological scopes of this research, and the types of power plants included in the study.

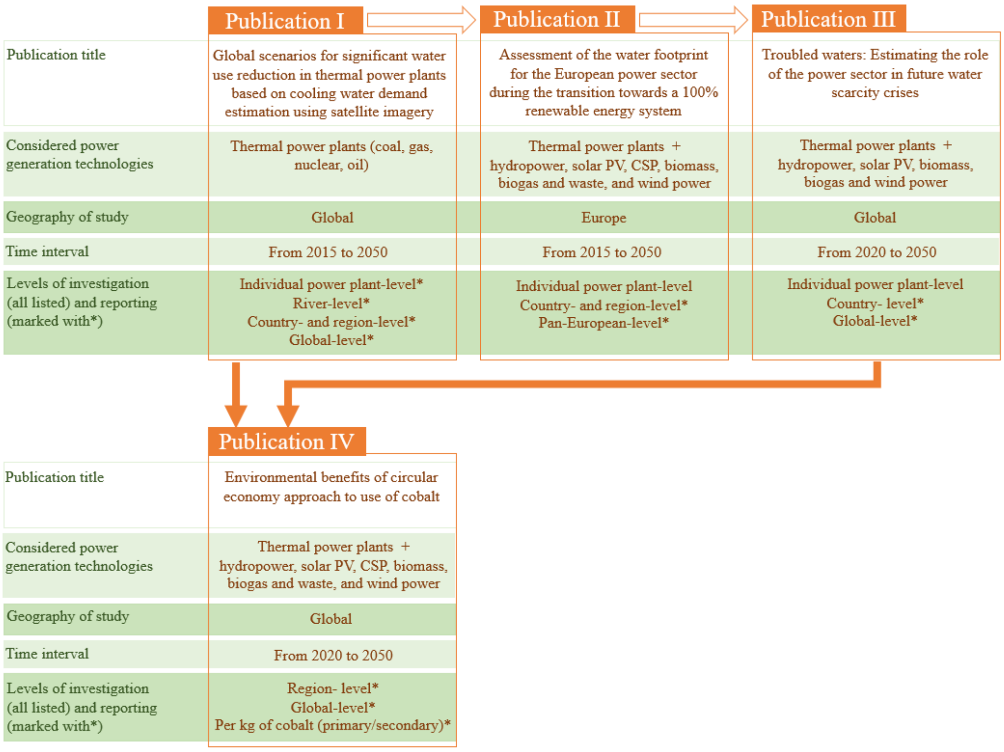

Figure 1.5 Scope of the study

The geographical scope of this study varies between publications: while **Publications I, III** and **IV** took a global approach, the geographical scope of **Publication II** was Europe. In addition, depending on the publication, the results were reported on the country, region, and river levels, per capita or per kilogramme of product.

All publications extended their projections to 2050.

Regarding the power generation technologies that are considered in this study, **Publication I** analysed the water demand of only conventional thermal power plants: coal, gas, nuclear and oil power plants. **Publications II–IV** extended this analysis to include other power generation technologies: hydropower plants, solar photovoltaic (PV) plants, concentrated solar thermal power (CSP) plants, biomass, biogas and waste power plants, and wind power plants. Geothermal power plants were not included in this study since their share in the global power generation mix is negligible: about 0.5% of the total global renewable energy capacity in 2022 (International Renewable Energy Agency (IRENA), 2022). However, it is crucial to mention that geothermal power plants have a considerable water footprint (second largest after hydropower, which is explained by the forced water evaporation from a large water surface area), up to 19.5 m^3 per MWh (Macknick et al., 2012).

1.7 Scientific contributions of the research

This doctoral dissertation aims to contribute to filling the observed research and knowledge gap within the topic of the water–energy nexus, with a focus on the water demand of the global power sector. The main contributions of this dissertation are as follows:

1. Collection of the cooling technology and location data (latitude and longitude) for 13,863 thermal power plant units globally, each exceeding 50 MW. Allocation of individual thermal power plants to the nearest water source (river, lake, sea, etc.) for the water footprint analysis was carried out in a high spatial resolution. The compiled power plant database was published as Supplementary Material for **Publication I** and is freely available online for future research.

2. Projection of the water withdrawal and water consumption of thermal power plants globally. River water footprint analysis. Analysis of the potential water use reduction, which can be achieved by 2050 through gradual decommissioning of old thermal power plants as part of a transition towards a system with a high share of renewables.

3. Energy system-wide analysis of the current and future water demand for power generation on the Pan-European level and on the global level. This analysis also included the investigation of cases (countries) characterised by the limited availability of water resources and where the water demand of the power sector was projected to further increase in the future. These results can help policy makers identify potential barriers to the future energy transition as the water stress and the competition for water resources are projected to worsen globally in the upcoming decades (WRI, 2021). In addition, the obtained results demonstrate the potential water-related advantages of establishing power transmission interconnections between Europe's regions.

4. Estimation of the specific water consumption (SWC) of the power sector (or water consumption per unit of generated electricity) on the Pan-European level and on the global level. Estimation of the development of the SWC until 2050 resulting from a future global energy system transition. The obtained estimates can be used to assess the current and future water footprint of different services and products.

5. Estimation of the water footprint of the global cobalt production. The results obtained in this study contribute to the discussion of the transition to a sustainable renewable energy system, as the composition of the energy system not only affects the direct water demand of the power sector, but also indirectly influences the water footprints of many products and services.

1.8 Structure of the dissertation

Following the introduction, which includes a brief description of the work, its motivation, objectives and scientific contributions, Chapter 2 provides the context of this dissertation and further discusses the existing research gap. Chapter 3 goes through the methods deployed over the course of this study as well as their limitations, and Chapters 4 and 5 include a summary of the results presented in the publications. The closing chapters (Chapters 6 and 7) provide a discussion of the results, their practical implications, and conclusions.

2 Background

The identification of cooling technologies installed in power plants worldwide is a crucial part of this study, since the subsequent estimation of the water demand for the global power sector is built on it. Therefore, before introducing the methods applied in this study for water demand estimation, first, it is important to review the types of cooling systems considered in this analysis.

This section illustrates the operating principles of the main cooling system types and discusses factors that may influence the selection of these cooling technologies for power plants. In addition, current and historical global installation trends of cooling system installations are discussed. This section concludes with a brief overview of the most common approaches for cooling system identification found in the literature.

2.1 Thermal power generation and water use

The water used in power generation, especially in thermal power generation, is one of the most crucial areas of focus in studies on the water–energy nexus.

In conventional thermal power plants (i.e., steam power plants), the heat energy obtained from fuel combustion is used to convert water into steam. This steam, in turn, is deployed to rotate a turbine connected to a generator, which converts the kinetic energy of the turbine into electric energy. After passing the turbine, the steam should be condensed before it can be used again in the power generation cycle. The steam's temperature is lowered via a cooling system, which is an essential part of the power plant.

Although there are cooling systems that do not use water (i.e., dry cooling systems), thermal power plants are generally characterised by their high dependence on water resource availability for cooling. In thermal power plants, water is also used in other processes, such as the control of emissions, cooling of auxiliary equipment, power plant maintenance (e.g., cleaning) and personal usage by power plant employees (California Energy Commission and Electric Power Research Institute (EPRI), 2002; Larsen et al., 2019). However, according to Tsou and Maulbetsch (2013), cooling systems of thermal power plants are the most water-demanding component of the power generation process. In particular, cooling technologies account for about 90% of the water used in the power plant (Tsou and Maulbetsch, 2013). Hence, an assessment of the amount of water used for cooling in thermal power plants may offer opportunities to reduce the use of water in power plants and in the power sector as a whole.

The next section provides a brief overview of the cooling technology types that were included in this study. This study includes neither the investigation of the thermodynamic processes of cooling nor the thermodynamic processes of power generation.

2.2 Cooling technologies used in thermal power generation

In this section, five major types of cooling systems are reviewed: closed-cycle wet cooling, which comprises (1) recirculating tower cooling and (2) recirculating pond cooling, (3) once-through cooling (or so-called open-cycle wet cooling), (4) dry cooling and (5) inlet cooling (see Figure 2.1).

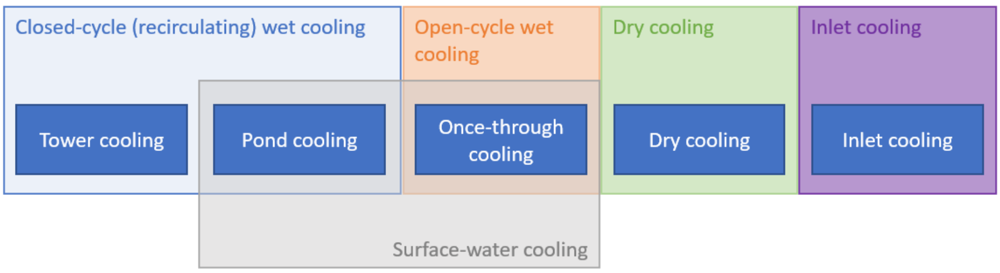

Figure 2.1 Classification of cooling systems

The selection of the cooling system type for a new thermal power plant is a nontrivial task because every cooling system type has its benefits and downsides, which should be considered before the construction of the power plant (EPRI, 2002). To illustrate the operating principles of the main cooling system types and to discuss their benefits and drawbacks, recirculating pond cooling and once-through cooling systems were combined into the group of surface-cooling systems, as presented in Figure 2.1 (grey colour) and as discussed by Diehl et al. (2013).

Recirculating tower cooling systems include natural draft cooling towers, mechanical induced-draft and mechanical forced-draft cooling towers. Natural draft cooling towers are large hyperboloid or cylindrical structures with sizeable top openings. In contrast, mechanical draft cooling towers are equipped with large fans, which ensure the transfer of air through the cooling tower construction. Mechanical induced-draft and mechanical forced-draft cooling towers differ in the location of their fans; induced-draft towers have fans on top of their construction, which pull the air up through the tower. Compared to induced-draft cooling towers, the air fans of forced-draft cooling towers are located at the bottom—they push the air up through the tower.

As demonstrated in Figure 2.2, recirculating tower cooling systems (here, natural draft cooling) use water as a cooling medium to cool steam in the steam condenser. Then the heated-up cooling medium is transferred to the tower, where the collected heat is dissipated into the atmosphere through evaporative cooling (Luo, Krishnaswami and Li, 2018). Finally, chilled cooling water is collected back into the reservoir. Some of the circulating water is usually discharged as ‘blowdown’ to avoid corrosion and scaling by limiting the build-up of impurities in the circulating water that are brought into the cooling system by the make-up water (Maulbetsch and Stallings, 2012). Due to their large size (up to 200 metres tall and up to 100 metres in diameter), cooling towers are easy to identify using satellite imagery.

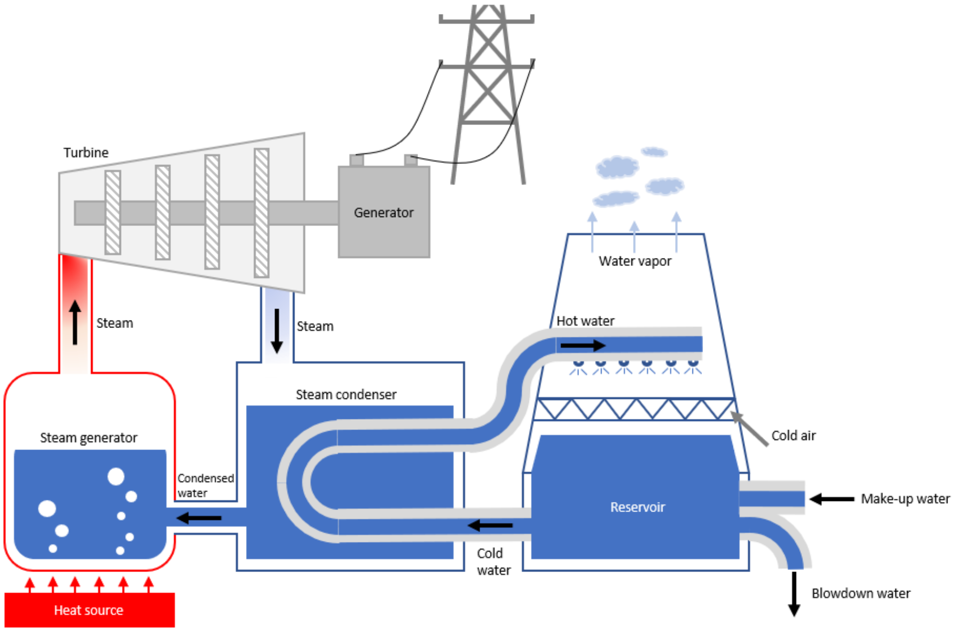

Figure 2.2 Conceptual diagram of recirculating tower cooling systems (natural draft cooling tower), modified from Williams and Simmons (2013)

Table 2.1 Summary of advantages and drawbacks of tower cooling systems compared to other cooling technologies

Benefits	Drawbacks
• Reduced water withdrawal • Reduced chemical water pollution	• High capital and operating costs • The highest water consumption among all technologies • Requires extensive site space • Chemical water pollution (through blowdown water) • Emissions in the air (through the evaporation of water containing pollutants and pathogens)

Tower cooling is considered by many (e.g., Fleischli and Hayat (2014)) the best cooling technology available, striking a good balance between the cost of the system and its environmental impact. Tower cooling systems typically withdraw only 2% to 3% of the amount of water withdrawn by once-through cooling systems, as they enable water to be reused instead of being directly discharged back into the water body (EPRI, 2002). However, even a small fraction of the water (blowdown water) that is returned to the environment may cause considerable water pollution of the water body (Bloemkolk and van der Schaaf, 1996). Compared to other cooling technologies, cooling towers have the highest evaporation rate (water consumption rate) (EPRI, 2002): they consume about 300% more water than once-through cooling systems (Macknick et al., 2012). Moreover, cooling towers are associated with high initial capital costs, high material requirements and the need for large site space due to their considerable size (EPRI, 2002). The main benefits and disadvantages of tower cooling systems are summarized in Table 2.1.

The next large group of cooling systems is surface-water cooling systems, which comprise recirculating *cooling pond systems* and *once-through cooling*. In these systems, the cooling medium (water) is extracted from the water source and passes through a heat exchanger, where the heat from the electricity generation process is transferred to the cooling medium, and then the heated-up cooling medium is discharged back to the water source. Figure 2.3 depicts a conceptual diagram of a typical surface-water cooling system.

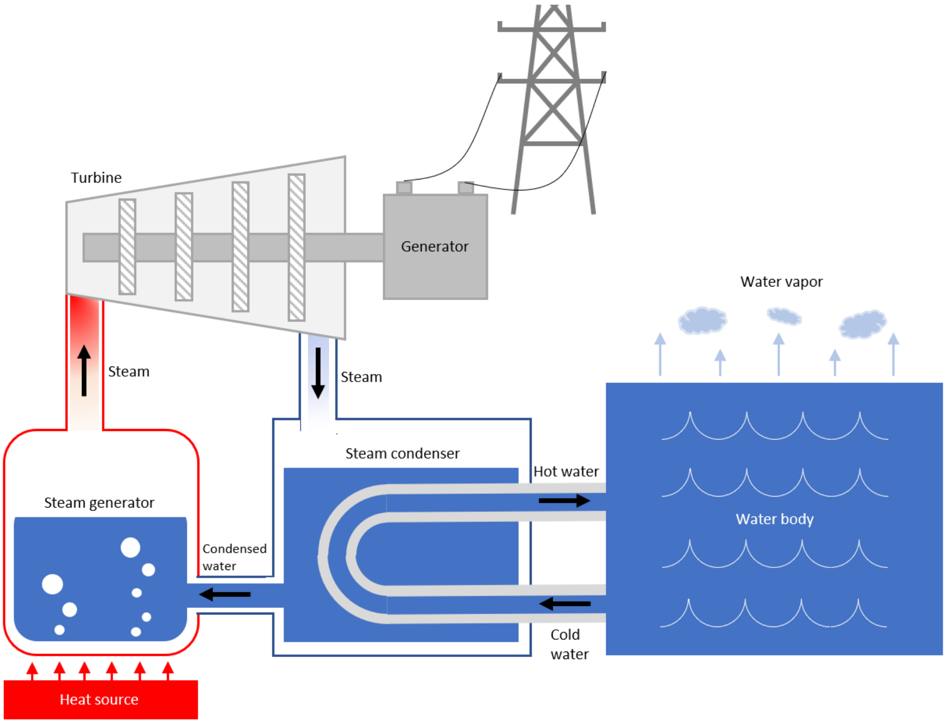

Figure 2.3 Conceptual diagram of surface-water cooling systems, modified from the work of Williams and Simmons (2013)

Surface-water cooling systems can be visually identified by their cooling water intake and discharge structures (such as screens and pumps) located in water bodies near the power plant, making it typical for power plants with surface-water cooling systems to be located in coastal areas, near large rivers, lakes or large ponds. In studies that focus on water demand estimation, lakes and ponds are typically differentiated since the water footprint of once-through lake cooling systems and recirculating cooling pond systems is different (Macknick et al., 2012). Usually, lakes can be easily distinguished from ponds on satellite images; they are characterised by a bigger size and irregular natural shorelines (Diehl et al., 2013). In contrast, recirculating ponds are small (3–10 times the size of the power plant area), man-made reservoirs (Luo, Krishnaswami and Li, 2018).

Once-through cooling is widely used in thermal power generation and are characterised by their ability to dissipate a large amount of heat into the environment (EPRI, 2002). Hence, they are commonly used in nuclear power plants, which continuously generate a large amount of heat that should be dissipated into the atmosphere in order to ensure the safety of the power plant operation (World Nuclear Association, 2023). Remarkably, 60% of currently active nuclear power plants are equipped with once-through cooling systems (Lohrmann, Lohrmann and Luukka, 2022b). In addition, once-through cooling systems are associated with the lowest capital and operational costs since they do not require additional infrastructure, such as cooling towers (Qadrdan et al., 2019).

However, in many parts of the world, the use of these cooling systems has been limited, and the installation of new power plants equipped with once-through systems has been prohibited basis of numerous environmental concerns related to their operation (Maulbetsch and Stallings, 2012; Fleischli and Hayat, 2014). In particular, once-through cooling systems extract a large amount of water during their operation, which is (on average) 35 times larger than the water extractions of tower cooling systems (Macknick et al., 2012). For this reason, the operation of power plants with once-through cooling systems can be compromised during periods of limited availability of water resources (e.g., draughts). Hence, once-through cooling systems are typically installed in power plants located in areas with abundant water resources: coastal areas and near large rivers and lakes (Qadrdan et al., 2019). In addition, once-through cooling is associated with thermal pollution: The temperature of water at the water discharge point usually rises by about 10 °C, affecting local aquatic ecosystems (Lee et al., 2018). Furthermore, water containing conditioning chemicals is discharged after the cooling process, which leads to contamination of the water body (Bloemkolk and van der Schaaf, 1996). Moreover, the inlet facilities of once-through inlet systems trap and kill fish and other wildlife. It was reported that in 2014, once-through-cooled power plants located in the United States killed more fish than the country’s entire fishing industry (Fleischli and Hayat, 2014). Table 2.2 summarizes the main advantages and drawbacks of once-through cooling systems.

Table 2.2 Summary of advantages and drawbacks of once-through cooling systems compared to other cooling technologies

Benefits	Drawbacks
• Highest cooling efficiency • Lowest capital and operating costs • Low water consumption	• Highest water withdrawal rate • Considerable environmental concerns (chemical water pollution and thermal discharge)

In contrast to the previously discussed cooling system types, *dry cooling* uses air as the cooling medium for the cooling process. Thus, these systems are also known as air-cooled condensers. Most dry cooling systems consist of large water pipes that surround the structure and have a radiator-like appearance, which helps in their identification using aerial imagery (Diehl et al., 2013). Air fans are used to intensify heat transfer from the generator's steam into the atmosphere. Figure 2.4 presents a conceptual diagram of a dry cooling system.

Dry cooling systems considerably reduce the use of water in the power generation process, as no water is used for steam condensation. Although dry cooling systems are more water-efficient than other cooling technologies, their installation is associated with high capital costs. Dry cooling is reported to be the most expensive type of cooling. The initial capital costs of dry cooling systems were reported to be 6.7 to 11.5 times higher than the initial capital costs of wet cooling systems (EPRI, 2002). Moreover, dry cooling systems decrease the overall efficiency of the thermal power plant (in other words, power plant output compared to the total energy content of a power plant's fuel) since they require a considerable amount of electricity for operation of the air fans, which usually corresponds to about 1–1.5% of the power output of the power plant (European Climate Adaptation Platform, 2019). The electricity requirements of dry cooling installations were estimated to be 4–6 times higher than those of wet cooling systems (EPRI, 2002). Hence, the operation of dry cooling systems leads to an increase in power generation costs and greenhouse gas (GHG) emissions per unit of generated electricity (Maulbetsch and Stallings, 2012). In addition, it also elevates the condensation temperature, which increases the back pressure. Due to its high costs and negative impact on power plant efficiency, dry cooling is commonly used in power plants characterised by high efficiency and/or minimal heat discharge. Consequently, dry cooling systems are mainly used in gas and oil power plants with a capacity of up to 1,000 MW (Lohrmann, Lohrmann and Luukka, 2022b). Table 2.3 highlights the main benefits and drawbacks of dry cooling systems.

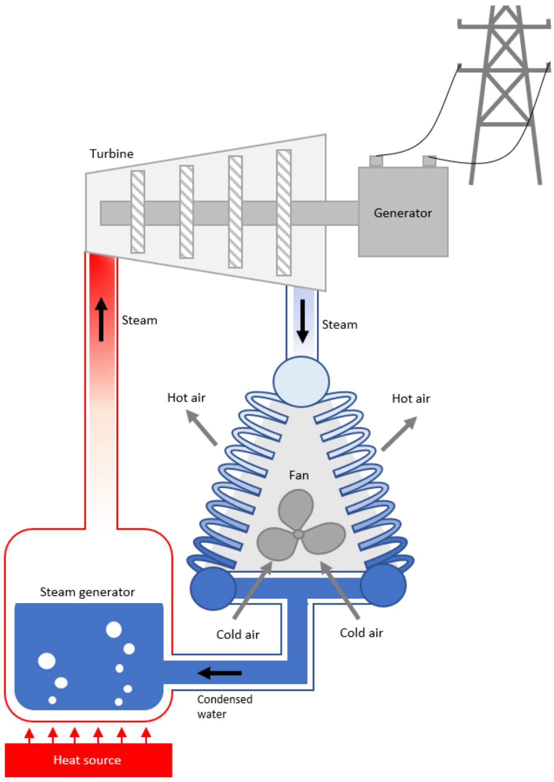

Figure 2.4 Conceptual diagram of dry cooling systems, modified from the work of Williams and Simmons (2013)

Table 2.3 Summary of advantages and drawbacks of dry cooling systems compared to other cooling technologies

Benefits	Drawbacks
• Lowest water consumption and water withdrawal rates • No chemical water pollution	• Highest capital and operating costs • Highest decrease in power plant efficiency • Load limitations on hot days • Large site space required • Possibly increased frequency of maintenance (EPRI, 2002)

The last type of cooling that was considered in this study, *inlet cooling*, is commonly used in gas turbine thermal power plants, in which air from the atmosphere is first cooled in the power plant's air intake structures, then goes through the compressor (which increases its pressure) and enters the combustion chamber, where it is mixed with fuel and burned. After the combustion chamber, high-pressure and high-temperature gas enters the turbine and rotates it. The turbine is connected to the generator, which finally converts the kinetic energy of the turbine into electric energy. Compared to previously discussed steam thermal power plants, no steam (water) is directly used in the power generation process in gas turbine power plants. Hence, the purpose of inlet cooling is not the condensation of steam after the turbine (as it is done in steam power plants) but the cooling of inlet air before the compressor to increase the power output of a power plant.

Figure 2.5 presents a conceptual diagram of an inlet cooling system. The figure shows the process of cooling, in which the ambient air is cooled by water evaporation from the wet surface of the cooling panel to the air (Santos and Andrade, 2012).

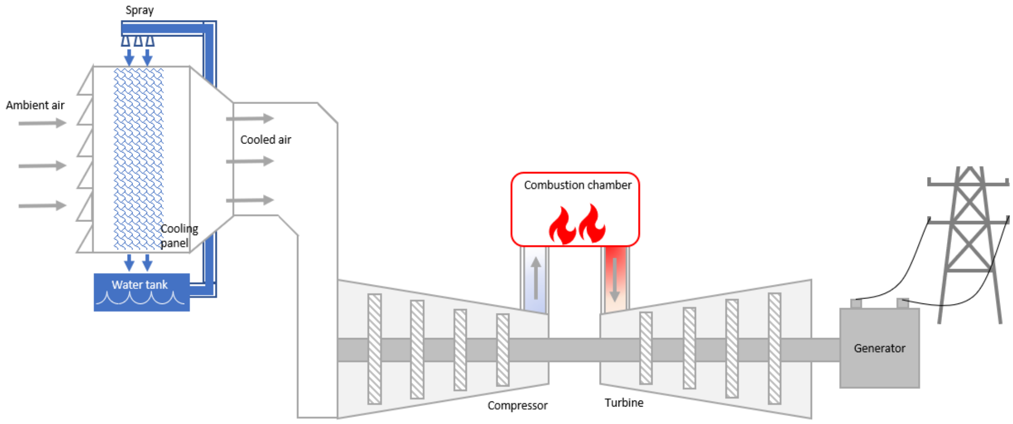

Figure 2.5 Conceptual diagram of inlet cooling systems, modified from the work of Santos and Andrade (2012)

Inlet cooling systems can be visually recognized by the large air intake structures of gas turbine power plants.

According to the information reported by power plant operators, inlet cooling can increase the power output of a gas turbine power plant by about 20% (Saudi Arabian Oil Company, 2021). This increase can be explained by the fact that the power output of the power plant is directly proportional to the air mass flow through the turbine. Air after the inlet cooling system is colder than the ambient air; thus, it has a higher density. The higher density results in a higher air mass flow through the turbine. This, in turn, increases the power output of the power plant (Firmansyah and Prabowo, 2022). Moreover, the power demand of the compressor depends on the volume flow rate of the air, which drops after the cooling in the inlet system. This decreases the auxiliary electricity consumption of the power plant and, consequently, increases the power output of the power plant. Therefore, inlet cooling systems are the most beneficial in dry, hot climates. However, inlet cooling systems are associated with very high water consumption rates, which are comparable to the water consumption rates of tower cooling systems (Macknick et al., 2012), which contradicts the preferred use of inlet cooling in a dry climate. Table 2.4 presents the main advantages and drawbacks of inlet cooling systems.

Table 2.4 Summary of advantages and drawbacks of inlet cooling systems compared to other cooling technologies

Benefits	Drawbacks
• Low cost of the system • Increases power output of the power plant	• Limited application: only for power plants with gas turbines • High water consumption

It is crucial to mention that some other classifications of cooling systems can be found in the scientific literature. For instance, based on the number of steps involved in cooling, cooling technologies are classified into indirect and direct cooling (Tsou and Maulbetsch, 2013). Indirect cooling has two (or more) cooling steps (as shown in Figure 2.2). During the first step, the steam is cooled in the condenser using a cooling medium (water). In the next step, the heat that was absorbed by the cooling medium is transferred to the environment via the cooling system (e.g., cooling tower). In contrast, in the process of direct cooling (as demonstrated in Figure 2.4), the heat from the steam is transferred directly into the atmosphere in a single step, without the use of the cooling medium (water).

2.3 Trends in cooling technology installation

The differences in the cooling system design and corresponding sustainability concerns have resulted in variations in the cooling system installations worldwide. Figure 2.6 reflects the global historical trends in cooling technology installations from 1923 to 2015.

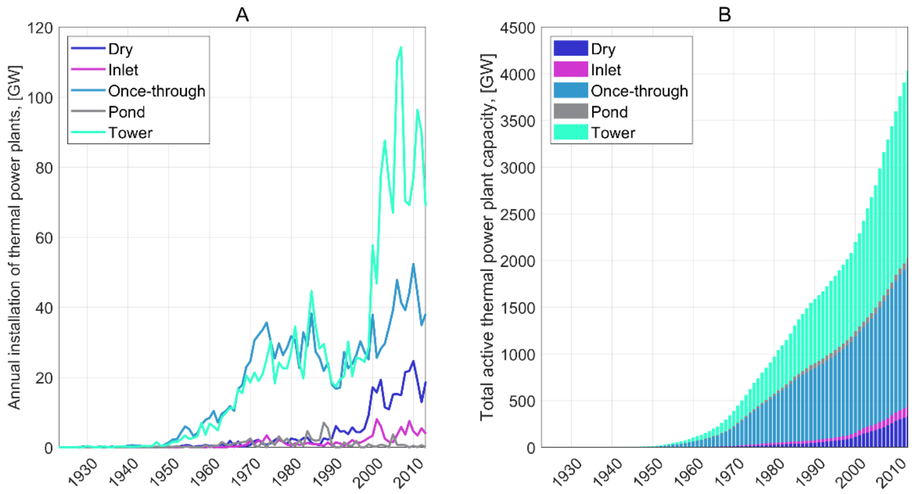

Figure 2.6 Cooling technology installations globally, modified from the work of Lohrmann et al. (2022a)

Based on the cooling technology data collected in **Publication I**, nowadays, about half (50.1%) of active thermal power plants are equipped with cooling towers. The second most common cooling technology is once-through cooling, which is currently installed in 37.4% of global thermal capacities. For example, in the United States only, once-through cooling currently is installed in about 1,200 generating units (which correspond to about 40% of the U.S. capacity) (Maulbetsch and Stallings, 2012). However, the relative share of annual installations of once-through cooling systems has decreased over time: for instance, in the 1980s, more than half of newly built power capacities had once-through cooling, whereas in the 2010s, these systems were installed in less than a third of new power plant capacities.

As demonstrated in Figure 2.6, a clear upward trend in cooling tower and dry cooling installations can be observed after the 2000s. About 8.3% of the global active thermal power capacity is currently equipped with dry cooling systems, and this share is projected to increase considerably in the future (Davies, Kyle and Edmonds, 2013). This persistent upward trend in the installation of dry and tower cooling systems over the past decades reflects a development towards the reduction of water use in the power sector, since these types of cooling use considerably less water per unit of generated electricity than other cooling technologies (Macknick et al., 2012). This global tendency towards a more sustainable use of water resources in power generation has most likely been caused by the increasing global competition for water resources and by climate change, which has already resulted in forced reductions in electricity generation in many regions worldwide (Roehrkasten, Schaeuble and Helgenberger, 2015).

In contrast, the share of power plants with cooling ponds is generally low: about 1.7% of the global thermal capacities currently use this type of cooling. In addition, only around

2.5% of the global thermal power capacity is currently equipped with inlet cooling. As shown in Figure 2.6, major installations of inlet cooling were observed after 2003, which, as discussed by Lohrmann et al. (2022a), were driven by investments in the United States, Australia and countries of South America, Africa and the Middle East and North Africa (MENA) region.

2.4 Existing approaches to cooling system identification

Information on installed cooling technologies is widely used for the assessment of water demand in the power generation sector since distinct types of cooling are associated with a different water demand per unit of generated electricity (Macknick et al., 2012). However, for researchers, the information regarding the cooling technologies installed in individual thermal power plants is usually limited or completely unavailable (Larsen et al., 2019).

As mentioned previously, power plant operators seldom report the amount of water withdrawn and consumed during the power generation process or the cooling system types installed in each specific power plant. The problem of cooling technology data availability has been raised by many scholars. A recent study by Larsen et al. (2019) investigated the existing challenges of the availability of cooling technology data for water–energy nexus studies. They conclude that cooling technology information is usually not registered for reasons such as lack of control and bookkeeping (Gerlach and Franceys, 2010) and commercial interests of power plant operators (EcoFys BV, 2014). Although there are some freely available power plant inventories that report cooling technology information—for instance, EIA (2015b)—many widely used power plant directories do not contain information about the installed cooling systems (Department for Business Energy & Industrial Strategy of UK, 2021; Enerdata, 2020; European Network of Transmission System Operators for Electricity (ENTSO-E), 2022; Global Energy Observatory (GEO) et al., 2019; Open Power System Data, 2020; The Federation of Electric Power Companies of Japan, 2015) or only do so for a limited number of power plants/entries in the database (GEO, 2018; GlobalData Plc, 2020, 2014). One example is the world's most-used power plant database, the World Electric Power Plants Database (S&P Global, 2016), which contains information regarding installed cooling technology for only 59% of the power plants presented in the database (Schleifer and Luo, 2018). This limited availability of data hampers the assessment of water use in individual power plants and in the power sector in general.

Knowledge of distinctive features of different cooling types, of installation trends and of factors that influence the cooling system selection help scholars to estimate cooling technologies installed in power plants in those cases where this information is not accessible. To do so, the scholars develop approaches for cooling system estimation that consider various factors that are expected to affect the selection of the cooling system in each specific power plant. For example, the approach introduced by Vassolo and Döll (2005), considered historical trends of cooling technology installations in the United

States and Canada. Cooling system type was assigned based on the reported year in which each specific power plant was connected to the net (‘year online’ or ‘commission year’): Power plants constructed before 1970 were considered likelier to deploy once-through cooling systems, whereas newer power units were assumed to use tower cooling systems more often.

Other approaches for cooling system estimation were based on the hypothesis that some characteristics of the power plant location determine the selection of the cooling system before the construction of the power plant (EPRI, 2002; EcoFys BV, 2014). In this regard, one of the most common factors to consider was the availability of water resources at the power plant location and the geographical location of the power plant in proximity to various water bodies. In general, water resource availability at the power plant location is a critical factor in the choice of the cooling system, since wet cooling systems are characterised by a high reliance on the constant availability of large quantities of cooling water. There are a few cases in which water is pumped over long distances and large differences in elevation to cover the water demand of the power plant (Zhou and Tol, 2005; World Nuclear Association, 2015); however, power plants that are equipped with highly water-demanding wet cooling systems are usually located directly at the water source (e.g., rivers, lakes or ocean shorelines). Following this line of reasoning, Biesheuvel et al. (2016) assumed that once-through cooling technology is used in all power plants located within 20 kilometres of the ocean shoreline. In another study, all power plants that were located nearest to the coastline were assumed to use once-through cooling, whereas power plants near large rivers, lakes and channels were estimated to use cooling towers (EcoFys BV, 2014).

Another widely applied approach to cooling system estimation is to use the shares of cooling technologies found in various literature sources. In this method, the cooling systems of all power plants in the country/ region are randomly assigned based on the reported shares of cooling technologies in the country/ region. This method was mainly used in early water–energy nexus research (e.g. Davies et al. (2013), Spang et al. (2014)), when the available power plant databases contained limited or no information regarding the year of construction of the power plants in question and no information regarding their location. However, even recent studies (e.g. Larsen et al. (2019)) widely deploy this method due to the continued limited availability of data for the analysis.

Another rather new method for cooling system assignment is based on the visual identification of cooling technologies using aerial satellite imagery. This approach requires a visual inspection of the image of the power plant site by a trained specialist, using different web platforms, for instance, Google Earth, Bing and Yandex.Maps. Although this method is considerably more time- and work-intensive and requires knowledge of the principal components of different cooling types, it has been widely applied in recent studies (e.g., Liao et al., 2021; Zhang et al., 2021) due to its high accuracy and applicability for different countries/regions (Luo, Krishnaswami and Li, 2018). In the future, this method is expected to be more easily implemented by replacing the human workforce required to perform this task with a machine learning algorithm using machine vision (Luo, Krishnaswami and Li, 2018; Takeda et al., 2022).

By combining the strategies used in previous studies, several approaches to cooling system identification were developed over the course of this research. The methods that were introduced and applied in this study are discussed in the next section of this dissertation.

3 Methods

This chapter describes the methodology that was developed and deployed for water demand estimations over the course of this study. The approaches presented in this chapter were mostly developed while working on **Publications I–III**. The main steps of the analysis and the corresponding sections of this dissertation describing them are presented in Figure 3.1.

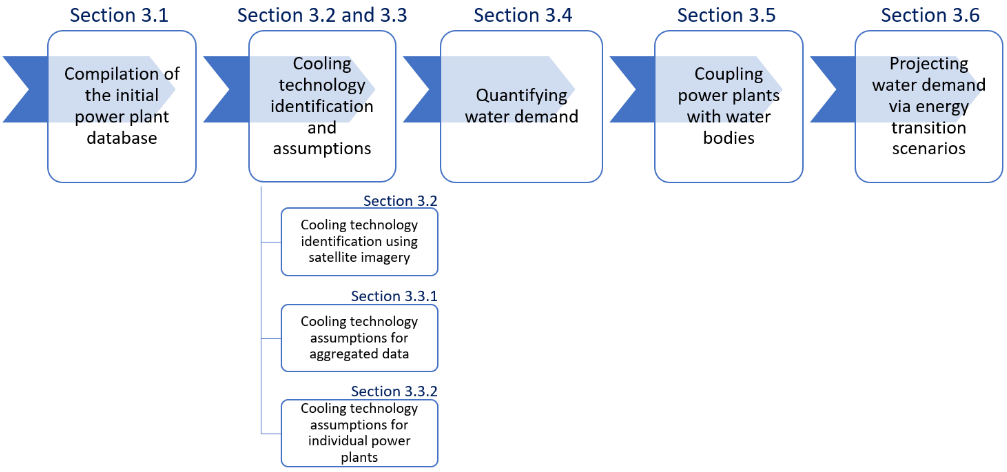

Figure 3.1 The main steps of the water demand analysis performed in this study

3.1 Power plant data

The main source of power plant data in this research was the GlobalData database (GlobalData Plc, 2014), which was previously complemented and modified by Farfan and Breyer (2017) through information contained in other power plant databases (Gerlach et al., 2015; IRENA, 2015; Lehner et al., 2011; S&P Global, 2016). The power plant data obtained from this database were used for the assessment of the water demand for the reference year 2015. Then, the initial database was complemented with information contained in the more recent version of the GlobalData database (GlobalData Plc, 2020). This final database was used to update the estimates of the water demand of the power sector in 2020 and, in addition, to project the future water demand, since the database also contained information on future (planned, announced and financed) thermal power plants. Figure 3.2 contains information concerning the power plant data extracted from the above-mentioned power plant databases.

	Publication I	Publication II	Publication III	Publication IV
Thermal power plants (coal, gas, nuclear, oil) exceeding 50 MW, currently active, commissioned before 2015 – from *GlobalData (2015)*	X	X	X	X
Thermal power plants (biogas, biomass and waste) exceeding 50 MW Non-thermal power plants (hydropower plants, solar PV, concentrated solar thermal power (CSP) plants, wind power plants) – all currently active, commissioned before 2015 – from *GlobalData (2015)*		X		
Thermal power plants (coal, gas, nuclear, oil) exceeding 50 MW, currently active, commissioned between 2015-2020 – from *GlobalData (2020)*			X	
Thermal power plants (coal, gas, nuclear, oil) exceeding 50 MW, to be commissioned in the future (planned, announced, financed) – from *GlobalData (2020)*			X	

Figure 3.2 Power plant databases used in this study

As depicted in Figure 3.2, the power plant databases were filtered to include only thermal power plants exceeding 50 MW. This delimitation stems from the following considerations: First, thermal power plants of low capacity require a comparably low quantity of water for cooling compared to larger plants because they are typically equipped with low-water demanding dry cooling systems. Second, the share of these power plants in the power sector is relatively small; thermal power plants of low capacity currently represent only 4.2% of the global thermal power plant capacity. Finally, the exact location and the installed cooling systems of these power plants are difficult to identify due to their small size (as discussed in Section 3.2 of Methods). Hence, low-capacity thermal power plants were left out of the scope of this research.

The power plant databases used in this study did not include information regarding the exact location (geographic coordinates) of the power plants, their installed cooling systems or the type of water used for cooling. However, this information was crucial for a water demand assessment: The exact location of power plants enables the analysis of water demand on the local level (individual power plant level, river level and region level). In addition, it enables the identification of the type of water used for cooling purposes (as discussed in Section 3.5.1). The type of water, in turn, appears to be linked to the type of cooling technology used in individual power plants (see Section 3.3.2). Finally, the selection of cooling technologies impacts the amount of water used for cooling in each individual power plant, as different types of cooling are associated with different water demand (see Section 3.4).

The following sections of the methods describe the approaches that were used to fill in the gaps in the power plant data regarding the exact location (geographic coordinates) of the power plants, the installed cooling technology and the type of water used for cooling, and which, consequently, enabled the analysis of the water footprint of the power generation sector in this study.

3.2 Cooling technology identification using satellite imagery

To link the locations where the water demand originates (for the power plants) with the corresponding water sources (e.g., oceans, rivers and lakes), the exact location of each individual power plant should be identified. In addition, to quantify the water demand for thermal power plants, the cooling systems installed in each power plant should be determined. In the course of this work, this task was performed manually using aerial imageries available through Google Earth, Yandex.Maps and Bing. The initial database only contained general information on the location such as the province and/or city, which is insufficient to conduct the GIS analysis and, for example, have a reliable estimate of the proximity to the closest water body. Information available in the initial database (name of the specific power plant unit, type of fuel, capacity, country, province and town of its location) helped to determine the exact location (latitude and longitude) of individual power plants. The specific location of each power plant was attributed to the geographical centre of the power generation facility instead of their water intake facilities. This was done to use a unified methodology for standalone power plants and power plants located within large industrial areas.

The installed cooling technologies were visually identified following the instructions provided by the United States Geological Survey (USGS) (Diehl et al., 2013) and Luo et al. (2018). Figure 3.3 and Figure 3.4 illustrate examples of the visual identification of the cooling technology using Google Earth. Generally, five types of cooling technologies were considered: dry cooling, inlet cooling, once-through cooling, recirculating tower cooling and recirculating pond cooling.

Over the course of this study, this identification step was the most time-consuming and work-intensive. The main work on completing the initial power plant database containing the power plant location and the cooling technology information was conducted during the preparation of **Publication I**. Depending on the satellite image resolution and timing of the satellite shot, there were cases in which the identification of the cooling technologies was not possible. This became one of the limitations of the study and one reason to leave power plants of capacity below 50 MW out of the scope of the study. The exact location and the installed cooling technologies of, in total, 13,583 individual power plant units (coal, gas, nuclear and oil) were identified globally.

Publication II focused on Europe’s entire power sector. Hence, in addition to coal, gas, nuclear and oil power plants (their location and cooling systems were previously identified in **Publication I**), the location of power plants of other types was determined. This includes Europe’s hydropower, biomass and CSP plants, which require water for their operation and, thus, were considered in this study. In addition, the installed cooling systems of Europe's biomass power plants were identified via visual inspection of satellite images, as discussed above. After this identification step, the power plant database, which was extended for this publication, contained information on 3,276 power plants with identified location and cooling technology (in the case of thermal power plants).

A

Gibson coal power plant, the United States

Imagery @2022 IndianaMap Framework Data, Landsat/ Copernicus, Maxar Technologies, USDA/FPAC/GEO, Map data @2022 Google

B

Olkiluoto nuclear power plant, Finland

Imagery @2022 CNES/ Airbus, Maxar Technologies, Map data @2022

C

Alba gas power plant, Bahrain

Imagery Map data @2022, Map data @2022

D

Goose Creek Energy Center, gas-fired, the United States

Imagery @2022 CNES/ Airbus, Maxar Technologies, Platt County, USDA/FPAC/GEO, Map data @2022

Figure 3.3: Examples of visual identification of the cooling systems - 1. A—cooling pond, B—once-through cooling, C—dry cooling, D—inlet cooling.

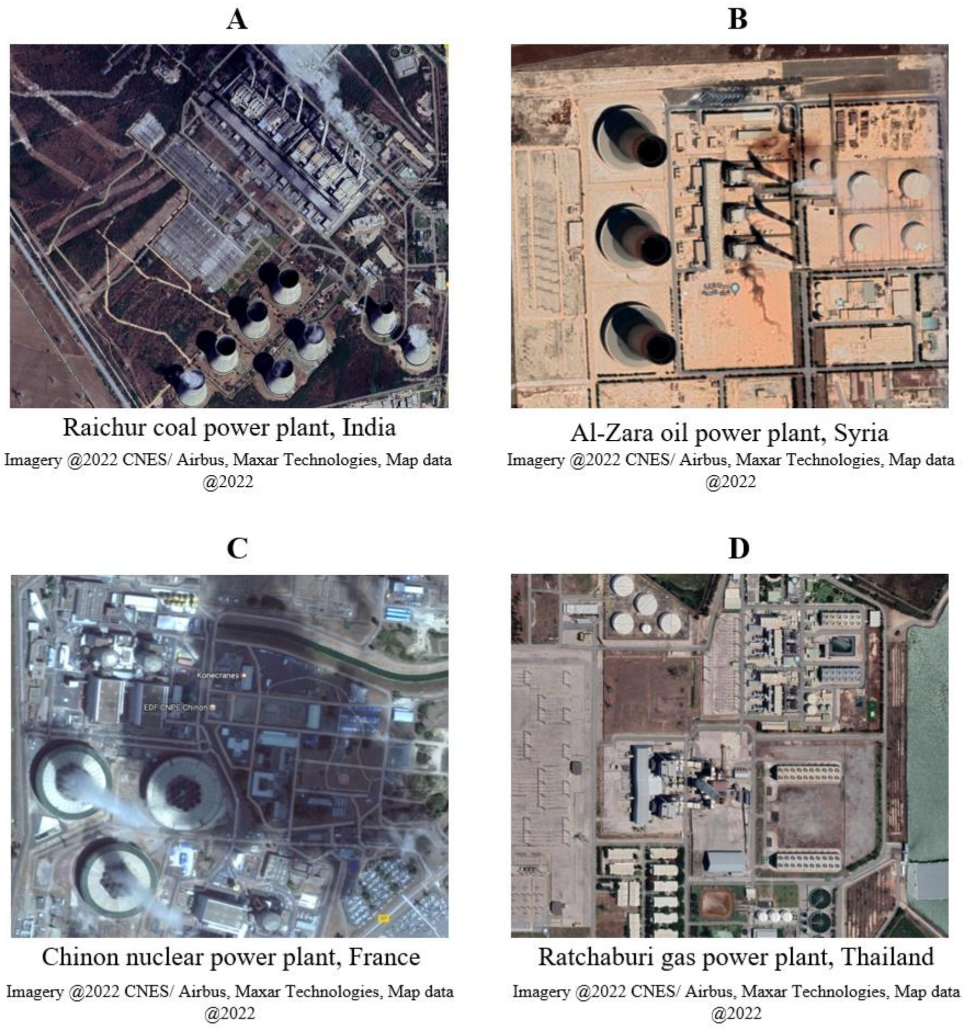

Figure 3.4: Examples of visual identification of tower cooling systems - 2. A–C—natural draft cooling towers, D—mechanical draft cooling towers.

3.3 Cooling technology assumptions

In some cases, it was not possible to identify the cooling technologies of thermal power plants using visual inspection of satellite imagery. For example, it was challenging to identify cooling technologies of power plants located within large industrial complexes in which different types of cooling are used. In addition, some once-through power plants had their intake and discharge facilities submerged, which complicated their identification. In this study, the share of these visually unidentifiable power plants accounts for less than 1% of the total number of power plants encompassed in the database.

Also, the method of using satellite imagery for cooling type identification appeared to be ineffective for aggregated capacities, which were manually added to the power plant database by Farfan and Breyer (2017) to bridge the reported capacities corresponding to the actual power generation (for each year, country and fuel type) and the power plant capacities presented in the GlobalData database. These aggregated capacities accounted for about 8.8% of the total active capacity in 2015.

Although the above-mentioned groups of power plants represent only a small share of the thermal power plant fleet, the main issue of the cooling technology identification was with future (planned) power plants that have not yet been built. For instance, the energy transition scenarios used in **Publications I** and **II** provided only aggregated capacity values for the future thermal power plant fleet. In contrast, **Publication III** was built on data of future power plants that were reported on a per power unit level (for more information, see Figure 3.5). In both cases, cooling technology identification using satellite imagery was not possible.

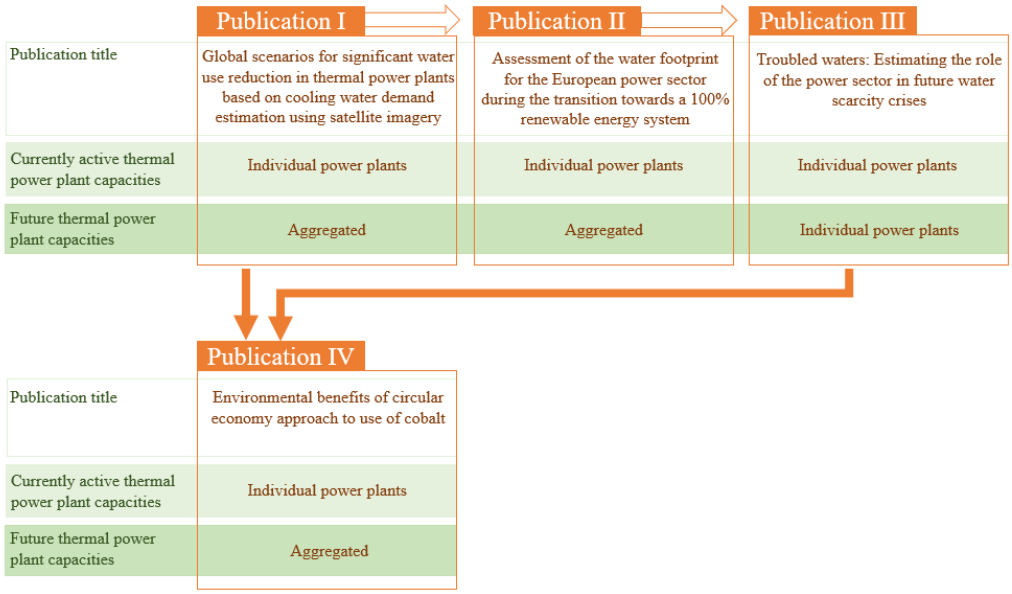

Figure 3.5 Types of power plant data used in this research

In the course of this study, two approaches were used to overcome these limitations. The first approach, which was used for the assignment of cooling technologies for aggregated capacities in **Publications I and II**, is described in Section 3.3.1. The second approach, which was applied to individual power plants in **Publication III**, is discussed in Section 3.3.2.

3.3.1 Cooling technology assumptions for aggregated data

To fill in the gaps in the cooling technology data and to assign cooling technologies for the future power plant fleet, a simple statistical analysis was performed in **Publications I** and **II** (see Figure 3.6**)**: Using the collected data on the installed cooling systems and the information available in the power plant database, for each type of fuel (coal, gas, nuclear and oil) and for each specific country, the most common generator type and cooling technology types over the past 15 years were determined. If it was not possible for a specific type of power plant to determine this combination (e.g., all power plants of this specific type were commissioned more than 15 years ago), then the most common cooling technology of the power generators of a given country was assigned to it.

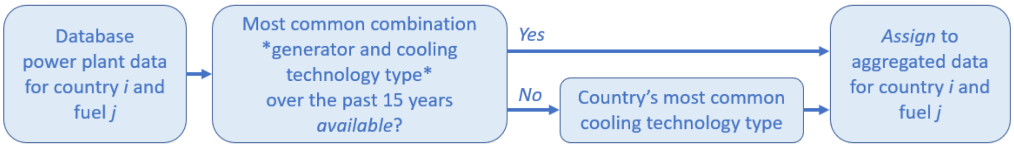

Figure 3.6 Flow diagram of the process of the cooling technology estimation for aggregated data

Over the course of this study, this method was applied to both aggregated capacities and individual power plants, which were listed in the initial database and for which the cooling technology was unknown. In addition, in **Publication I** and **II**, it was deployed for the assignment of cooling technologies to future thermal capacities, which were provided in the database as aggregated capacities.

3.3.2 Cooling technology assumptions for individual power plants

A more sophisticated approach to the cooling system assignment was implemented in **Publication III**. This approach incorporated machine learning techniques for the cooling type identification for individual power plants. It was designed to utilize information on the technical characteristics of future power plants available in the power plant database and, in addition, to consider several local factors at the power plant location that are not typically included in power plant databases but are potentially relevant for the cooling technology assignment. This approach was used to improve the prediction accuracy for the assignment of cooling technologies with a focus on individual power plants.

Figure 3.7 illustrates a flow chart of the model and depicts the local factors (independent variables), which were also collected for the cooling technology identification in **Publication III**. The selection of these specific local factors, which were obtained from various databases (FAO, 2021; GlobalPetrolPrices, 2020; Sadovskaia *et al*., 2019; WRI, 2021), was based on a literature analysis of previous studies (Vassolo and Döll, 2005; Davies, Kyle and Edmonds, 2013; Spang et al., 2014; Luo, Krishnaswami and Li, 2018; Larsen and Drews, 2019; Larsen et al., 2019; Lohrmann et al., 2019) and reports (EPRI, 2002; EcoFys BV, 2014).

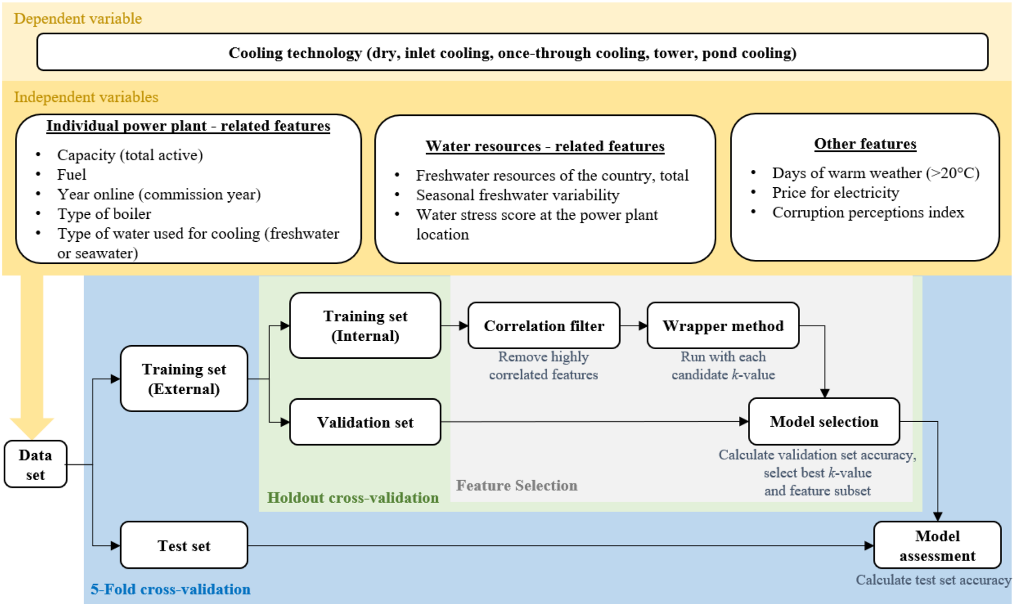

Figure 3.7 Model for cooling system identification

The main purpose of this model was to identify a set of features that are relevant (i.e., useful) for the cooling system identification on an individual power plant level and provide accurate assignments of the cooling technologies. The model that was used in this study deployed a hybrid approach. First, a linear correlation filter was used to remove potentially redundant features, since they are unlikely to add more information to the final set of features. This filter also helped to reduce the computational time of the next computationally more demanding wrapper method. In the wrapper method (obtained from Khushaba, Al-Ani and Al-Jumaily (2011), which was 'wrapped around' the K-Nearest Neighbour (KNN) classifier, various sets of features were iteratively generated using the internal training set, and their performance was evaluated with the classification accuracy using the validation set. The stopping criteria of this iterative process were as follows:

(1) The new feature subset does not lead to an improvement of the classification accuracy compared to the previously generated feature subset, and/or

(2) A classification accuracy of 100% is achieved.

The feature selection algorithm was run five times (five-fold cross-validation), and five subsets of features were obtained. Next, the frequency of occurrence of each feature was calculated to determine which features were more often selected and, thus, appeared to be more useful for the cooling system identification. The final feature subset was then used for the cooling system identification of future power plants using the KNN classifier.

The KNN classifier applies a Euclidian distance measure to identify the closest k observations from the training data to each new observation. Subsequently, it assigns the class label according to the most frequent class of these neighbours (Hastie, Tibshirani and Friedman, 2009). Figure 3.8 illustrates an example of 3-nearest neighbour and 5-nearest neighbour classification for point Y (marked on the figure as a green cross). In this regard, the cooling technology type, which was assigned by the KNN classifier to each individual future power plant using majority voting, represents the most common cooling technology of its nearest neighbours.

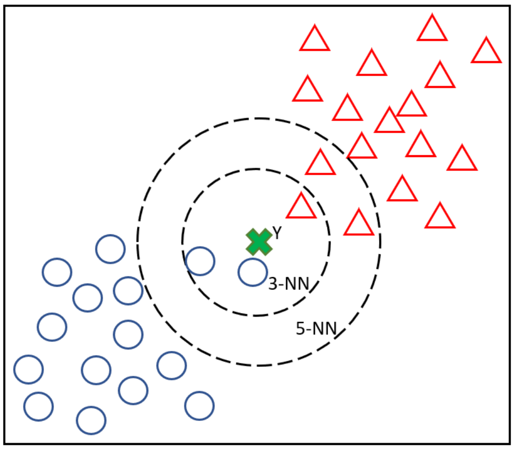

Figure 3.8 KNN classification – an illustrative example

The Euclidian distance for an n-dimensional space (representing several independent variables $(1,2,\dots n)$) between two points $X = (x_1, x_2, \dots, x_n)$ and $Y = (y_1, y_2, \dots, y_n)$ is calculated using Equation 3.1 (Kubat, 2017):

$$d_{EUC}(X,Y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \quad 3.1$$

Lastly, the accuracy of the method was determined using the final feature subset and the test set.

The classification accuracy of the model was calculated as the share of power plants in the test set, for which the cooling technology was identified correctly. The test set is used in the calculation of the accuracy because the test set represents an independent set of data, which was not used before for the training of the classification of the models or for the selection of the best model and its k-parameter and the final feature subset.

Table 3.1 provides the final feature subsets used by the classification models. As demonstrated, four classification models were used in this study: coal power plants, gas power plants, oil power plants and nuclear power plants.

Table 3.1 Feature subsets used by the classification model

Model	Type of power plants	Feature subset used by classification model
I	Coal-fired power plants	• *Power plant capacity (total active)* • *Seawater-cooling* • *Water stress score, province* • *Freshwater total per country*
II	Gas-fired power plants	• *Power plant capacity (total active)* • *Water stress score, province* • *Type of boiler* • *Days of warm weather*
III	Oil-fired power plants	• *Power plant capacity (total active)* • *Seawater-cooling* • *Type of boiler* • *Days of warm weather* • *Seasonal water variability per country* • *Electricity price per country*
IV	Nuclear power plants	• *Power plant capacity (total active)* • *Seawater-cooling* • *Water stress score, province* • *Corruption Perceptions Index per country*

3.4 Quantifying water demand

For the water demand estimation, the study employed a bottom-up approach, meaning that, at first, the water footprint of individual power plants (WF) was calculated using the following equation:

$$WF = WUI \times CAP \times FLH \qquad 3.2$$

where WUI is water use intensity factor given in m^3 of water per MWh of generated electricity, CAP is active capacity of an individual power plant in MW, and FLH full load hours of the power generation in hours.

The calculation of water consumption and withdrawal differs in the use of the corresponding WUI factors. WUI factors were assigned to individual power plants depending on the fuel used, the installed generator type and the cooling technology. The WUI factors were obtained from Macknick et al. (2012). Although these factors were initially reported for power plants located in the United States, Macknick et al. (2012) suggested their usage for water demand assessment worldwide. In previous studies, these factors were widely applied for the water demand estimation of power plants located in European countries (Roidt et al., 2020), China (Liao and Hall, 2018) and India (Srinivasan et al., 2018). In **Publication II,** these WUI factors were compared to the WUI factors applied in previous studies in the context of Europe (Rio Carrillo and Frei, 2009; EcoFys BV, 2014; Mertens et al., 2015; Vandecasteele et al., 2016; Behrens et al., 2017; Sesma Martín and Rubio-Varas, 2017; Terrapon-Pfaff et al., 2020), to demonstrate that these factors can be used for power plants located outside of the United States. However, it is acknowledged that any changes in the technological process of cooling might result in variations in WUI factors. It is also crucial to mention that, since WUI factors for oil power plants were not available, over the course of this study, gas and oil power plants were grouped and the WUI factors for gas power plants were applied for the water demand estimation of oil plants, as was done in previous studies (Feeley et al., 2008; Luo, Krishnaswami and Li, 2018). Since no information regarding the full load hours of individual power plants is available globally, average values were assigned to each power plant according to its fuel type and location (region/country). For the reference years 2015 (in **Publication I** and **II**) and 2020 (in **Publication III**), country-specific FLH were derived from the database of the IEA statistics (IEA, 2018).

In **Publications II** and **III,** Equation 3.2 was also used for the water demand estimation of power plants that did not require water for cooling but used it during the power generation process (e.g., solar PV and hydropower plants).

Compared to other existing approaches for water demand estimation, this method allows to quantify the water demand on a per power plant level, which, consequently, enables allocation of this water demand to the nearest water sources.

3.5 Coupling power plants with water bodies

Power plants may use freshwater or seawater for cooling purposes. However, the emphasis in this study was on the freshwater demand of power plants, since it is a vital resource for many other sectors of the economy, such as food production. Information concerning the type of water used for cooling in individual power plants is typically unavailable in commonly used power plant databases. Hence, over the course of this study, two approaches were used for the water type identification: the Geographic Information System (GIS) analysis (see Section 3.5.1) and assignment of the water type using the pre-determined shares of the seawater-cooled power capacities in each specific country (see Section 3.5.2).

3.5.1 GIS method for water type identification

To link individual power plants with water bodies, GIS analysis was used. In **Publication I** and **II**, this method was applied for individual, currently active power plants, for which the exact location (latitude, longitude) was known / identified during the previous steps of the study. The Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) (Wessel and Smith, 1996) was used as a source of data for the global ocean coastlines, rivers, lakes and political borders. The database provides the location (geographical coordinates) of 25,960 rivers worldwide in high resolution.

As in previous studies (for example, in Biesheuvel et al. (2016)), the assumptions concerning the type of water used for cooling were based on the relative position of the individual power plant to the closest water body:

(1) Power plants located within 20 km from the ocean coastline were assigned to use seawater for cooling;

(2) Power plants located within 5 km from rivers and lakes were assigned to have a direct freshwater source;

(3) Power plants that did not fall into the first two categories (about 10% of the total active thermal capacity) were assigned underground sources of freshwater for cooling.

Figure 3.9 demonstrates the results of the GIS analysis in the example of Europe.

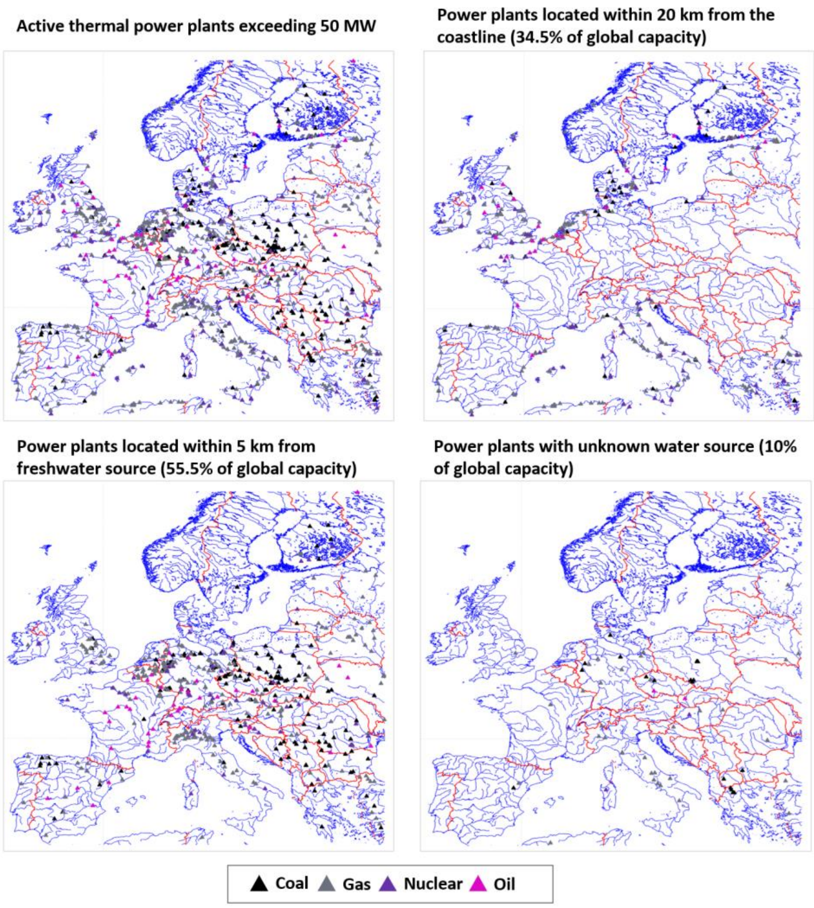

Figure 3.9 Identification of the type of water used for cooling in thermal power plants (GIS method)

It is crucial to mention that this GIS assignment of the water type for cooling was adjusted in the case of India and China to include previously reported information that only 50% of coal power plants located within 20 km from the ocean coastline in China and 85% of such power plants in India use seawater for cooling purposes (Biesheuvel et al., 2016). The corresponding adjustment was only performed for power plants located in China and India because of a lack of similar information for other countries.

3.5.2 Water type assumptions for future power plants

In the case of future power plants, for which the location is unknown, the GIS method for water type identification cannot be used. To address this limitation, in **Publications I** and **II**, all power capacities that were projected to be commissioned after the year 2015 were assumed to use freshwater for cooling. In this regard, it is acknowledged that the water demand estimates that were calculated in these studies represent a worst-case scenario.

In **Publication III**, a different approach was implemented: the type of water was assigned to individual future power plants using the current shares of seawater cooling in each specific country, which were calculated in **Publication I**. This approach, although often used in previous studies (for instance, in Davies et al. (2013)), may add uncertainty to the results of the study. However, the decision to use this approach was based on the hypothesis that these shares of seawater-cooled power plants will remain stable in the future: Thermal power plants are typically linked to large population and industrial centres, and their location will (with high certainty) remain unchanged in the next decades.

3.6 Energy transition scenarios

In order to estimate the future water demand of thermal power plants (as well as other power generation technologies considered in this study), the future generation profile should be known. Hence, the assessment of the future water demand of the power sector depends heavily on the availability of generation data on the individual power plant level as well as on the country and global levels. Although there are currently more than 600 energy transition scenarios published in various scientific journals and reports according to some estimates (Khalili and Breyer, 2022), detailed information (including the projected FLH for different power generation technologies) is typically unavailable for public use. The development of new future energy transition scenarios was not part of the current study, which relied on the available energy transition scenarios.

Figure 3.10 depicts the energy transition scenarios used for water demand estimations over the course of this study. Depending on the applied scenario, the generation data was either available at the country or region level—scenarios based on the LUT energy system transition model (Bogdanov et al., 2019; Child et al., 2019) used in **Publications I**, **II** and **IV** and the IRENA Remap2030 scenario (IRENA, 2018) used in **Publication I**—or available on a global level (Bloomberg New Energy Finance (NEF) scenario (Bloomberg

NEF, 2020) and United States Energy Information Administration (EIA) scenarios (EIA and U.S. Department of Energy, 2021) used in **Publication III**. The assumptions that were initially introduced in these scenarios might have affected the results presented in the current study.

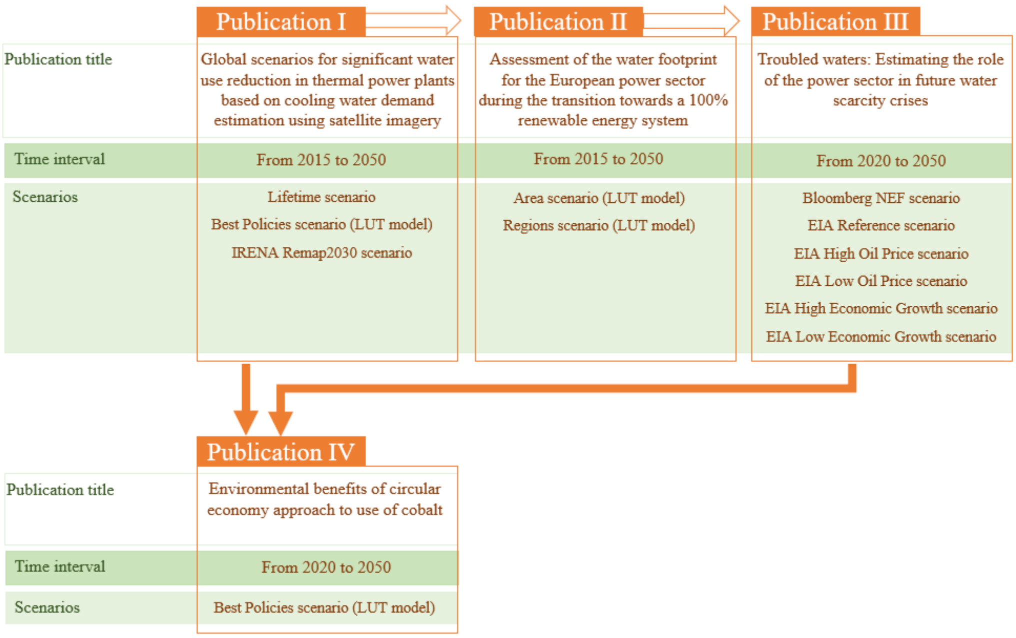

Figure 3.10 Energy transition scenarios used for water demand estimations

All scenarios applied in this study consider that the technical lifetime of individual power plants is limited. This implies that the operation of all individual thermal power plants was assumed to discontinue at the point of their expected decommissioning. The average technical lifetime of gas and oil power plants was assumed to account for 34 years, while it was 40 years for coal and nuclear plants, as reported by Farfan and Breyer (2017b). Equation 3.3 was used to calculate the water footprint of the power sector in the selected country/region (WFC) in a specific year *t*.

$$WFC_t = \sum_{i=1}^{m}(CAPold_{\,i,t} \times FLH_{\,i,t} \times WUI_i) - \sum_{i=1}^{m}(CAPdec_{i,t} \times FLH_{\,i,t} \times WUI_i) + \sum_{i=1}^{m}(CAPnew_{\,i,t} \times FLH_{\,i,t} \times WUInew_i) \quad (3.3)$$

where *i* represents the specific type of power generation (coal, gas, nuclear, oil, solar PV, hydropower, biomass, etc. – depending on the scope of the study). $CAPold$ – previously installed and still active capacity in the year *t*, $CAPdec$ – capacity that was decommissioned before the year *t*, $CAPold$ – new capacity projected to be commissioned in the year *t*.

3.7 Sensitivity analysis

As discussed in previous sections of the Methods chapter, over the course of this research, many assumptions were introduced in order to compensate for the lack of data on cooling technology and water type that were requited for the analysis. To evaluate the impact of the introduced assumptions on the presented results, several tests were performed.

In **Publications I** and **II**, a sensitivity analysis was conducted to investigate the effect of the assignment of different cooling technology types to individual power plants, for which cooling technology was impossible to identify using aerial imagery, and to aggregated capacities.

The sensitivity analysis was performed in several steps. First, all empirically observed combinations of the generator and cooling technology types were determined for each type of fuel in each specific country. Second, for each identified combination, the probability of assignment (PA) was calculated as power plants of that combination and fuel type divided by the number of power plants of that fuel type in the country. Lastly, the corresponding water footprint of the power sector in the selected country/region was calculated using the following formula:

$$\begin{bmatrix} WFC_1 \\ \vdots \\ WFC_p \end{bmatrix} = WF_{kn} + CAP_{uk} \times FLH \times \begin{bmatrix} WUI_1 \\ \vdots \\ WUI_p \end{bmatrix} \quad 3.4$$

where $WUI_1 \dots WUI_p$ were derived from Macknick et al.'s (2012) work for each identified combination of the generator and cooling technology type (for each type of fuel) observed in the country. *kn* stands for power plants with known cooling technology and *uk* – power plants with assigned cooling technology.

The results of the sensitivity analysis were presented on a per-country level and contained all combinations of the water demand values and the corresponding PA.

Another sensitivity test was performed to evaluate the potential effect of the selection of the 20-kilometre seawater cooling buffer zone on freshwater demand estimates (in **Publication I**). The analysis was conducted by gradually reducing the 20-kilometre seawater cooling range to 2 kilometres, in 2-kilometre steps, and, subsequently, by calculating the resulting freshwater demand.

In general, there are different approaches to analysing sensitivity. Another approach that could have been used for the sensitivity assessment in this study is to investigate the combined influence of several variables (e.g., the assignment of different cooling technology types and the assignment of the seawater cooling buffer zone to individual power plants) on the water demand estimates while simultaneously considering their uncertainties. Such an investigation was not part of this study, however, it can be applied for sensitivity analysis in future research.

To the author's knowledge, sensitivity analysis was not performed in previous studies focused on the water footprint assessment of the power sector.

3.8 Limitations of water demand estimations

Over the course of this study, the following limitations were introduced:

- *Local factors:* The current study approached the water footprint assessment task from the perspective of the power plant's water demand. In other words, the water consumption and the water withdrawal of individual power plants were calculated using the assumed generation load (as discussed previously), the information regarding the capacity, cooling system and the type of generation system that is provided for each individual power plant. However, the water supply side, which implies that the water demand of thermal power plants is also affected by local conditions, is not considered in this approach. In this regard, such factors as the monthly averages of the ambient air temperature, the ambient surface-water temperature, the wind speed and other factors that may affect a power plant's local water demand (Diehl et al., 2013), were not part of this analysis due to the limited availability of this data for the global analysis. Moreover, the analysis of the water footprint did not consider changes in water quality at a power plant's discharge outlets. However, it is acknowledged that the consideration of these factors is advisable for local-level water demand analysis and further research is needed to evaluate their impact.

- *Carbon capture and storage (CCS):* According to some estimates, the use of CCS technologies can increase the operational water consumption of an individual power plant by up to 92%, depending on the type of power plant and the installed cooling system (Macknick et al., 2012). In the current study, the use of CCS technologies in thermal power plants was not considered, because the energy transition scenarios applied in this study do not encompass information concerning the implementation of CCS technologies in the future. Hence, the actual future water demand of the thermal power sector may be higher than our estimates. Thus, further research is needed to assess the effects of CCS on the water demand of future energy systems.

- *Technological innovations and water efficiency improvements:* Technological improvements of power plants typically aim to enhance the thermal efficiency of electricity generation. In addition, power plant operators may also implement technological innovations to increase the water efficiency of individual power plants. Unfortunately, this information is typically not recorded in power plant databases. Moreover, the energy transition scenarios applied in this study do not contain information concerning the projected technological innovations in thermal power plants. Therefore, in **Publications I–III,** technological trends were only considered indirectly by determining and assigning the most common generator type during the past 15 years to the new capacities when the generator type was unknown. However, including information regarding water efficiency innovations in power plants may considerably improve the water demand estimates of electricity generation, especially at the local level.

4 Results

This section briefly discusses the aims and methods of each of the publications and presents their main results. After presenting each publication individually, the section concludes with an overview of the publications' main results and contributions.

4.1 Publication I: Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery

Aim and methods

The main objective of this publication is to connect the currently active thermal power plant fleet with its associated water demand at a high spatial resolution. The reason behind carrying out this analysis is that the amount of water used in the process of power generation is seldomly reported by power plant operators or in widely used power plant databases (Larsen et al., 2019).

The first step of the study was to collect data on cooling technologies installed in thermal power plants worldwide through an inspection of their aerial imageries. Second, using the collected data, the water consumption and water withdrawal needed for cooling in the power generation process were estimated on different levels: power plant-level, river-level, country/region-level and, finally, global-level. The methods developed in this study make it possible to project potential water savings in the power sector resulting from the decommissioning of the old thermal power plant fleet. The study examines two decommission strategies: the Lifetime scenario and the Best Policies scenario, which projects the replacement of old thermal power capacities with renewable energy technologies. In addition, the GIS analysis performed in this study allows us to differentiate between seawater and freshwater demand on the individual power plant level.

Results

In the base year 2015, the total water withdrawal of the global thermal power sector was estimated to be at the level of 500 cubic kilometres, out of which about 290 cubic kilometres of water (or 58%) were extracted from freshwater sources. In the same year, total water consumption was about 25 cubic kilometres, out of which freshwater losses constituted 18 cubic kilometres of water (72% of the total amount of water). On the country level, the countries with the highest water consumption (both total and freshwater) were China, the United States, India and Russia. China was responsible for about 31.5% of global freshwater losses in the thermal power sector, whereas the United States accounted for 35.7% of global freshwater withdrawals. The study demonstrates that, depending on the decommissioning scenario, the total water withdrawal of the global thermal power plant fleet can be reduced by up to 91.5% until 2050 and the total water consumption by up to 97.7%.

The global GIS analysis shows that about 33.4% of the global thermal power capacity is located within 20 kilometres from the ocean coastline, 55.5% is located within five kilometres of main global rivers and the remaining 11.1% is extracted water from an unknown freshwater source. These results were used in **Publication III** to estimate the source of water for the cooling of future power plants.

The results of the analysis of 354 main global rivers worldwide reveal that the Ohio River, the Yellow River and the Mississippi River are currently facing the largest water consumption from the thermal power sector, while the Yangtze River, the Mississippi River and the Tennessee River are the rivers most affected by water withdrawal. It was estimated that thermal power plants withdraw about 12 cubic kilometres of water from the Yangtze River annually.

Main contribution

The paper demonstrates that a considerable water use reduction in the power generation sector is feasible via the gradual decommissioning of thermal power plants and the associated transition to renewable energy technologies.

4.2 Publication II: Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system

Aim and methods

In **Publication I**, the water footprint of the power system (current and future) was investigated only from the perspective of thermal power plants. However, other components of the power system (for instance, hydropower generation, biomass power plants, CSP plants, etc.) also require a considerable amount of water for their operation. Hence, the primary goal of **Publication II** is to quantify the current water footprint of the entire energy system and to project it until 2050. The geographical scope of this study is the European continent due to (1) the availability of data for different types of power plants located in Europe and (2) access to energy transition scenarios. The secondary goal of this study is to quantify the potential benefits for the water footprint of establishing power transmission interconnections between Europe’s regions.

Two energy transition scenarios were used in this study. The Regions scenario was used to investigate the potential future water footprint of Europe’s energy system without power transmission interconnections between regions. The Area scenario was used to investigate the power system with interconnections between regions. Both scenarios, which were derived from the work of Child, Bogdanov and Breyer (2018) and Child et al. (2019), project the transition towards a 100% renewable energy system in Europe.

Results

The results of the study revealed that Europe’s energy sector consumed 15.54 cubic kilometres of water in 2015. Hydropower capacities were responsible for about 61.5% of the water lost in the power generation process. The highest water consumption was detected in France (2.39 cubic kilometres of water lost annually) and Norway (1.89 cubic kilometres of water). The lowest water demand was calculated for Denmark, with its water consumption in 2015 being 0.02 cubic kilometres, of which only 16% originated from freshwater sources (such as rivers and lakes).

One of the key results of the study is the estimate of SWC, which considers the electricity generation profile of each specific country/region, and which can be used in other studies for the water footprint assessment of different services and products manufactured in Europe. Table 4.1 demonstrates the estimated SWC values per region in Europe in 2015.

Table 4.1 Estimated specific water consumption per European region/ country in 2015.

Region	Countries	Specific water consumption, m^3/MWh
AUH	Austria, Hungary	8.55
BKN-E	Balkan-East: Romania, Bulgaria, Greece	3.87
BKN-W	Balkan-West: Slovenia, Croatia, Bosnia & Herzegovina, Serbia, Kosovo, Montenegro, Macedonia, Albania	6.94
BLT	Baltic: Estonia, Latvia, Lithuania	1.74
BNL	Belgium, Netherlands, Luxembourg	1.31
BRI	British Isles: Ireland, United Kingdom, Isle of Man, Guernsey, Jersey	1.33
CH	Switzerland, Liechtenstein	10.24
CRS	Czech Republic, Slovakia	3.7
DE	Germany	2.04
DK	Denmark	0.55
FI	Finland	4.22
FR	France, Monaco, Andorra	4.23
IBE	Iberia: Portugal, Spain, Gibraltar	3.74
IS	Iceland	13.19
IT	Italy, San Marino, Vatican	1.4
NO	Norway	15.47
PL	Poland	2.07
SE	Sweden	7.66
TR	Turkey, Cyprus	5.41
UA	Ukraine, Moldova	2.79

In 2050, the power sector of Europe is projected to consume between 11.14 (in the case of the Area scenario) and 11.77 (in the case of the Regions scenario) cubic kilometres of water, which corresponds to a 28.3% and 24.2% reduction in water consumption compared to 2015 levels, respectively. This result highlights the benefit of establishing power transmission interconnections between Europe’s regions (assumed in the Area scenario).

In most of Europe’s regions, the water demand of the energy sector will decrease as a result of the projected energy transition (according to both scenarios considered in this study). However, in five out of 20 regions, the water consumption and water withdrawal are projected to increase on average by 14% until 2050, from 7% in Balkan-West countries to 24% in Sweden. Turkey’s energy sector is estimated to become the largest water consumer in Europe by 2050, when it is projected to have increased its water demand by about 11% compared to 2015 levels.

Main contribution

The paper demonstrates the positive water-related key benefits of establishing power transmission interconnections among regions of Europe.

4.3 Publication III: Troubled waters: Estimating the role of the power sector in future water scarcity crises

Aims and methods

The work on the previous two publications highlights some peculiarities of existing energy transition scenarios. On the one hand, energy transition scenarios typically focus on decarbonization strategies for the future energy system, but overlook the water footprint of the proposed energy system. On the other hand, energy transition scenarios usually do not consider the governments’ plans to commission new thermal power plant capacity in the future. This capacity includes already planned, announced, financed and power plants under construction, which, thus, have a high likelihood of being commissioned in the future.

To address these concerns, **Publication III** aimed to examine six publicly available and commonly used energy transition scenarios from the perspective of the potential water footprint. The estimation of the water demand of the future thermal power plant fleet (contained in the power plant database (GlobalData Plc, 2020)) were conducted using a machine learning model for classification, which was trained using the cooling technology data collected over the work on **Publications I** and **II**. In contrast to **Publication I**, this study considered the water footprint of the entire energy sector, and compared to **Publication II**, the geographical scope of this study was global.

Results

In 2020, the total water consumption of the global power sector was about 88 cubic kilometres, of which about 22% (or about 20 cubic kilometres of water) originated from thermal power plants. Although all energy system transition scenarios project a drastic increase of low water-demanding technologies, such as solar PV and wind (from about 10% of the global generation mix in 2020 to about 56% by 2050), the SWC of the global energy sector was projected to decrease only by 20%: from about 3.74 cubic metres per MWh in 2020 to 3.04 cubic metres per MWh in 2050. The water consumption of the future global power sector in 2050 is estimated to be between 104 and 132 cubic kilometres of water, depending on the energy transition scenario representing an increase in water consumption between 35% and 50% as a consequence of the increase in electricity demand, despite the lower SWC projected.

One of the key observations of this study is that the SWC of the thermal power sector is projected to increase in the future, from 1.2 to 1.7 cubic metres of water per MWh of generated electricity. This could be explained by the fact that thermal power capacities tend to increase over time: large power plants use more water-demanding cooling technologies to transfer large amounts of waste heat, whereas smaller plants are typically equipped with dry cooling systems (Lohrmann et al., 2022a).

The water consumption criticality (WCC) matrix developed in this study is used to identify countries that are potentially critical from the perspective of limited water resource availability for power generation. Kazakhstan, Pakistan, Syria, Uzbekistan, India, Belgium and Australia were classified into the extremely high WCC category. Additionally, Saudi Arabia, Iran, Turkey, Greece, Spain, Mexico, China, the United States, Armenia, North Macedonia, Mongolia and Peru were assigned to the group of countries with the high WCC.

Main contribution

The paper demonstrates that despite the energy transition to a system with a high share of water-free solar and wind technologies, the future water consumption of the power sector is still projected to worsen.

4.4 Publication IV: Environmental benefits of circular economy approach to use of cobalt

Aims and methods

Cobalt is an essential material in a broad number of products, such as for batteries, electronics, pigments, magnets, chemical catalysts, etc. (Graedel and Miatto, 2022). Moreover, cobalt is needed for energy transition and is classified as a critical material due to its high supply risk, high environmental, social and corporate governance (ESG) risk, and scarcity as a natural resource (Bamana *et al.*, 2021; Campbell, 2020; European Commission and Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2017). It has been previously highlighted that the circular economy approach might mitigate the future potential supply risk of cobalt and reduce the environmental impact associated with its production (Ferron, 2016; Tkaczyk et al., 2018).

As a part of the study, **Publication IV** aims to estimate the potential role of cobalt recycling in the reduction of the water consumption caused by global cobalt production. The investigation was conducted using the SWC values for 145 regions globally, which were calculated based on the power system data from **Publication I.** The study considered the primary and secondary production of cobalt (recycling), as well as the direct (processing-related) and indirect (energy-related) water consumption. The study had a global scope and considered the time period from 2020 to 2050.

Results

In 2020, the total global water consumption of cobalt production constituted 37.47 million cubic metres, out of which the indirect (energy-related) water consumption accounted for about 91%. On the country level, China was estimated to be responsible for about 57% of the water lost globally by the primary production of cobalt and for 28% of water consumed by its secondary production. The study also investigated the specific total water demand for the production of one (1) kilogramme of cobalt (STWD). In 2020, the STWD was calculated at the level of 0.25 cubic metres of water per kg of primary cobalt and 0.13 cubic metres of water per kg of secondary cobalt.

Publication IV considers the gradual decarbonization of the global energy system during the investigation period, which was projected by the energy system transition scenario used in this study (Bogdanov et al., 2019). As a result of the projected gradual decommissioning of the water-demanding thermal power plant fleet and its replacement by low water-demanding renewable energy technologies by the end of 2050, the STWD of primary and secondary cobalt production is estimated to decrease to 0.12 and 0.07 cubic metres of water per kg of cobalt, respectively. Consequently, a projected 230% increase in global cobalt production from 2020 to 2050 coupled with the anticipated surge of its recycling (supplying up to 25% of the total demand for cobalt) is estimated to lead to only a 9.6% growth in total water consumption.

Main contribution

The paper demonstrates that effective recycling of cobalt could considerably reduce the water consumption of its entire supply chain.

Figure 4.1 summarises the main results and contributions of each publication.

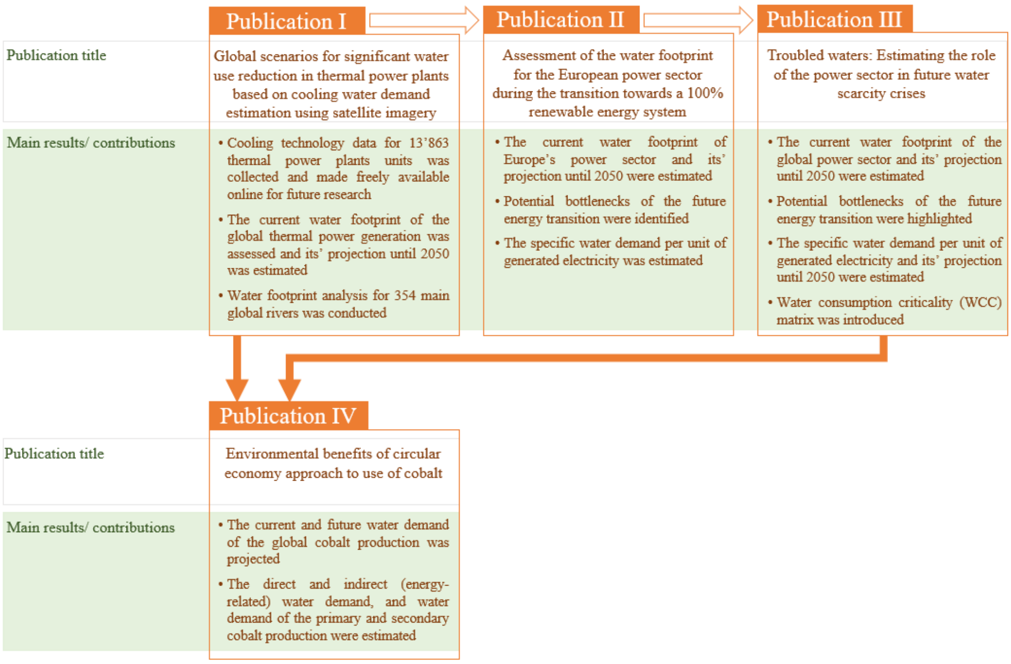

Figure 4.1 Summary of the main results and the contributions of the publications

5 Validation of results

Over the course of this study, a series of tests were performed to support the choice of the selected methods and to evaluate their potential impact on water demand estimates. It is crucial to mention that most tests were performed in **Publication I**, where the majority of the methods were initially developed.

This section presents a brief description of these tests and the corresponding results. The section follows the structure of the methods section: The first group of tests is related to the method for cooling technology identification and for the cooling technology assumptions introduced in this study. The second group of tests is related to the assumptions introduced for the quantification of water demand. The third group of tests evaluated the method of water type estimation. Finally, the section presents the results of the validation of the water demand estimates.

5.1 Validation of the cooling technology identification methods

In **Publication I**, to justify the application of the method of *cooling technology identification using satellite imagery*, the results of the identification using this approach were compared against published data for individual power plants located in the United States available from the EIA database (EIA, 2015). The results of this comparison demonstrate that the applied method can provide the correct result in 81% of cases. This appears consistent with Luo et al. (2018), who developed the method based on USGS recommendations (Diehl et al., 2013) and reported an accuracy of 90%.

The next test was to validate the approach for the *cooling technology estimation for aggregated data*. It was not possible to evaluate the accuracy of the method using the aggregated capacities since they were artificially created and added to the database by Farfan and Breyer (2017a) and no information about the actually installed cooling technologies is available for these capacities. Therefore, to overcome this limitation, the calculation of the accuracy was computed using the GlobalData database (GlobalData Plc, 2014) without the aggregated capacities and it was assumed that the results would generalise to aggregated data. The accuracy of this approach for the cooling technology assignment was estimated in Lohrmann et al. (2022) using a five-fold cross-validation: the model was trained (the most common generator type and cooling technology was determined using the training data set), and it was tested using the independent test data set. The results demonstrated an average test set accuracy of about 65%, which can still be considered high for a rather balanced five-class problem.

In addition, a sensitivity analysis was performed in **Publications I** and **II** to examine the potential impact of cooling technology assignment on water demand estimates at the country level. The results demonstrated that in most cases, this approach leads to a slight overestimation of the water footprint. However, since the aggregated capacities represent only a small share of the total thermal capacities in this study, the impact of this overestimation on water demand estimates is marginal.

Finally, the estimated performance of the machine learning-based model, which was used for the *cooling technology assumptions for individual power plants* in **Publication III**, is demonstrated in Table 5.1. The average accuracy of the classification model was 85.42% (± 1.60% standard deviation). This demonstrates that very high accuracy (for a five-class problem) can be achieved using this method.

Table 5.1 Performance of the classification model

Model	Type of power plants	Performance of the model (test-set accuracy)
I	Coal-fired power plants	91.36% (± 1.82%)
II	Gas-fired power plants	81.34% (± 1.21%)
III	Oil-fired power plants	80.69% (± 1.79%)
IV	Nuclear power plants	93.57% (± 3.54%)

These accuracies for cooling technology identification and estimation can be compared to the accuracies of alternative methods used in the relevant research (benchmark studies). Due to their high citation scores, studies by Davies et al. (2013), Vassolo and Döll (2005), Spang et al. (2014) and EcoFys (EcoFys BV, 2014) were selected for this analysis as benchmark studies based on the results of the literature review. However, the accuracies of the cooling system estimation approaches in these studies were not reported. To overcome this limitation, the approaches were tested by following the instructions provided in the method sections of the corresponding studies. Subsequently, the accuracies were calculated by using the GlobalData database (GlobalData Plc, 2014) and 5-fold cross-validation. As demonstrated in Lohrmann et al. (2022), the computed approaches based on Davies et al. (2013), Vassolo and Döll (2005) and EcoFys (EcoFys BV, 2014) revealed an average accuracy of 35%, whereas the approach of Spang et al. (2014) has an accuracy of about 58% for this five-class problem.

As demonstrated, the estimated accuracies of the benchmark approaches were considerably lower than the accuracies of the approaches for cooling technology identification developed over the course of this study.

5.2 Evaluation of the FLH assumptions for the water demand calculations

Publication I analysed the potential impact of assuming region- and country-average FLH for individual power plants. In particular, the average FLH assumed in this study was compared to the reported data on the actual net generation of individual power plants located in the United States, which is available from the EIA database (EIA, 2015b, 2015a). The results of this comparison show that although there might be a difference in FLH on an individual power plant level (especially in the case of gas and oil power plants), this will not considerably affect the country-level water demand estimates. The actual net generation of individual power plants located in the United States was only 1.3% higher than the values used in this research. The results also demonstrated that the use of the same value of FLH for all types of cooling for a given fuel type appears appropriate.

5.3 Validation of the water type estimation

To validate the approach for water type estimation, the results of this assignment were compared with the power plant data for the United States reported by the EIA (EIA, 2015a) (**Publication I)**. The results of this comparison demonstrated that for 93% of the cases, the selected approach correctly identified the water type. In addition, the obtained results are strongly aligned with the data reported for seawater cooling in power plants in the MENA region, with a difference of only about 5% (Siddiqi and Anadon, 2011).

In addition, a sensitivity analysis was conducted to assess the impact of this assignment on water demand estimates. It was demonstrated that if the sea cooling range could be reduced from 20 km (as estimated in this study) to 12 km, the freshwater demand estimates (both consumption and withdrawal) would increase only by about 2% compared to the 20 km assumption. If the range were reduced to 2 km, the freshwater consumption values would increase by 12.3%, and the freshwater withdrawal values would grow by 8.6%. The low sensitivity of these results could be explained by the fact that power plants tend to be built closer to coastlines.

5.4 Validation of the water demand estimates

As a final point, it is crucial to investigate how the water demand estimates obtained in this study differ from the values reported by other researchers and practitioners.

In **Publication I,** the water consumption estimates for the United States in 2015 were compared with the reported values by the EIA database (EIA, 2015b) and by Diehl & Harris (2014). The results of this comparison are provided in Table 5.2. As shown in the table, the water consumption estimates of Diehl & Harris (2014) range between 4.5 and 4.8 cubic kilometres, which is slightly less than the median values of the water consumption reported in this study, but well within the min-max interval. The difference could be explained by the fact that the estimates of Diehl & Harris (2014) were provided for the year 2010, whereas the values of this study were computed for 2015. Since the water demand of the power sector is increasing over time (according to the results of this study), the estimates of Diehl & Harris (2014) appear to be consistent with the results of this study.

Apart from that, a difference of almost 33% in the median water consumption was detected for the EIA database (EIA, 2015b). However, a closer look at the power plant data provided by the EIA database (EIA, 2015b) revealed that for 29% of the power plants, the database reported zero water consumption. All these power plants were reported to be using a once-through cooling system or a cooling pond system, which consume a considerable quantity of water during their operation (Macknick et al., 2012). Hence, it can be concluded that there might be an underestimation of water consumption in the EIA database (EIA, 2015b).

Table 5.2 Comparison of the water consumption estimates for the United States; values are given in cubic kilometres

Data source	Min	Median	Max
EIA database (EIA, 2015b)	-	3.99	-
Diehl & Harris (2014)	4.5	-	4.8
This study	4.23	5.38	7.21

Future projections of the water demand depend on energy transition scenarios. Therefore, the comparison of the water demand estimates of future thermal power generation with other studies might not help for fully validating the obtained results.

6 Discussion

The primary objective of this study is to assess the water footprint of the power sector from the perspective of the amount of water used in power plants. The previous section provides the results of this analysis. Further discussion of the results shows the potential implications of the obtained results (Sections 6.1.1–6.1.3), their relevance to the Sustainable Development Goals (SDGs) (UN, 2015) (Section 6.1.4) and their limitations (Section 6.2). This chapter concludes with a brief outlook of future research, which highlights potential areas of interest for the doctoral candidate (Section 6.3).

6.1 General discussion of the results and their implications

6.1.1 Allocating water demand for water resource management

Due to climate change, the water supply is becoming more unreliable, more unpredictable and more scarce in many areas (UN Water, 2022). Water resource management (WRM) aims to mitigate water-related risks and eventually achieve water security in each country/region as well as globally (Aquatech, 2019). The spatial allocation of the actual water demand (in the context of this dissertation, of thermal power plants) to the sources of water supply and the assessment of the water use quantity are one of the most essential parts of WRM (Sheffield et al., 2018).

One of the main contributions of this work is the compilation of a database to fill in the existing information gap regarding the cooling technologies installed in individual thermal power plants worldwide. The database contains 13,864 rows (power plant units) and is freely available online as supplementary data to **Publication I**. In addition to the cooling technology information, the database also includes the exact location of the power plant units (geographical coordinates), which were identified along with the cooling technology data, and the estimated type of water used for cooling. Moreover, it presents estimates of yearly water consumption and water withdrawal for each power plant unit. The power plant data collected in this study can be widely deployed for WRM as a better understanding of each power plant’s water demand and source of water may prove beneficial for tackling the consequences of the current water crisis (OECD, 2015).

The river analysis conducted during work on **Publication I** provides an example of the allocation of the energy-related water demand to the corresponding sources of freshwater. While such studies for separate river basins exist (e.g. Sesma-Martín, 2019), in this study an analysis of the 354 main rivers around the world was performed. Moreover, the potential changes in the amount of water withdrawn from the rivers by thermal power plants during the time of the anticipated energy transition were projected.

In the example of the Danube River, it was demonstrated that by 2050, all water withdrawals associated with thermal power generation can be mitigated if the decarbonisation strategies of the optimal energy transition scenario are implemented.

Similar results were obtained for the other 353 rivers present in the analysis, which provides a clear benefit of the decarbonisation of the power sector for global rivers. This is especially crucial in light of recent events in the summer of 2022, when major European rivers (such as Po, Garonne, Rhône, and Rhine) were severely affected by drought, altering river transportation, agriculture and thermal power plants (Toreti et al., 2022). In the future, to provide a more comprehensive view on the energy-related water demand from rivers, studies should consider other forms of energy generation in addition to the thermal power plant-only allocation, such as hydropower plants.

A similar analysis with energy-related water demand allocation could also be performed for other geographical objects, for instance, major cities worldwide. Currently, the sustainable energy transition in major global cities is becoming a focus of research by many scientists around the world (Simoes et al., 2018; IRENA, 2021; Ram et al., 2022). Thus, an energy-related water demand analysis may provide yet another dimension to the discussion of the energy transition scenarios in major cities and of their sustainability.

6.1.2 New fossil power plants

Fossil-based electricity generation continues to grow in many regions of the world after its previous decline during the COVID-19 pandemic (Boehm et al., 2022). Despite countries' commitments to reduce carbon emissions in the power sector to tackle climate change (for instance, a recent report issued by China's Department of Resource Conservation and Environmental Protection (2021)), many of them continue to add more fossil-based capacities to their power generation profile. For instance, having already been the world's largest coal power plant fleet, China is expected to add another 270 GW of new coal capacity by 2025, which is reportedly larger than the entire coal power fleet of the United States (Cang, 2022). Another example is India, which plans to commission 58 GW of new coal capacities by 2030 (Shah, 2021). Additionally, after the start of the war in Ukraine, countries like Austria, Germany, Italy and the Netherlands have restarted inoperative coal-fired power plants to address the problem of the reduced gas supply from Russia (Morris, Westfall and Thebaut, 2022). These changes are projected to have a long-term effect on the power generation sector and its environmental impact (Boehm et al., 2022). In the context of this dissertation, this relates to the water footprint of the power sector, which may increase considerably if the above-mentioned plans for the commissioning of new fossil-based capacities are implemented.

The estimation of the future water footprint is a nontrivial task, since (1) many scenarios of the future energy transition fail to account for these planned future thermal power capacities, and (2) information regarding the planned thermal capacities is usually very limited. **Publication III** attempted to provide such an estimation using available information regarding the planned, announced and financed thermal power plants worldwide. The results estimated an increase in the water demand of the thermal power plant sector of up to 54% by 2050 compared to the 2020 level. However, since the presented results are exclusively based on currently available information in the GlobalData database (GlobalData Plc, 2020), which most probably does not include all power plants to be installed worldwide by 2050, these results should be interpreted as an optimistic scenario, but a more realistic one compared to the previous estimates, which were solely based on the energy transition scenarios and thus did not consider newly commissioned power plants (e.g., Terrapon-Pfaff et al., 2020).

Considering that information regarding the planned thermal capacities is very limited or is completely unavailable for researchers, the question is if it is still possible to draw concrete conclusions on future water use by the power sector and to give recommendations regarding it? In **Publication III**, this challenge was approached by introducing the water consumption criticality (WCC) matrix. The matrix highlights geographical regions (countries) that are potentially critical from the perspective of the availability of freshwater resources for energy-related freshwater consumption. The WCC matrix for 2020 is shown in Figure 6.1.

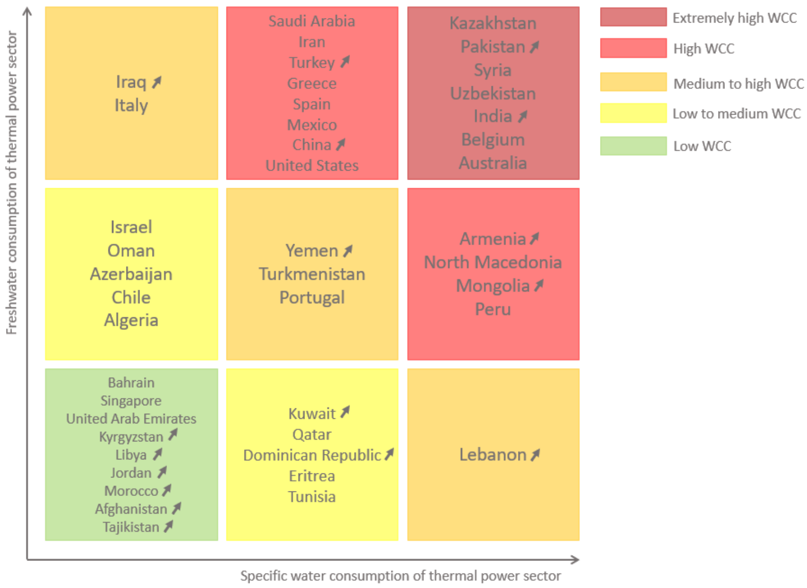

Figure 6.1 Water consumption criticality (WCC) matrix, modified from **Publication III**. The countries are positioned in descending order according to their water stress score (WRI, 2021). The arrows indicate that the freshwater consumption of the country's energy sector will increase by 2040, compared to the 2020 level, which is based on the available power plant data on the planned, announced and financed thermal power plants (GlobalData Plc, 2020).

The WCC matrix only includes nations that experience high or extremely high levels of water stress, indicating high competition for freshwater resources. Therefore, in all countries presented in the matrix, (1) the operation of additional thermal power capacities may be constrained due to already limited freshwater resources and/or (2) the installation of new thermal capacities may amplify the competition for water resources with other sectors of the economy (in other words, worsen the water stress situation). Thus, the future development of the thermal power sector in these countries should be monitored closely. However, among the countries characterised by high and extremely high WCC, the study highlighted three countries that are of the highest concern: Turkey, India and Pakistan. According to the GlobalData database (GlobalData Plc, 2020), the thermal power sectors of these countries are projected to increase by 130%, 84% and 61% by 2040, respectively, while the SWC is expected to grow as well. To address this concern, this study calls for a change in the water policies in these countries to (1) counteract the increase in thermal power capacities with more water-saving technologies (e.g. by using dry cooling) and/or to (2) ensure that the planned thermal capacities are installed in regions with abundant water resources (e.g., in coastal areas) or in areas characterised by low water stress.

A similar approach to assess the potential water criticality was used in the study of Holland et al. (2015), who identified critical geographical areas by plotting the estimated freshwater consumption of the power sector against first- and second-order scarcity. In the context of that study, the first-order scarcity represented a physical shortage of freshwater, whereas the second-order water scarcity reflected the impact of the physical shortage of water on society (including the Human Development Index (HDI) and child malnutrition). The results of that study highlighted certain areas of India, Pakistan, China and the United States as being critical in terms of having significant pressure on freshwater resources (first-order scarcity), and regions of India, Pakistan and sub-Saharan Africa were deemed critical in the context of the pressure of the physical shortage of freshwater on society (second-order scarcity). The results obtained in the study of Holland et al. (2015) for criticality related to first-order scarcity (which is close to the subject of this study) are somewhat similar to the findings of **Publication III**.

In previous studies (for example, in the abovementioned work of Holland et al. (2015)), the results of similar analyses were usually presented in the form of maps. As demonstrated over the course of this research, there are usually many factors that may influence the criticality of freshwater use. Presenting them on a map in the form of one variable (which combines several factors through weighting coefficients) may obscure the responsibility of individual factors for the final score and, thus, potentially influence their interpretation. In contrast, the WCC matrix enables interpretability of different aspects on the assessment of the criticality of the water demand in certain regions and presents the results in a simple way for convenient further use by researchers and, potentially, policy makers. In general, the WCC matrix could be applied to a smaller-scale analysis, for instance, for individual towns or provinces of the same country. In the future, other freshwater-demanding technologies could be added into the matrix, for example, hydropower generation.

6.1.3 Energy-related water footprint in the supply chain of products and services

Many companies around the world are seeking to reduce their GHG emissions throughout their operation (Morgan, 2019). Nowadays, it is not just a compliance issue when it comes to disclosing a company's supply chain carbon footprint. Reporting on the supply chain carbon footprint can help businesses earn the trust of their stakeholders and loyalty of their customers (Lapini and Farbstein, 2021).

But what about the company’s water footprint? In light of the current climate change, which makes water resource availability increasingly unreliable, many companies around the world are starting to realise that they need to manage their water-related risks by considering the water footprints of their upstream and downstream operations along with their carbon footprints (Water Footprint Network, 2021). Water shortages impose a direct risk on companies if there is not enough water available for factories and production (Chapagain and Orr, 2008). Indirect water risks include increased insurance prices, along with the political and social stability of countries with limited water supplies (Chapagain and Orr, 2008).

Electricity generation indirectly impacts the water footprint of the supply chains for various products and services that require electricity for their production. To investigate this potential indirect impact, a case study was conducted. **Publication IV** focused on the assessment of the water footprint of global cobalt production while considering the entire supply chain of cobalt (including mining and processing of cobalt and cobalt production and recycling stages).

The results of this demonstrated that the energy-related water consumption of the global cobalt production (indirect consumption that originates in the supply chain) is estimated at the level of 90.9% of the total water consumption of the cobalt supply chain, whereas the direct water consumption, which is related to the processing of cobalt at the plants, accounts for only 9.1%.

The key observation here is the expected high share of energy-related components in total water demand. This indicates that total water consumption can be considerably reduced through the transition towards an energy system based on low water-demanding renewable energy technologies (for instance, solar PV and wind). This hypothesis was tested in **Publication IV**, which demonstrated that a twofold decrease in STWD of both primary and secondary cobalt can be achieved by 2050 as a result of the energy transition.

This estimated considerable reduction of the water footprint throughout the supply chain of all products and services that require electricity can be considered a side benefit of the energy transition and should support its acceleration.

6.1.4 Sustainable Development Goals

This research not only combines aspects of different disciplines (energy technology, water footprint analysis and machine learning) but directs them towards the objective of meeting the environmental and climate targets imposed by the COP 21 Paris Agreement (United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, 2015). In addition, the main findings of the research correspond to two Sustainable Development Goals (SDGs) set up by the UN member states (UN, 2015):

SDG6: ‘Ensure availability and sustainable management of water and sanitation for all’.

- ➔ SDG6.4: ‘By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity’.

SDG7: ‘Ensure access to affordable, reliable, sustainable and modern energy for all’.

- ➔ SDG7.2: ‘By 2030, increase the share of renewable energy in the global energy mix substantially’.

In particular, some of the future projections of the water demand in this research were based on energy transition scenarios. For example, the ‘Best Policies’ scenario in **Publication I** and the ‘Area’ and ‘Regions’ scenarios in **Publication II** were developed based on the projections of the LUT Energy System Transition model (Child, Bogdanov and Breyer, 2018; Bogdanov et al., 2019; Child et al., 2019), which were reported to be fully consistent with the targets of the COP 21 Paris Agreement (UNFCCC Secretariat, 2015). The ‘Bloomberg NEF’ scenario in **Publication III** was based on the NEO Climate Scenario released by Bloomberg, which aims to ‘meet a well-below-two-degree emissions budget’ (Bloomberg NEF, 2020). It was demonstrated that by following these energy systems decarbonization strategies (SDG7.2), the water footprint associated with electricity generation can be reduced considerably in many parts of the world by 2050, compared to the current level. This may potentially ease the water stress in these regions, and, as a result, the corresponding saved water can be redistributed for other purposes, for instance, agricultural food production (SDG6.4).

Moreover, the findings of **Publications II** and **III** highlighted geographical areas where the sustainable use of freshwater may be compromised due to the considerable increase in freshwater demand by the power sector resulting from the projected energy transition. These results call for the consideration of the water footprint at the stage of the development of energy scenarios.

Therefore, the research addresses a broader community to advance an essential discourse on issues related to water and energy security and on the sustainable use of both.

6.2 Policy recommendations

Based on the results obtained over the course of this study, policy recommendations for freshwater resource conservation during the ongoing energy transition can be highlighted. The following recommendations were arranged into two groups: (1) for thermal power generation and (2) for the electricity generation mix.

Based on the above, numerous governmental reports, there is an understanding that more thermal power capacities will be introduced in the near future. Thus, the first group of policy recommendations concerns the future thermal power sector:

1. Transition from heavily water-demanding coal-based electricity generation to combined cycle gas power plants (which in the future could be converted to using synthetic fuels). This also includes coal power plants equipped with CCS systems since, as discussed previously in Section 3.8, the use of CCS considerably increases the water demand for power generation (Macknick et al., 2012).
2. Transition from the widespread use of freshwater and seawater for cooling to the use of reclaimed water.
3. Restrict the use of once-through cooling (due to numerous environmental concerns) and to transition to tower cooling or, more preferable, to dry cooling.
4. Ensure that newly built thermal power plants are in regions characterised by low water stress and/or have abundant water resources (for instance, seawater in coastal areas).

Recommendations for the future electricity generation mix:

1. Increase the shares of low water-demanding solar PV and wind, as well as to decrease the share of thermal power generation in the final generation mix.
2. Restrict the installation of new in-stream hydropower capacities in regions characterised by low water stress.

The above-mentioned recommendations are solely based on the water–energy nexus analysis from the perspective of water demand of the global power sector and may neither include other stakeholders (e.g., agriculture, other sectors of the economy) nor other considerations (such as the carbon footprint, land use and economic aspects, etc.). To address this concern, the water–energy nexus concept was expanded to the water–energy–food nexus (Muthu, 2021), water–energy–carbon nexus (Ghodrati et al., 2023), water–energy–land–food nexus (Venghaus et al., 2019), etc., which provide a more comprehensive view on the water resource conservation problem.

6.3 Limitations of the study

This dissertation discussed the water footprint of power plants from the perspective of the water demand for the power generation process. However, some water-related environmental aspects of power generation were left outside the scope of this study. For instance, warm water discharge from thermal power plants after the cooling process is one of the main concerns of researchers and environmentalists (Langenbrunner, 2020). Thermal pollution causes changes in the local ecosystems' conditions (World Nuclear Association, 2015) and affects the organisms that inhabit them (Madden, Lewis and Davis, 2013). Conducting research on the thermal pollution of power plants on the global level might add another dimension to the discussion of the environmental impact of global thermal power generation. However, the lack of water discharge data on the individual power plant level might impose an additional constraint for conducting such a study on the global level.

This study focused on the assessment of the direct water demand of power generation. This was done to couple the results of this analysis with the nearest water body (e.g. rivers and lakes) (as demonstrated in **Publication I**). However, in addition to the operational water use by power plants, many foreground and background processes of the energy production (e.g., extraction of fossil fuels and their treatment, production of power plant equipment or cultivation of biomass) are associated with considerable water extractions (the 'indirect water footprint'). Hence, it is acknowledged that more comprehensive and spatially explicit research is needed to couple the results of the current study with the water demand of the foreground and background processes of energy production in an LCA analysis. In this regard, however, an accurate allocation of the calculated water demand to water bodies may be challenging unless all lifecycle processes of power generation are located within the same geographical area. Some authors (e.g., Siddiqi and Anadon, 2011 and Wu et al. 2019) have already investigated the water demand for the selected local thermal power generation using LCA techniques. However, to our knowledge, such analysis does not yet exist on the global level, and this represents a knowledge gap.

In this study, the accuracy of the water demand estimates was determined via a comparison of the collected data (e.g., cooling technology and FLH) with the information provided in the available power plant databases. It is noteworthy that this assessment could also be conducted by computing energy balances for individual power plants using the estimates of the temperature increase in the heat exchanges of the cooling circuits and of the quantities of evaporated water. However, this method would require additional information on a per power plant-level, which was not available in this research.

6.4 Future research

The ongoing climate change makes water resources less available and water stress is projected to worsen worldwide in the upcoming decades (WRI, 2021). This is already reflected in water pricing worldwide: water becomes noticeably more expensive (Parry et al., 2007) as the adaptation costs for climate change impacts increase considerably (Caretta et al., 2022). However, as demonstrated over the course of this research, a large amount of freshwater is lost during the power generation process. At the same time, the water consumption of power plants is currently not regulated in many parts of the world, and power plant operators usually do not report on the amount of water used in the process of power generation (Schleifer and Luo, 2018). It is also not clear how and whether the water cost is included in the electricity price as an operational cost. In this regard, the following questions arise: Should power plant operators pay the full price for freshwater resources they are using, as do all other businesses and the population? Alternatively, should governments introduce a water tax to encourage a more sustainable use of freshwater (similarly to a carbon tax, which was introduced to incentivize businesses and industries to reduce their carbon emissions)? Finally, will such measures influence the choice of the cooling system type in thermal power plants, or will they affect the choice of the power generation technology, leading to a faster transition towards water-free renewable systems? In order to address these questions, a comprehensive review on the water-related economics of power generation is required—this will be the focus of future studies.

Another potential topic for future research is a water demand analysis of other energy technologies in order to expand the knowledge concerning water use in the energy sector. One of the potential topics is the production of hydrogen, as the global demand for hydrogen is estimated to ramp up eightfold by 2050 (IEA, 2019). In this regard, the production of hydrogen from water via an electrolysis process is projected to become a mainstream method of hydrogen production in the years to come. However, there is a growing concern that hydrogen production using electrolysis (particularly in such large quantities) will require a considerable amount of water. To address this, research must determine the hydrogen industry's future water consumption and to investigate its potential effects on water resource availability, particularly in areas with significant water stress. The data may be used for grouping of countries based on, for example, their hydrogen production and water stress, and this information could potentially be used for such purposes as policy planning.

One other potential topic for future work is the development of a GIS algorithm for power plant identification. In this study, the locations of power plants were manually identified using satellite imagery, which was highly time-consuming, whereas GIS tools were only used for coupling power plants with the closest water body. The question arises whether it is possible to identify the location of a power plant using thermal images of the Earth’s surface and whether based on the nature of thermal pollution it is possible to distinguish different cooling systems. Such an algorithm may also help researchers to find the exact location of large industrial centres, such as cement and steel plants, which may potentially reduce the time invested by researchers to manually identify them.

7 Conclusions

In this study, the water demand of the global power sector is estimated for the period spanning 2015–2050 in 5-year time intervals. The results demonstrate that the current global power generation system requires a considerable amount of water for its operation. In particular, in 2020, water consumption of the global power sector was estimated at the level of 88 cubic kilometres, of which about 20 cubic kilometres was consumed by thermal power plants.

Many scholars agree that future population growth, increased industrialization, and urbanization will further increase the global electricity demand (Intergovernmental Panel on Climate Change (IPCC), 2022). This implies that the water demand of the power generation sector will increase if no changes are introduced. Water scarcity, which is projected to worsen in the upcoming decades (WRI, 2021), puts into question the reliability of future electricity generation (Cullmann et al., 2022).

The results of **Publication I** showed that the water consumption of the global thermal power sector can be decreased by 98% by 2050 through the gradual decommissioning of the old thermal power plant fleet and its replacement with renewable energy. However, the analysis of the planned and announced power plants worldwide in **Publication III** revealed that the water demand of the global power sector will continue to grow in the future (according to all scenarios considered in the study). Nevertheless, it was demonstrated that due to the anticipated future energy transition, the water demand of the power sector may grow considerably more slowly than the size of the power sector itself: The projected 170% growth in the electricity installed generation capacity during 2019-2050 may result in an increase in the corresponding water demand for power generation of just 20%. This finding provides a strong case for the acceleration of the transition to energy systems that rely heavily on, or consist entirely of, ‘low water’ renewable energy technologies such as wind and solar.

The high water demand of the power sector estimated in this study influences the water footprint of all services and products that require electricity for their manufacturing. As demonstrated in this dissertation, about 91% of the total amount of water used in the global production of cobalt (**Publication IV**) is associated with the water demand of the power sector. Moreover, the results of **Publication IV** show that the water footprint of the production of one kilogram of cobalt can be considerably reduced in the future if energy generation transitions to renewable sources. Therefore, the results of **Publication IV** provide yet another argument for the replacement of high water-demanding thermal power plants with solar PV and wind systems, which demand a negligible amount of water for their operation.

The findings of **Publications II** and **III**, however, revealed that for some countries, which experience high and extremely high water stress, the projected increase in the water demand for power generation may impose additional stress on the already limited water resources and, consequently, it may escalate the competition for water resources with other crucial sectors of the economy, such as agriculture. **Publication III** introduces the WCC matrix, which may prove to be relevant for policy makers as it displays geographical areas (countries) that may be potentially critical in terms of the water resource availability for energy-related water demand.

References

Aquatech (2019) *Water Resource Management: Essential guide to water resource management. Objectives, policy & strategies*. Available at: https://www.aquatechtrade.com/news/water-treatment/water-resource-management-essential-guide/.

Azevedo Rocha, P. and Mathis, W. (2022) 'European Power Hits Record as Extreme Heat, Drought Parch Europe,' *Bloomberg*. Available at: https://www.bloomberg.com/news/articles/2022-08-02/german-power-prices-hit-fresh-record-as-consumer-costs-mount.

Bamana, G. et al. (2021) 'Addressing the social life cycle inventory analysis data gap: Insights from a case study of cobalt mining in the Democratic Republic of the Congo,' *One Earth*, 4(12), pp. 1704–1714. doi: https://doi.org/10.1016/j.oneear.2021.11.007.

Behrens, P. et al. (2017) 'Climate change and the vulnerability of electricity generation to water stress in the European Union,' *Nature Energy*, 2, p. 17114. doi: 10.1038/nenergy.2017.114.

Biesheuvel, A. et al. (2016) *Methods and Results Report: Modelling Global Water Demand for Coal Based Power Generation*. Available at: http://www.greenpeace.org/international/Global/international/briefings/climate/2016/Coal-Water/Technical-Report-Coal-Water-Methods-Results.pdf.

Bloemkolk, J. W. and van der Schaaf, R. J. (1996) 'Design alternatives for the use of cooling water in the process industry: Minimization of the environmental impact from cooling systems,' *Journal of Cleaner Production*, 4(1), pp. 21–27. doi: https://doi.org/10.1016/S0959-6526(96)00022-4.

Bloomberg New Energy Finance (Bloomberg NEF) (2020) *New energy outlook 2020*. New York, NY, USA. Available at: https://about.bnef.com/new-energy-outlook/.

Boehm, S. et al. (2022) *State of Climate Action 2022*. Berlin and Cologne, Germany, San Francisco, CA, and Washington, DC. doi: 10.46830/wrirpt.22.00028.

Bogdanov, D. et al. (2019) 'Radical transformation pathway towards sustainable electricity via evolutionary steps,' *Nature Communications*, 10(1), p. 1077. doi: 10.1038/s41467-019-08855-1.

Boretti, A. and Rosa, L. (2019) 'Reassessing the projections of the World Water Development Report,' *NPJ Clean Water*, 2(1), p. 15. doi: 10.1038/s41545-019-0039-9.

Burek, P. et al. (2016) *Water futures and solution: fast track initiative (final report), International Institute for Applied Systems Analysis*. Laxenburg, Austria. Available at: https://pure.iiasa.ac.at/id/eprint/13008/.

California Energy Commission and Electric Power Research Institute (EPRI) (2002) *Comparison of Alternate Cooling Technologies for California Power Plants. Economic, Environmental and Other Tradeoffs*. Palo Alto, California, USA. Available at: https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1167.pdf (Accessed: December 18, 2021).

Campbell, G. A. (2020) 'The cobalt market revisited,' *Mineral Economics*, 33(1), pp. 21–28. doi: 10.1007/s13563-019-00173-8.

Cang, A. (2022) 'China Climate Advisers Say More Coal Needed for Energy Security,' *Bloomberg*. Available at: https://www.bloomberg.com/news/articles/2022-11-15/china-climate-advisers-say-more-coal-needed-for-energy-security.

Caretta, M. A. et al. (2022) 'Water. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,' in Pörtner, H.-O. et al. (eds.) *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Cambridge, UK and New York, NY, USA: Cambridge University Press, pp. 551–712. doi: 10.1017/9781009325844.006.

Chapagain, A. and Orr, S. (2008) *UK Water Footprint: the impact of the UK's food and fibre consumption on global water resources Volume one*, *WWF-UK*. Godalming. Available at: http://assets.wwf.org.uk/downloads/water_footprint_uk.pdf.

Child, M. et al. (2019) 'Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe,' *Renewable Energy*, 139, pp. 80–101. doi: 10.1016/J.RENENE.2019.02.077.

Child, M., Bogdanov, D. and Breyer, C. (2018) 'The role of storage technologies for the transition to a 100% renewable energy system in Europe,' *Energy Procedia*, 155, pp. 44–60. doi: 10.1016/J.EGYPRO.2018.11.067.

Cuff, M. (2022) 'Extreme drought in 2022 exposed fragility of Europe's energy system,' *NewScienist*. Available at: https://www.newscientist.com/article/mg25634175-800-extreme-drought-in-2022-exposed-fragility-of-europes-energy-system/.

Cullmann, J. et al. (2022) *2022 State of Climate Services: Energy*. Geneva, Switzerland. Available at: https://library.wmo.int/doc_num.php?explnum_id=11340.

Davies, E. G. R., Kyle, P. and Edmonds, J. A. (2013) 'An integrated assessment of global and regional water demands for electricity generation to 2095,' *Advances in Water Resources*, 52, pp. 296–313. doi: 10.1016/J.ADVWATRES.2012.11.020.

Department for Business Energy & Industrial Strategy of UK (2021) *Digest of UK Energy Statistics (DUKES): electricity*. Available at: https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes (Accessed: December 18, 2021).

Department of Resource Conservation and Environmental Protection of People's Republic of China (2021) *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy*. Beijing. Available at: https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html.

Diehl, T. H. et al. (2013) *Methods for Estimating Water Consumption for Thermoelectric Power Plants in the United States*. doi: http://dx.doi.org/10.3133/sir20135188.

Diehl, T. H. and Harris, M. A. (2014) *Withdrawal and consumption of water by thermoelectric power plants in the United States, 2010*. Reston, VA, United States. doi: 10.3133/sir20145184.

EcoFys BV (2014) *Pilot project on availability, use and sustainability of water production of nuclear and fossil energy. Geo-localised inventory of water use in cooling processes, assessment of vulnerability and of water use management measures*. Utrecht, Netherlands. Available at: https://ec.europa.eu/environment/archives/water/adaptation/pdf/InventoryCoolingWaterUse.pdf.

EIA U.S. Energy Information Administration (2015a) *Form EIA-860 detailed data with previous form data (EIA-860A/860B)*. Available at: https://www.eia.gov/electricity/data/eia860/ (Accessed: June 29, 2019).

EIA U.S. Energy Information Administration (2015b) *Form EIA-923 detailed data with previous form data (EIA-906/920)*. Available at: https://www.eia.gov/electricity/data/eia923/ (Accessed: June 29, 2019).

Enerdata (2020) *Power Plant Tracker*. Grenoble, France. Available at: https://www.enerdata.net/research/power-plant-database.html (Accessed: December 18, 2021).

European Climate Adaptation Platform (2019) *Reducing water consumption for cooling of thermal generation plants - Adaptation option*. Available at: https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/reducing-water-consumption-for-cooling-of-thermal-generation-plants.

European Commission and Directorate-General for Internal Market; Industry; Entrepreneurship and SMEs (2017) *Study on the review of the list of critical raw materials : final report*. Publications Office. doi: doi/10.2873/876644.

European Environment Agency (EEA) (1991) *Environment in the European Union at the turn of the century. Environmental assessment report No 2*, *EEA Glossary*. Copenhagen. Available at: http://glossary.eea.europa.eu/EEAGlossary.

European Environment Agency (EEA) (2004) *Environmental impact of energy*, *EEA Glossary*.

European Network of Transmission System Operators for Electricity (ENTSO-E) (2022) *Transparency Platform*. Available at: https://transparency.entsoe.eu/ (Accessed: December 18, 2021).

Eurostat (2014) *Water use in industry*. Luxembourg. Available at: http://ec.europa.eu/eurostat/statisticsexplained/%0Aindex.php/Water_use_in_industry.

Farfan, J. and Breyer, C. (2017a) 'Aging of European power plant infrastructure as an opportunity to evolve towards sustainability,' *International Journal of Hydrogen Energy*, 42(28), pp. 18081–18091. doi: 10.1016/j.ijhydene.2016.12.138.

Farfan, J. and Breyer, C. (2017b) 'Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator,' *Journal of Cleaner Production*, pp. 370–384. doi: 10.1016/j.jclepro.2016.09.068.

Feeley, T. J. et al. (2008) 'Water: A critical resource in the thermoelectric power industry,' *Energy*, 33(1), pp. 1–11. doi: 10.1016/j.energy.2007.08.007.

Ferron, C. J. (2016) 'The Recycling of Cobalt from Alloy Scrap, Spent Batteries or Catalysts and Metallurgical Residues — an Overview BT - Ni-Co 2013,' in Battle, T. et al. (eds.). Cham: Springer International Publishing, pp. 53–71. doi: 10.1007/978-3-319-48147-0_3.

Firmansyah, I. and Prabowo (2022) 'The Effect of Inlet Air Cooling to Power Output Enhancement of Gas Turbine BT - Recent Advances in Renewable Energy Systems,' in Kolhe, M. et al. (eds.). Singapore: Springer Nature Singapore, pp. 241–248.

Fleischli, S. and Hayat, B. (2014) *Power Plant Cooling and Associated Impacts: The Need to Modernize U.S. Power Plants and Protect Our Water Resources and Aquatic Ecosystems*. New York, NY, USA. Available at: https://assets.nrdc.org/sites/default/files/power-plant-cooling-IB.pdf.

Food and Agriculture Organization of the United Nations (FAO) (2021) *AQUASTAT Main Database*. Available at: http://www.fao.org/aquastat/statistics/query/index.html;jsessionid=6C067D308754D4DA7FEF0D86786A4BAB (Accessed: October 5, 2021).

Food and Agriculture Organization of the United Nations (FAO) and UN-Water (2018) *Progress on Level of Water Stress Global baseline for SDG indicator 6.4.2*. Rome. Available at: https://www.unwater.org/sites/default/files/app/uploads/2019/06/SDG6_Indicator_Report_642_Progress-on-Level-of-Water-Stress_2018_ENGLISH_LR.pdf.pdf.

G. Simoes, S. et al. (2018) 'INSMART – Insights on integrated modelling of EU cities energy system transition,' *Energy Strategy Reviews*, 20, pp. 150–155. doi:

https://doi.org/10.1016/j.esr.2018.02.003.

Ganguli, P., Kumar, D. and Ganguly, A. R. (2017) 'US Power Production at Risk from Water Stress in a Changing Climate,' *Scientific Reports*, 7(1). doi: 10.1038/s41598-017-12133-9.

Gerlach, A. et al. (2015) 'Latest Developments in Global Installed Photovoltaic Capacity and Hidden Growth Markets,' in. Hamburg: 31st EU PVSEC, pp. 1–12. doi: 10.4229/31stEUPVSEC2015-7DO.5.2.

Gerlach, E. and Franceys, R. (2010) 'Regulating Water Services for All in Developing Economies,' *World Development*, 38(9), pp. 1229–1240. doi: https://doi.org/10.1016/j.worlddev.2010.02.006.

Ghodrati, S. et al. (2023) 'Assessing the water–energy–carbon nexus (WECN) in combined cycle power plants in Iran,' *International journal of environmental science and technology (Tehran)*. doi: 10.1007/s13762-022-04749-w.

Global Energy Observatory et al. (2019) *Resource Watch*, *Published on Resource Watch (http://resourcewatch.org/) and Google Earth Engine (https://earthengine.google.com/)*. Available at: www.resourcewatch.org (Accessed: January 18, 2022).

Global Energy Observatory (GEO) (2018) *Power plants database*. New Mexico. Available at: http://globalenergyobservatory.org/ (Accessed: December 18, 2021).

GlobalData Plc (2014) *GlobalData Power plant database*. London. Available at: https://www.globaldata.com/ (Accessed: May 2, 2016).

GlobalData Plc (2020) *GlobalData Power plant database*. London. Available at: https://www.globaldata.com/ (Accessed: May 10, 2021).

GlobalPetrolPrices (2020) *Electricity prices*. Available at: https://www.globalpetrolprices.com/electricity_prices/ (Accessed: January 20, 2021).

Graedel, T. E. and Miatto, A. (2022) 'U.S. Cobalt: A Cycle of Diverse and Important Uses,' *Resources, Conservation and Recycling*, 184, p. 106441. doi: https://doi.org/10.1016/j.resconrec.2022.106441.

Green Initiatives (2021) *What are the Most Extracted Natural Resources on Our Planet?* Available at: https://greeninitiatives.cn/what-are-the-most-extracted-natural-resources-on-our-planet/.

Hastie, T., Tibshirani, R. and Friedman, J. H. (2009) *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. Springer (Springer series in statistics). Available at: https://books.google.fi/books?id=eBSgoAEACAAJ.

Helerea, E., Calin, M. D. and Musuroi, C. (2023) ‘Water Energy Nexus and Energy Transition—A Review,’ *Energies*. doi: 10.3390/en16041879.

Hofste, R. et al. (2019) *Aqueduct 3.0: Updated DecisionRelevant Global Water Risk Indicators. Technical Note*. Washington, DC, USA. Available at: https://www.wri.org/publication/aqueduct-30.

Hofste, R. W., Reig, P. and Schleifer, L. (2019) *17 Countries, Home to One-Quarter of the World’s Population, Face Extremely High Water Stress*, *Water Resources Institute (WRI)*. Available at: https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress.

Holland, R. A. et al. (2015) ‘Global impacts of energy demand on the freshwater resources of nations,’ *Proceedings of the National Academy of Sciences*, 112(48), pp. E6707–E6716. doi: 10.1073/pnas.1507701112.

Hosseiny, S. H., Bozorg-Haddad, O. and Bocchiola, D. (2021) ‘9 - Water, culture, civilization, and history,’ in Bozorg-Haddad Political, and Social Issues in Water Resources, O. B. T.-E. (ed.). Elsevier, pp. 189–216. doi: https://doi.org/10.1016/B978-0-323-90567-1.00010-3.

IEA (International Energy Agency) (2016) ‘Water Energy Nexus- Excerpt from the World Energy Outlook 2016,’ *International Energy Agency*, p. 60. doi: 10.1021/es903811p.

Institute for Global Environmental Strategies (IGES) (2015) *WEPA Outlook on Water Environmental Management in Asia*. Kanagawa, Japan. Available at: http://wepa-db.net/pdf/2015outlook/WEPA_Outlook2015_english.pdf.

Intergovernmental Panel on Climate Change (IPCC) (2022) *Climate change 2022: Impacts, adaptation and vulnerability*. Edited by H.-O. Pörtner et al. Cambridge, UK and New York, NY, USA: Cambridge University Press: doi: 10.1017/9781009325844.

Intermational Energy Agency (2018) *Statistics. Global energy data at your fingertips*.

International Energy Agency (IEA) (2019) *The Future of Hydrogen. Seizing today’s opportunities. Report prepared by the IEA for the G20, Japan*. Paris. Available at: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

International Energy Agency (IEA) (2022) *World Energy Outlook 2022*. Paris. Available at: https://www.iea.org/reports/world-energy-outlook-2022.

International Energy Agency (IEA) (2023) *Electricity Market Report 2023*. Paris. Available at: https://www.iea.org/reports/electricity-market-report-2023.

International Renewable Energy Agency (IRENA) (2015) ‘Renewable Energy Capacity Statistics 2015,’ *Irena*. Abu Dhabi, p. 44. doi: 10.1016/j.renene.2014.09.059.

International Renewable Energy Agency (IRENA) (2018) *Global Energy Transformation: A Roadmap to 2050, /publications/2018/Apr/Global-Energy-Transition-A-Roadmap-to-2050*. doi: Doi 10.1002/(Sici)1097-0029(19990915)46:6<398::Aid-Jemt8>3.0.Co;2-H.

International Renewable Energy Agency (IRENA) (2021) *Renewable Energy Policies for Cities: Experiences in China, Uganda and Costa Rica*. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Policies_for_Cities_2021-V2.pdf?rev=1c2888850c50435684db0d328fa3b036.

International Renewable Energy Agency (IRENA) (2022) *Renewable Energy Statistics 2022*. Abu Dhabi. Available at: https://www.irena.org/publications/2022/Jul/Renewable-Energy-Statistics-2022.

Jones, D. et al. (2023) *European Electricity Review 2023*. London. Available at: https://ember-climate.org/app/uploads/2023/01/Report-European-Electricity-Review-2023.pdf.

Kenny, J. F. et al. (2009) *Estimated Use of Water in the United States in 2005 Circular 1344*, *Water*. doi: http://dx.doi.org/10.3133/cir1405.

Khalili, S. and Breyer, C. (2022) ‘Review on 100% Renewable Energy System Analyses—A Bibliometric Perspective,’ *IEEE Access*, 10, pp. 125792–125834. doi: 10.1109/ACCESS.2022.3221155.

Khushaba, R. N., Al-Ani, A. and Al-Jumaily, A. (2011) ‘Feature subset selection using differential evolution and a statistical repair mechanism,’ *Expert Systems with Applications*, 38(9), pp. 11515–11526. doi: https://doi.org/10.1016/j.eswa.2011.03.028.

Kubat, M. (2017) ‘Similarities: Nearest-Neighbour Classifiers,’ in *An Introduction to Machine Learning*. Cham: Springer International Publishing, pp. 43–64. doi: 10.1007/978-3-319-63913-0_3.

Kummu, M. et al. (2016) ‘The world’s road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability,’ *Scientific Reports*, 6(1), p. 38495. doi: 10.1038/srep38495.

Langenbrunner, B. (2020) ‘Power plants warm rivers,’ *Nature Climate Change*, 10(10), p. 888. doi: 10.1038/s41558-020-00928-0.

Lapini, S. and Farbstein, E. (2021) *Why your value chain’s carbon footprint matters*, *Normative*. Available at: https://normative.io/insight/calculate-supply-chain-carbon-footprint/.

Larsen, M. A. D. et al. (2019) 'Challenges of data availability: Analysing the water–energy nexus in electricity generation,' *Energy Strategy Reviews*, 26, p. 100426. doi: https://doi.org/10.1016/j.esr.2019.100426.

Larsen, M. A. D. and Drews, M. (2019) 'Water use in electricity generation for water–energy nexus analyses: The European case,' *Science of The Total Environment*, 651, pp. 2044–2058. doi: https://doi.org/10.1016/j.scitotenv.2018.10.045.

Lee, G. et al. (2018) 'Preliminary study on the effect of dry/wet cooling combinations for the sustainable management of water of cooling tower,' *International Journal of Low-Carbon Technologies*, 13(1), pp. 61–66. doi: 10.1093/ijlct/ctx020.

Lehner, B. et al. (2011) 'High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management,' *Frontiers in Ecology and the Environment*, pp. 494–502. doi: 10.1890/100125.

Liao, X. and Hall, J. W. (2018) 'Drivers of water use in China's electric power sector from 2000 to 2015,' *Environmental Research Letters*, 13(9), p. 094010. doi: 10.1088/1748-9326/aada3a.

Liao, X. W. et al. (2021) 'Water shortage risks for China's coal power plants under climate change,' *Environmental Research Letters*, 16(4), p. 044011. doi: 10.1088/1748-9326/abba52.

Lohrmann, A. et al. (2019) 'Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery,' *Nature Energy*, 4(12), pp. 1040–1048. doi: 10.1038/s41560-019-0501-4.

Lohrmann, A., Lohrmann, C. and Luukka, P. (2021) 'A region-based approach for missing value imputation of cooling technologies for the global thermal power plant fleet using a decision tree classifier,' in Luukka, P. and Stoklasa, J. (eds.) *Intelligent Systems and Applications in Business and Finance*. Cham, Switzerland: Springer Nature Switzerland AG.

Lohrmann, A., Lohrmann, C. and Luukka, P. (2022a) 'A Region-Based Approach for Missing Value Imputation of Cooling Technologies for the Global Thermal Power Plant Fleet Using a Decision Tree Classifier BT - Intelligent Systems and Applications in Business and Finance,' in Luukka, P. and Stoklasa, J. (eds.). Cham: Springer International Publishing, pp. 93–125. doi: 10.1007/978-3-030-93699-0_5.

Lohrmann, A., Lohrmann, C. and Luukka, P. (2022b) 'Global and regional models for identification of cooling technology in thermal power generation for water demand estimations in water–energy nexus studies,' *Journal of Cleaner Production*, 380, p. 134842. doi: 10.1016/J.JCLEPRO.2022.134842.

Luo, T., Krishnaswami, A. and Li, X. (2018) *A mehodology to estimate water demand for thermal power plants in data-scarce regions using satellite images. Technical note.* Washington, DC. Available at: www.wri.org/publication/water-power-methodology.

Macknick, J. et al. (2012) 'Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature,' *Environmental Research Letters*, 7(4). doi: 10.1088/1748-9326/7/4/045802.

Madden, N., Lewis, A. and Davis, M. (2013) 'Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature,' *Environmental Research Letters*, 8(3), p. 035006. doi: 10.1088/1748-9326/8/3/035006.

Maulbetsch, J. and Stallings, J. (2012) 'Evaluating the Economics of Alternative Cooling Technologies.,' *Power Engineering*, 116(11), pp. 120–128.

Maupin, M. A. et al. (2014) *Estimated use of water in the United States in 2010, U.S. Geological Survey Circular 1405*. doi: 10.3133/cir1405.

Mekonnen, M. M. and Hoekstra, A. Y. (2016) 'Four billion people facing severe water scarcity,' *Science Advances*, 2(2), p. e1500323. doi: 10.1126/sciadv.1500323.

Mertens, J. et al. (2015) 'Water footprinting of electricity generated by combined cycle gas turbines using different cooling technologies: a practitioner's experience,' *Journal of Cleaner Production*, 86, pp. 201–208. doi: https://doi.org/10.1016/j.jclepro.2014.08.046.

Morgan, B. (2019) *101 Companies Committed To Reducing Their Carbon Footprint, Forbes*. Available at: https://www.forbes.com/sites/blakemorgan/2019/08/26/101-companies-committed-to-reducing-their-carbon-footprint/?sh=73258b2c260b.

Morris, L., Westfall, S. and Thebaut, R. (2022) 'Russia's chokehold over gas could send Europe back to coal,' *Washington Post*. Available at: https://www.washingtonpost.com/world/2022/06/22/coal-plant-europe-germany-austria-netherlands-russia-gas/.

Muthu, S. S. (2021) *The water–energy-food nexus : concept and assessments* . 1st ed. 2021. Gateway East, Singapore: Springer (Environmental Footprints and Eco-design of Products and Processes). doi: 10.1007/978-981-16-0239-9.

Open Power System Data and (Primary data from various sources: for a complete list see URL) (2020) 'Data Package Conventional power plants. Version 2020-10-01.' Berlin. Available at: https://doi.org/10.25832/conventional_power_plants/2020-10-01 (Accessed: December 18, 2021).

Organisation for Economic Co-operation and Development (OECD) (2015) *Water Resources Allocation: Sharing Risks and Opportunities*. Paris: OECD (OECD Studies on Water). doi: 10.1787/9789264229631-en.

Organisation for Economic Co-operation and Development (OECD) (2021) *Water risks, disasters and climate change*, *OECD Water*. Available at: https://www.oecd.org/water/risks-disasters-and-climate-change.htm.

Parry, M. L. et al. (2007) *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Geneva, Switzerland. Available at: https://archive.ipcc.ch/publications_and_data/ar4/wg2/en/ch3s3-5-1.html.

Qadrdan, M. et al. (2019) 'Electricity systems capacity expansion under cooling water availability constraints,' *IET Energy Systems Integration*, 1(1), pp. 23–33. doi: https://doi.org/10.1049/iet-esi.2018.0024.

Ram, M. et al. (2022) 'Energy transition in megacities towards 100% renewable energy: A case for Delhi,' *Renewable Energy*, 195, pp. 578–589. doi: https://doi.org/10.1016/j.renene.2022.06.073.

Rio Carrillo, A. M. and Frei, C. (2009) 'Water: A key resource in energy production,' *Energy Policy*, 37(11), pp. 4303–4312. doi: https://doi.org/10.1016/j.enpol.2009.05.074.

Roehrkasten, S., Schaeuble, D. and Helgenberger, S. (2015) 'Secure and sustainable power generation in a water-constrained world,' in. Potsdam: Institute for Advanced Sustainability Studies (IASS). Available at: , Secure and Sustainable Power Generation in a Water-Constrained World.

Roidt, M. et al. (2020) 'Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe,' *Cite This: Environ. Sci. Technol. Lett*, 7, pp. 683–689. doi: 10.1021/acs.estlett.0c00381.

S&P Global (2016) *Platts World Electric Power Plants Database*. Washington. Available at: http://www.platts.com/products/world-electric-power-plants-database (Accessed: May 10, 2021).

Sadovskaia, K. et al. (2019) 'Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally,' *International Journal of Electrical Power & Energy Systems*, 107, pp. 98–109. doi: 10.1016/J.IJEPES.2018.11.012.

Santos, A. P. and Andrade, C. R. (2012) 'Analysis of Gas Turbine Performance with Inlet Air Cooling Techniques Applied to Brazilian Sites,' *Journal of Aerospace Technology and Management*. scielo .

Saudi Arabian Oil Company (2021) *Saudi ARAMCO Power Plant - Turbine Inlet Air Cooling. Case Study*. Dubai, United Arab Emirates. Available at: https://content.araner.com/aramco-case-study.

Schleifer, L. and Luo, T. (2018) *Power Plants Use Water, But We Have No Idea How*

Much, *World Resources Institute*. Available at: https://www.wri.org/insights/power-plants-use-water-we-have-no-idea-how-much.

Schulte, P. and Morrison, J. (2014) *Driving harmonization of water-related terminology. Discussion Paper, CEO Water Mandate*. Oakland, CA. Available at: https://ceowatermandate.org/wp-content/uploads/2019/11/terminology.pdf.

Sesma-Martín, D. (2019) 'The River's Light: Water Needs for Thermoelectric Power Generation in the Ebro River Basin, 1969–2015,' *Water*, 11(3), p. 441. doi: 10.3390/w11030441.

Sesma Martín, D. and Rubio-Varas, M. del M. (2017) 'Freshwater for Cooling Needs: A Long-Run Approach to the Nuclear Water Footprint in Spain,' *Ecological Economics*, 140, pp. 146–156. doi: https://doi.org/10.1016/j.ecolecon.2017.04.032.

Shah, K. (2021) *New coal-fired power plants in India: Reality or just numbers?* Lakewood, OH. Available at: https://ieefa.org/resources/new-coal-fired-power-plants-india-reality-or-just-numbers.

Sheffield, J. et al. (2018) 'Satellite Remote Sensing for Water Resources Management: Potential for Supporting Sustainable Development in Data-Poor Regions,' *Water Resources Research*, 54(12), pp. 9724–9758. doi: 10.1029/2017WR022437.

Siddiqi, A. and Anadon, L. D. (2011) 'The water–energy nexus in Middle East and North Africa,' *Energy Policy*, 39(8), pp. 4529–4540. doi: 10.1016/j.enpol.2011.04.023.

Spang, E. S. et al. (2014) 'The water consumption of energy production: An international comparison,' *Environmental Research Letters*, 9(10). doi: 10.1088/1748-9326/9/10/105002.

Srinivasan, S. et al. (2018) 'Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation,' *Applied Energy*, 210, pp. 673–684. doi: https://doi.org/10.1016/j.apenergy.2017.04.079.

Takeda, S. et al. (2022) 'Satellite Data Applications for Sustainable Energy Transitions,' *Frontiers in Sustainability | www.frontiersin.org*, 3, p. 910924. doi: 10.3389/frsus.2022.910924.

Terrapon-Pfaff, J. C. et al. (2020) 'Water Demand Scenarios for Electricity Generation at the Global and Regional Levels,' *Water*, 12(9). doi: 10.3390/w12092482.

The Federation of Electric Power Companies of Japan (2015) *Principal Thermal Power Plants (1,500MW or greater)*. Available at: https://www.fepc.or.jp/english/energy_electricity/location/thermal/index.html (Accessed: December 18, 2021).

Tkaczyk, A. H. et al. (2018) 'Sustainability evaluation of essential critical raw materials: cobalt, niobium, tungsten and rare earth elements,' *Journal of Physics D: Applied Physics*, 51(20), p. 203001. doi: 10.1088/1361-6463/aaba99.

Toreti, A. et al. (2022) *Drought in Europe August 202*. Luxembourg. doi: 10.2760/264241.

Tsou, J. L. and Maulbetsch, J. (2013) *Power Plant Cooling System Overview for Researchers and Technology Developers*. Palo Alto, CA. Available at: http://www.mcilvainecompany.com/Decision_Tree/subscriber/Tree/DescriptionTextLinks/EPRIoverview.pdf.

U.S. Energy Information Administration (EIA) and U.S. Department of Energy (2021) *International energy outlook 2021*. Washington, DC, USA. Available at: https://www.eia.gov/outlooks/ieo/pdf/IEO2021_Narrative.pdf.

United Nations (2015) *Sustainable Development Goals*. Available at: https://sdgs.un.org/goals (Accessed: March 22, 2021).

United Nations (UN) Water (2022) *Water and Climate Change*. Available at: https://www.unwater.org/water-facts/water-and-climate-change.

United Nations Educational Scientific and Cultural Organization (UNESCO) (2019) *The United NationsWorld Water Development Report 2019: Leaving No One Behind*. Paris. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000367306/PDF/367306eng.pdf.multi.

United Nations Educational Scientific and Cultural Organization (UNESCO) (2022) *The United Nations World Water Development Report 2022: Groundwater: Making the invisible visible*. Paris. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000380721.

United Nations Environment Programme (UNEP) (2002) *Vital Water Graphics. An Overview of the State of the World's Fresh and Marine Waters*. Nairobi, Kenya. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/20624/Vital_water_graphics.pdf?sequence=1&amp%3BisAllowed=.

United Nations Environment Programme International Resource Panel (UNEP) (2015) *Options for decoupling economic growth from water use and water pollution. Report of the International Resource Panel Working Group on Sustainable Water Management*. Nairobi, Kenya. Available at: https://wedocs.unep.org/20.500.11822/7539.

United Nations Framework Convention on Climate Change (UNFCCC) Secretariat (2015) *Adoption of the Paris Agreement. Proposal by the President, Paris Climate Change Conference - November 2015, COP 21*. Paris. doi: FCCC/CP/2015/L.9/Rev.1.

Vandecasteele, I. et al. (2016) *An analysis of water consumption in Europe's energy production sector: The potential impact of the EU Energy Reference Scenario 2013 (LUISA configuration 2014)*. Luxembourg. doi: 10.2791/90068.

Vassolo, S. and Döll, P. (2005) 'Global-scale gridded estimates of thermoelectric power and manufacturing water use,' *Water Resources Research*, 41(4), pp. 1–11. doi: 10.1029/2004WR003360.

Venghaus, S. et al. (2019) 'Linking Environmental Policy Integration and the Water–energy-Land-(Food-)Nexus: A Review of the European Union's Energy, Water, and Agricultural Policies,' *Energies (Basel)*, 12(23), p. 4446. doi: 10.3390/en12234446.

Wang, H. and Guohua He, | (2022) 'Rivers: Linking nature, life, and civilization.' doi: 10.1002/rvr2.7.

Water Footprint Network (2021) *Business water footprint*. Available at: https://waterfootprint.org/en/water-footprint/business-water-footprint/.

Water Footprint Network (2022) *What is a water footprint?* Available at: https://waterfootprint.org/en/water-footprint/what-is-water-footprint/.

Water Resources Institute (WRI) (2021) *AQUEDUCT Water Risk Atlas*. Washington DC. Available at: https://www.wri.org/applications/aqueduct/water-risk-atlas (Accessed: March 18, 2020).

Wessel, P. and Smith, W. H. F. (1996) 'A global, self-consistent, hierarchical, high-resolution shoreline database,' *Journal of Geophysical Research: Solid Earth*, 101(B4), pp. 8741–8743. doi: 10.1029/96JB00104.

Williams, E. D. and Simmons, J. E. (2013) *Water in the energy industry. An introduction.* Available at: www.bp.com/energysustainabilitychallenge.

World Economic Forum (WEF) (2020) *The Global Risks Report 2020. 15th Edition*. Cologny, Switzerland. Available at: http://www3.weforum.org/docs/WEF_Global_Risk_Report_2020.pdf.

World Health Organization (WHO) (2018) *A global overview of national regulations and standards for drinking- water quality*. Geneva, Switzerland. Available at: https://apps.who.int/iris/rest/bitstreams/1135599/retrieve.

World Nuclear Association (2015) *Cooling Power Plants*. Available at: http://www.world-nuclear.org/information-library/current-and-future-generation/cooling-power-plants.aspx (Accessed: November 1, 2017).

World Nuclear Association (2023) *Is the Cooling of Power Plants a Constraint on the Future of Nuclear Power?* Available at: https://world-nuclear.org/our-association/publications/technical-positions/cooling-of-power-plants.aspx.

World Wide Fund for Nature (WWF) (2023) *WWF Risk Filter Suite*, *WWF*. Available at: https://riskfilter.org/.

Wu, X. D. et al. (2019) 'Water footprint of thermal power in China: Implications from the high amount of industrial water use by plant infrastructure of coal-fired generation system,' *Energy Policy*, 132, pp. 452–461. doi: https://doi.org/10.1016/j.enpol.2019.05.049.

Zhang, C. et al. (2021) 'Thermoelectric Power Generation and Water Stress in India: A Spatial and Temporal Analysis,' *Cite This: Environ. Sci. Technol*, 55, p. 4323. doi: 10.1021/acs.est.0c08724.

Zhongming, Z. et al. (2021) *UN World Water Development Report 2021 'Valuing Water.'* Paris. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000375724_eng.

Zhou, Y. and Tol, R. S. J. (2005) 'Evaluating the costs of desalination and water transport,' *Water Resources Research*, 41(3), pp. 1–10. doi: 10.1029/2004WR003749.

Appendix

The list of all research articles submitted and/ or published over the course of this research is provided below.

1. Ram M., Child M., Aghahosseini A., Bogdanov D., Lohrmann A., and Breyer C. (2018). A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. *Journal of Cleaner Production*, 199, pp. 687–704. doi.org/10.1016/j.jclepro.2018.07.159
2. Oyewo A.S., Aghahosseini A., Ram M., Lohrmann A., and Breyer C. (2019). Pathway towards achieving 100% renewable electricity by 2050 for South Africa. *Solar Energy*, 191, pp. 549–565. doi.org/10.1016/j.solener.2019.09.039
3. Farfan J., Lohrmann A., and Breyer C. (2019). Integration of greenhouse agriculture to the energy infrastructure as an alimentary solution. *Renewable and Sustainable Energy Reviews*, 110, pp. 368–377. doi.org/10.1016/j.rser.2019.04.084
4. Lohrmann A., Farfan J., Caldera U., Lohrmann C., and Breyer C. (2019). Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nature Energy*, 4(12), pp. 1040–1048. doi.org/10.1038/s41560-019-0501-4
5. Ram M., Child M., Aghahosseini A., Bogdanov D., Lohrmann A., and Breyer C. (2020). Authors' reply to the letter to the editor: Response to 'A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030.' *Journal of Cleaner Production*, 242:118530. doi.org/10.1016/j.jclepro.2019.118530
6. Lohrmann A., Child M., and Breyer C. (2021). Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system. *Energy*, 233, p. 121098. doi.org/10.1016/j.energy.2021.121098
7. Kozlova M. and Lohrmann A. (2021). Steering Renewable Energy Investments in Favor of Energy System Reliability: A Call for a Hybrid Model. *Sustainability*, 13(24):13510. doi.org/10.3390/su132413510
8. Lohrmann C. and Lohrmann A. (2021). Accuracy and Predictive Power of Sell-Side Target Prices for Global Clean Energy Companies. *Sustainability*, 13(22):12746. doi.org/10.3390/su132212746
9. Lohrmann A., Lohrmann C., and Luukka P. (2022). A region-based approach for missing value imputation of cooling technologies for the global thermal power plant fleet using a decision tree classifier. In: Luukka P. Stoklasa J. (eds). *Intelligent Systems and Applications in Business and Finance,* vol 415. Springer, Cham. doi.org/10.1007/978-3-030-93699-0_5

10. Rahimpour Golroudbary S., Farfan J., Lohrmann A., and Kraslawski A. (2022) Environmental benefits of circular economy approach to use of cobalt. *Global Environmental Change*, 76:102568. doi.org/10.1016/j.gloenvcha.2022.102568
11. Lohrmann A., Lohrmann C., and Luukka P. (2022). Global and regional models for identification of cooling technology in thermal power generation for water demand estimations in water–energy nexus studies. *Journal of Cleaner Production.* doi.org/10.1016/j.jclepro.2022.134842
12. Kozlova M., Huhta K., and Lohrmann A. (2023). The interface between support schemes for renewable energy and security of supply: reviewing capacity mechanisms and support schemes for renewable energy in Europe. *Energy Policy*, 181: 113707. doi.org/10.1016/j.enpol.2023.113707
13. Lohrmann A., Farfan J., Lohrmann C., Kölbel J., and Pettersson F. (2023). Troubled waters: Estimating the role of the power sector in future water scarcity crises. *Energy*, 282:128820. doi.org/10.1016/j.energy.2023.128820
14. Lundaev V., Solomon A. A., Le T., Lohrmann A., and Breyer C. (2023). Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity. *Minerals Engineering*, 203:108282. doi.org/10.1016/j.mineng.2023.108282
15. Lohrmann C., Lawryshyn Y., Lohrmann A., Kumbure M., and Luukka P. (2023). Promoting stability using ensemble feature selection with evolutionary and swarm intelligence algorithms. *20th World Congress of the International Fuzzy Systems Association (IFSA 2023)*

Publication I

Lohrmann A., Farfan J., Caldera U., Lohrmann C., and Breyer C.

Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery

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Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery

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Connecting research on the water demand of power plants with mitigation strategies for energy-based water use is an important step to ensure global water and energy security, and thus provide more sustainable use of both. Here, we assess the water footprint of 13,863 thermal power plants units with a total active capacity of 4,182 GW worldwide and give an estimate of the current water demand for power production at four different levels—global, regional, country and river. Furthermore, we provide a projection for the energy transition period towards a net zero greenhouse gas emissions economy by 2050. In particular, we show that by following a 'Best Policies Scenario' the water consumption of global power plants can be decreased by about 98%, and water withdrawal by 95% by 2050. Therefore, the suggested pathway provides one potential solution to the problem of water depletion that results from the water-energy nexus.

Water and energy are closely related. Thermal electricity generation constituted of coal, gas, oil, biomass and nuclear power plants requires water for cooling purposes. Water is also used in numerous technological processes to harness, extract and produce energy. Meanwhile, water extraction, treatment and distribution consume energy. This dependency is often called the water-energy nexus and is increasingly highlighted by many scholars and policymakers as a sustainability concern for future planning and for water security[1–3].

The currently used technologies of thermal power generation heavily depend on water availability. Water scarcity, often perceived as a side issue of climate change, directly affects the capacity and reliability of thermal power. Moreover, increased water temperatures and reduced river flow have led to forced reductions or even interruptions in power generation[4,5] worldwide. This limitation to electricity supply, coupled with rising production costs, may lead to a sharp rise in electricity prices[6,7].

Thus, it is crucial to understand the contributors to global water stress, one of which is the cooling water demand of thermal power plants, and implement strategies to overcome water resource depletion. The water footprint of cooling the global power plant fleet is typically analysed from the perspective of water withdrawal and water consumption[8]. Water withdrawal is defined as the total amount of water taken from the water source for cooling purposes. Water consumption represents the difference between water withdrawal and the amount of water returned to the source, and water is often 'lost' by means of evaporation[9].

Currently, research on the water demand of power plants is conducted using different estimation techniques (satellite images[10,11], historical data[12] and statistical data[8,13]), which is not commonly reported. Macknick et al.[14] reported water withdrawal and consumption factors for different thermal power plants in the United States. Owing to the lack of country-specific water demand data for thermal power plants, the factors provided by Macknick et al. were used in recent global studies on water withdrawal and consumption. Studies so far have focused on either the global[8,12,13,15,16] or regional and country[1,10,11,17] level. The research conducted by Flörke et al.[12] and Vassolo and Döll[16] is the base on which the commonly used Global Water System Project (GWSP) Digital Water Atlas[18] was produced. Subsequent studies on the water demand for the cooling of thermal power plants expand on the results of Flörke et al.[12], with the aim to generate comprehensive insights into a sector that plays a crucial role in the global water stress.

The main concern with estimating the water demand of the global thermal power plant fleet is the limited availability of data on the cooling technologies and the water source (seawater or freshwater) used for cooling[8,12,16]. In this research, we strive to overcome these limitations.

It is crucial to determine how the world's hunger for electricity can be met and also reduce the power sector's thirst for water. Behrens at al.[1] discussed the vulnerability of power generation to water scarcity and water temperature on the basin level and suggested adaptation strategies for the European Union. However, the authors did not include the ongoing development to replace once-through cooling systems by cooling towers. In contrast to once-through cooling systems, cooling towers, even though consuming large amounts of water, do not cause a temperature increase in downstream basins. In addition, unscheduled outages related to cooling water supply shortages at thermal power plants with cooling towers are minor and uncommon[4]. Maulbetsch and Stallings[19] discuss dry cooling, which results in an estimated cost reduction related to water conservation of \$0.81–1.62 m^{-3} of saved water, which is, in magnitude, comparable to tap water usage. However, along with high costs and material requirements for the cooling system set-up, dry cooling decreases the power plant efficiency. This leads to an increase in greenhouse gas emissions, which counteracts the targets imposed by the IPCC Special Report *Global Warming of 1.5°* (SR1.5)[20]. Therefore, dry cooling has a limited application and can be sustainably implemented only in cases of high thermal efficiency and low cooling needs, for instance, in combined cycle gas turbines. When discussing various approaches to mitigate the water demand of thermal power plants, it is crucial to consider the development of renewable energy as a solution to the problem of water scarcity.

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According to Roehrkasten et al.[5], over their entire lifecycle both solar photovoltaic systems and wind turbines withdraw and consume 2–15% and 0.1–14%, respectively, of the water that coal or nuclear power plants use to generate 1 MWh of electricity. In this regard, renewable energy represents a viable solution as it couples almost zero greenhouse gas emissions with very low to negligible water demand for power generation. Recent research highlighted that a high share of renewable energy is technically feasible and economically viable and, with the support of policy changes, can be implemented globally in the future[21–25]. However, this reality is not certain to happen. Following these insights, it is relevant and necessary to estimate the development of water demand in a world with increasing shares of renewable energy.

We determined the cooling technology of individual power plants and performed an analysis for the seawater and freshwater demand of the global thermal power plant fleet. Our research is based on the GlobalData dataset[26], of which we processed and analysed 13,863 thermal power plants and units that exceeded 50 MW with a total active capacity of 4,182 GW (95.8% of global thermal power plant capacity) worldwide. We then built a 'Best Policies Scenario' (BPS) on the LUT Energy System Transition modelling tool[21] to estimate the development of water demand for each level from the base year of 2015 to 2050 in five-year intervals[21]. The tool enables us to determine a least-cost scenario of the global energy transition towards a system based on 100% renewable energy and is fully compatible with the sustainability target of IPCC SR1.5. So far, a number of publications have indicated that there is no certainty that the above-mentioned sustainability target will be met in the future[27–29]. By the end of 2018, more than 180 peer-reviewed articles described 100% renewables for 2050 or earlier, as summarized by Hansen et al.[30]. The intention of this research is to educate on the potential water savings if the large majority of thermal power plants are replaced by renewable energy technologies. To address this concern, in addition to the scenarios incorporated in this study, the IRENA's Remap2030[29] scenario was considered. The scenario was applied for 24 countries presented in our database and the values of water withdrawal and water consumption were compared with the estimates based on the BPS for the year 2030 (Supplementary Tables 1 and 2 and Supplementary Fig. 1). We present the results for freshwater only and for aggregated water use to indicate the total amount of seawater and freshwater use at the global, regional and country levels. We present an impact analysis on the global–local level for all major rivers in the world carried out in a high temporal and spatial resolution.

Analytical approach

To evaluate the actual water abstractions of thermal power plants for cooling purposes and to address the above-mentioned issues and objectives, we developed a four-step method that follows a bottom-up approach.

As the first step, we identified the location and cooling system type for each power plant using free and easily accessible satellite images (for example, from Google Earth, Bing, Yandex.Maps or other high-resolution products). The methodology of this step is already described and applied[10,11]. Supplementary Fig. 2 gives visual examples. However, not for all power plants can the cooling technology be determined based on satellite images. To fill these gaps, we developed a statistical method premised on historical data and technological trends (Dataset on thermal power plants section, Methods). Next, we deployed the method of Geographic Information System (GIS) analysis to identify whether sea or freshwater is used for the cooling of each power plant.

For the second step, we calculated the footprint for cooling (focusing on both freshwater withdrawal and consumption) of each power plant taking into account its actual net generation, fuel type, technology and cooling system in 2015.

The third step was to compute the total water footprint on different levels—global, regional, country and river. We compare our results to the values reported by Flörke et al.[12] and the GWSP Digital Water Atlas[18] (Comparison with GWSP sheet in Supplementary Data 3 and Supplementary Fig. 3). In addition, we compared our estimations of water consumption with the data reported in 2015 by the Energy Information Administration (EIA) for 865 unique power plants located in the United States[31], as well as with previous studies conducted by Diehl and Harris[32] (Supplementary Table 3). The identification of the cooling system and water used for cooling was compared against individual plant data provided by the EIA for the United States and against individual power plants located in other countries, for which information from the GlobalData database was available. Our method was demonstrated to deliver the correct results in 81% of the cases for the cooling system identification (Supplementary Tables 4 and 5 and Supplementary Note 1) and in 93% of cases for the determination of the water type (Supplementary Tables 6 and 7 and Supplementary Note 2).

Lastly, with a specific identity number assigned to each of the power plants, the model allowed us to trace their specific decommission when reaching the end of their technical life as scheduled by the LUT model[21,33]. It also accounts for the changes in the operations of the power plants, which originate from the implementation of new renewable energy capacity and the adaptation of the energy system in each of the 145 modelled regions. We evaluated our model by comparing the results of the BPS with the outcomes of the scenario based on the lifetime of power plants[1,33]. In this research, the latter scenario is referred to as the Lifetime Scenario (LTS). More details on the above-mentioned scenarios and the model construction are provided in Methods.

Current and projected global water abstractions

The current status and the development of water demand on the global and regional levels is shown in Fig. 1. In the base year 2015, the total global water withdrawal (combined freshwater and seawater) for thermal electricity generation was 500 km^3 (Fig. 1a), of which freshwater withdrawal constituted 290 km^3, or 57.3%. Global water consumption was estimated at 25 km^3 (Fig. 1b), of which freshwater consumption accounted for 18 km^3 or 72%. Median, minimum and maximum values of the current global water abstractions are presented in Table 1.

The water consumption for power generation is not evenly distributed globally. In 2015, the top countries in both freshwater-only and total water consumption were China, the United States, India and Russia (Water demand per country sheet in Supplementary Data 3 and Supplementary Figs. 4 and 5). In the same year, China accounted for 31.5% of the global freshwater consumption, consuming almost 6 km^3 annually. The United States, with the largest freshwater withdrawals for thermal power generation in the world, extracted 102 km^3, which represents 35.7% of all freshwater withdrawals by the power sector globally.

In the case that the BPS is implemented, a rapid decline in both global water withdrawal and consumption can be of benefit during the period from 2015 to 2030, as a consequence of the projected decommissioning of old power plants (Fig. 1a,b,d,e) and replacement by renewable energy technologies that are less water demanding. In 2030, water withdrawal is projected to be reduced by 75.1% compared to 2015 levels. Global water consumption is further mitigated by 85.1% compared to 2015 levels. This tendency continues beyond 2030 to further reduce water withdrawal and consumption.

During the analysed period, 1,797 GW of new gas power plant capacities are scheduled to commission globally, from which 1,365 GW are open cycle units and 432 GW are combined cycle units. For this reason, in 2050, water withdrawals are projected to remain large in the territory from the northeast to the south of China, South Korea, Benelux countries, central regions of Russia and Iran.

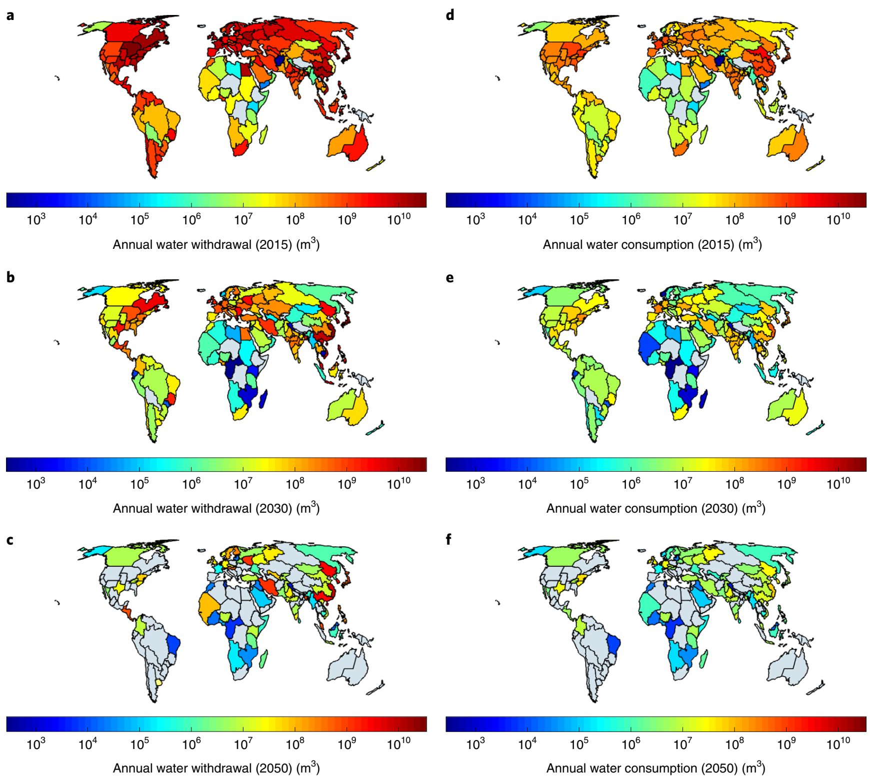

Fig. 1 | Water withdrawal and water consumption by thermal power plants at the regional resolution. Based on the LUT Energy System Transition model and on the BPS. **a–c**, global water withdrawal from 2015 through 2030 and 2050. The total global water withdrawal decreases from 4.99×10^{11} m^3 in 2015 to 1.24×10^{11} m^3 in 2030 and 2.45×10^{10} m^3 in 2050. **d–f**, Global water consumption from 2015 through 2030 and 2050. The total global water consumption decreases from 2.47×10^{10} m^3 in 2015 to 3.69×10^{9} m^3 in 2030 and 5.56×10^{8} m^3 in 2050.

Table 1 | Global total water and freshwater-only consumption and withdrawal (km^3)

	Consumption		Withdrawal	
	Sea- and freshwater	Freshwater	Sea- and freshwater	Freshwater
Median	25	18	500	290
Minimum	19	14	340	210
Maximum	33	24	660	366

The data reported are the values in 2015.

Similarly, water consumption of power generation facilities is estimated to remain high in the east of China, US Mid-Atlantic, South Korea, Russian Urals region, Great Britain and Ireland. During the transition period from 2015 to 2050, the global water withdrawal is projected to decrease by approximately 95.1%, whereas the consumption is projected to decline by 97.7%.

Power plants' local impact on river ecosystems

The GIS analysis shows that 55.5% of the global thermal power plant capacity is located within 5 km of the main global rivers and lakes, and is therefore assumed to be freshwater cooled. In addition, 11.1% of the global thermal power plant capacity has an unknown freshwater source. The global thermal power plant capacity located within 20 km from the ocean coastline is assumed to be seawater cooled and in total is 33.4% (Methods, GIS analysis/water source for cooling identification, and Supplementary Fig. 6).

Historically, rivers represent natural borders of neighbouring countries and regions. At the same time, many large rivers cross territories of multiple countries. Hence, in analysing water abstractions from local rivers, we paid special attention to the correct assignment of generation factors of power plants located at specific rivers and, at the same time, the membership to different regions or countries. These plant-specific data were then applied in calculations of water abstractions at the global, regional and country levels.

The outcome of our river analysis highlights that the Ohio River, Yellow River and Mississippi River are the rivers faced with the largest water consumption. Moreover, the Yangtze, Mississippi

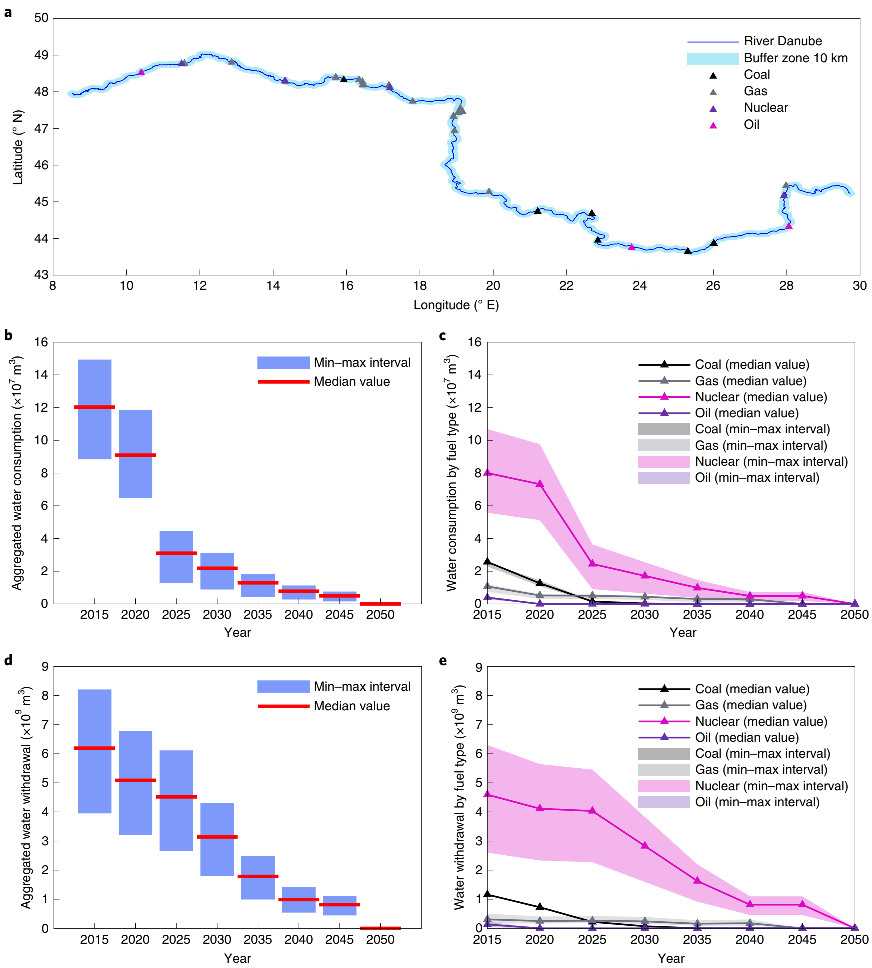

Fig. 2 | Transition scenario for the Danube river based on the BPS. a, Thermal power plants located within 10 km of the Danube river and with a power capacity of at least 50 MW. **b**,**c**, Annual changes in freshwater consumption (median values and minimum–maximum (min–max) intervals), both aggregated (**b**) and by fuel type used in power production (**c**). **d**,**e**, Annual changes in freshwater withdrawal (median values and min–max intervals), both aggregated (**d**) and by fuel type (**e**). Panel **c** highlights a decline in water consumption by nuclear power plants in 2020–2025. This can be explained by the fact that 44.4% of the active nuclear power capacity located at the Danube is scheduled for decommissioning during this period as 'very old' assets. These capacities are currently cooled by cooling towers, and thus there is a sudden drop in water consumption during 2020–2025. In contrast, water withdrawals do not follow the same trend (**e**). The water withdrawals are mostly caused by once-through cooled nuclear power plants (3,226 MW), which are scheduled to be gradually decommissioned by 2050.

and Tennessee Rivers experience the highest water withdrawals from the energy sector. Globally, the Yangtze River experiences the largest water withdrawals of about 12 km^3 (median value) annually (Supplementary Fig. 7).

The World Wide Fund for Nature released a list of ten global rivers that are most at risk, which includes the Danube[34]. We used the Danube river as a representative example for a transition analysis of rivers. The water footprint of 63 identified thermal power plants located within a 10 km buffer zone around the Danube corridor (Fig. 2a) was analysed. These power plants were detected in the territories of Germany, Austria, Slovakia, Hungary, Serbia, Romania and Bulgaria. Together, a total capacity of 18.04 GW, which comprised 2.54 GW of coal-fired, 8.08 GW of gas-fired, 1.61 GW of oil-fired and 5.80 GW of nuclear power plants, was identified.

Figure 2b–e illustrates the change in water use for power production based on the BPS. In 2015, 6.19 km^3 (median value) of water

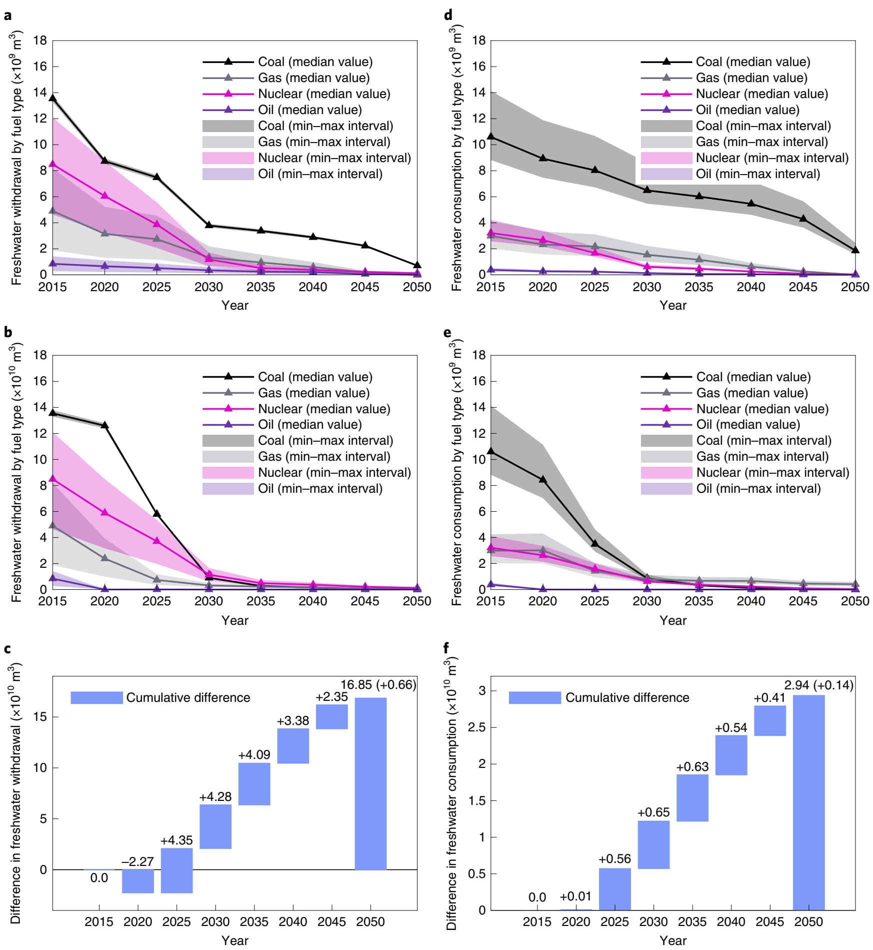

Fig. 3 | Analytical comparison between LTS and BPS. a,**d**, Development of global freshwater withdrawal and consumption in 2015–2050 by fuel type in the LTS. **b**,**e**, Development of global freshwater withdrawal and consumption in 2015–2050 by fuel type in the BPS. **c**,**f**, Cumulative difference in freshwater withdrawal (**c**) and cumulative difference in freshwater consumption (**f**). The numbers in **c** and **f** show the difference in water demand savings of the given time compared to those of the previous time interval.

were withdrawn and 0.12 km^3 (median value) were consumed for thermal electricity generation, of which 66.5% is related to nuclear power production. In the same year, power plants located in the German territory had the highest water consumption from the Danube (more than 59 million cubic metres, which represent 49% of the aggregated consumption). This high share can be explained by the fact that 97.7% of the analysed power plants located in Germany are equipped with cooling towers, which is the most water consuming cooling technology[14]. Power plants at the Danube with cooling towers add up to 6.73 GW (37.3%) of capacity. Opposed to that, power plants located in Bulgaria had the highest water withdrawal driven by coal and nuclear generation (more than 2.79 km^3, which represents 45% of the total withdrawals).

During the first ten years of the transition period (2015–2025), a strong decrease in water consumption of 73.9% is estimated for the Danube, based on the BPS. A total of 35 thermal power plants are scheduled for decommissioning during this period. The projected decline in water consumption is down to 6.9% in 2040 compared to the 2015 baseline. Water withdrawal does not show the same rapid declining trend. In 2025, cooling still requires 72.9% of the initial water withdrawal, whereas in 2040, 16.0% of the 2015 water withdrawal is still required. This could be explained by the fact that 49% of the overall capacity consists of power plants with once-through cooling systems, which need a comparably high amount of withdrawn water for cooling[14].

The simulation projects no water abstraction from the Danube associated with thermal electricity generation by 2050. The corresponding savings in water could be redistributed for other purposes, for example, agricultural irrigation. The 'Water consumption per river' and 'Water withdrawal per river' sheets in Supplementary Data 3 present the results for 354 rivers globally.

An optimal path towards water and energy sustainability

In choosing a sustainable energy transition scenario for a country or a region, the focus of policymakers should be on both compatibility with IPCC SR1.5 and to ensure better mitigation strategies for energy-based water use. To address this call from the perspective of water conservation and to perform the analytical comparison between the LTS and BPS, we deployed a metric of cumulative difference.

The cumulative difference constitutes the estimated amount of freshwater consumption and withdrawal that could be excluded from thermal power production globally in the case that the BPS is put into practice instead of the implementation of LTS. It is calculated as the disparity between the estimated global freshwater consumption and withdrawal in the LTS and its projected counterpart in the BPS for the same time period. The outcome of the analysis is presented in Fig. 3 for the transition period 2015–2050 at five-year intervals.

In 2020, the cumulative difference is estimated at 22.7 km^3 less global freshwater withdrawal in the case that the LTS is pursued. Beyond 2020 the estimated cumulative difference is reversed: between 2020 and 2050, the BPS allows us to consistently save up to 43.5 km^3 of freshwater withdrawn and up to 6.5 km^3 of freshwater consumed during each of the five-year periods. Figure 3c–f illustrates a 35-year perspective and shows cumulative savings of 168.5 km^3 of freshwater withdrawn and 29.4 km^3 consumed compared to those of the LTS from 2015 to 2050. This amount of freshwater 'saved' from consumption is pivotal, as this water would not return to the local water system if it evaporates.

Discussion

In our research we addressed the aspect of the water-energy nexus, which is related to the depletion of water resources due to the operation of thermal power plants. By implementing the BPS, we show that the water consumption of the global power plant fleet can be decreased by 97.7% and water withdrawal by 95.1% by the year 2050. The BPS was compared against the LTS and an advantage of the BPS highlighted. The water that is freed in the BPS could be used by aquatic ecosystems or allocated to other purposes, for instance, food production. Thus, the results of our research can potentially help in further studies on global food security to achieve a sustainable water–energy–food nexus[35].

The selected BPS represents a least-cost energy-system transition pathway and matches the targets of IPCC SR1.5. In addition, it is in line with leading research on energy transition pathways towards a very high level of sustainability[22,24,36,37]. The results of this research are premised on a compiled power plant database that contains the location of thermal power plants with a high accuracy. Coupled with high-resolution maps, this contributes to the precision of the applied estimates of water use for cooling purposes. Using this data, we detected the rivers most affected by the water footprint of thermal power plants worldwide and highlighted for all rivers how the water stress can be reduced under the BPS up to 2050.

The results of our research deviate from the water withdrawal values reported by Flörke et al.[12] and presented in the GWSP Digital Water Atlas[18]. The deviations from the GWSP data can be explained by the consideration of seawater and freshwater use in this research, as well as the allocation of cooling technologies for individual power plants. Our results could potentially be compared with the upcoming Water Resources Institute global water withdrawals and consumption research, in which there is a separation of seawater and freshwater demand and a detailed analysis of power plant cooling technologies[10].

In conclusion, we provide an extensive analysis of the water use of power plants that supports global and regional policy-making, and hence contribute to accomplish water security on a global–local level, which addresses the UN Sustainable Development Goal 6 'Ensure access to water and sanitation for all'[38]. Taking the BPS as an example of a possible pathway for the global energy sector, we show that the depletion of water resources caused by the water–energy nexus can be mitigated by transitioning to an electricity supply based on renewable energy.

Methods

Dataset on thermal power plants. The main source of the power plant data of this study is the GlobalData dataset[26]. Taking this as a starting point, the data was cross-referenced and curated with the information gathered from other datasets[39–42] by Farfan and Breyer[33] according to the SeaDataNet QC Manual[43]. However, the analysis by Farfan and Breyer[33] did not include the spatially highly resolved locations of the power plants, which is part of this study.

The data on power plants was then filtered to contain only thermal electricity generation, defined for this study as nuclear and fossil-fuelled (coal, gas and oil) power plants. This subset was further filtered by capacity to include only active power plant units that exceed 50 MW. The choice of this low boundary of capacity is because power plant units of lower capacity include microgeneration and cannot be identified using aerial imagery, which is the main method of identification of power plants' location in our research. For this set-up, 13,863 units with a total active capacity of 4,182 GW are present globally for further analysis, which represents 66.3% of the total global power plant capacity, and 95.8% of the global thermal capacities in 2015. Supplementary Note 3 gives more information regarding the technologies that were left out of the scope of the study.

We manually determined the exact location and cooling system type using aerial imagery through Google Earth, Bing and Yandex.Maps, following the instructions given by the US Geological Survey[11]. We considered five types of cooling systems: wet cooling towers (which include natural-draft towers and mechanical-draft towers), dry cooling systems (known also as air-cooled condensers), inlet cooling systems of gas power plants and the so-called surface-water cooling systems, which have two subcategories—once-through cooling systems and recirculating cooling-pond systems. More information concerning the applied approach of using satellite imagery for cooling systems identification is given in Supplementary Note 4.

To fill in the gaps for the cooling technology, several steps were performed. First, for each type of fuel (nuclear, coal, gas and oil) and for specific countries we identified the historically most common combination of generator type and cooling technology using a simple statistical analysis. If this combination could not be determined for a specific power plant, it was assigned the most common cooling technology of power generators for the given country.

For countries with missing values of the cooling technology, a sensitivity analysis was performed to analyse the effect of the assignment of different combinations of generator type and cooling technology on the water demand (Supplementary Note 5, Supplementary Table 8 and Supplementary Fig. 8). The sensitivity values at country level together with the probabilities of these values are presented in the sheets in Supplementary Data 3 for both consumption ('Sensitivity of country cons.' sheet) and withdrawal ('Sensitivity of country withd.' sheet).

The results of the identification of the cooling technology were compared against data for individual power plants presented in the GlobalData dataset (Supplementary Table 4). In addition, we compared our results with information reported by the EIA for the United States[44]. As depicted in Supplementary Table 5 and Supplementary Data 2, our method of cooling system identification was demonstrated to deliver the correct results in 81% of the cases.

Analysis of water footprint of power plants. In this research we deployed a bottom-up approach. We calculated the water footprint of each power plant separately for water consumption and water withdrawal using equation (1):

$$\text{Water footprint of thermal power generation} = \text{active capacity} \times \text{full load hours} \times \text{WUI} \quad (1)$$

where the active capacity of installed power plants is given in megawatts, water use intensity (WUI) in $m^3\,MW^{-1}\,h^{-1}$ and full load hours of power generation in hours.

The difference between the calculation of the water footprint for water consumption and water withdrawal is in the WUI in equation (1). The values for the WUI were derived based on empirical records of water use by power plants and reported by Macknick et al.[14]. Supplementary Table 9 contains the values of WUI that were applied for this research. Some scholars[32,45] raised the problem that the water consumption factors of once-through cooling systems are underestimated because forced evaporation downstream of the discharge point was excluded. Forced evaporation depends on various factors (site-specific average natural water temperature, average wind speed and the water surface area over which heat is dissipated[11]). Consequently, it has to be calculated for every specific case, which was out of scope of our research. In addition, the WUI values reported by Macknick et al. currently are widely applied by respected institutions and research[8,10]. In this stage, we grouped oil- and gas-fired power plants into one category as no oil plant data are available. The same method was used in previous research papers[10,46]. However, we acknowledge the higher water dependency of oil power plants in comparison to that of gas plants.

The first two values in equation (1) (active capacity and full load hours) characterize the actual net generation of the given power plant. Full load hours for the year 2015 were obtained from International Energy Agency (IEA) Statistics[47] and were also used by Bogdanov et al.[21] and assigned to each power plant according to the fuel type and location (region in the global LUT model matched with the respective country according to the IEA Statistics) presented in the database. Differentiating the full load hours based on the location and fuel type adds to the accuracy of the study when the full load hours of individual power plants are not accessible. However, owing to the lack of information concerning the actual generation data of individual power plants, the average values were used in the calculations. One differentiation not considered in this study is the potentially different average operating hours for the categories of gas steam and combined cycle, which in the present study are considered as equal. As shown in Supplementary Table 9, the withdrawal and consumption coefficients are significantly higher for gas steam than for combined cycle. However, owing to the unavailability of accurate data at a global level, we acknowledge that this as a limitation in the present study. A large variation in the actual values of the full load hours of power plants of a given fuel in a given region might impact the correctness of the water demand estimations. Using the openly available data provided by the EIA for the United States, we calculated the coefficient of variation of annual hours in service for thermal power plants[31,44] (Supplementary Table 10). The results highlight that the average coefficient of variation of the annual hours in service of coal and nuclear power plants is low (4%). Thus, the use of average full load hours for coal and nuclear power plants will not significantly affect the correctness of water demand estimations. In the case of gas and oil power plants, the average coefficient of variation is higher—about 19%. Therefore, the use of average full load hours for gas and oil power plants might impact the accuracy of the results at the plant level. However, this plant-to-plant difference in hours in service might not significantly affect the country-level estimates of water use as the value reported by the EIA[48] for the total net electricity generation of thermal power plants in 2015 was only 1.3% higher than the corresponding value provided by the LUT model. Using the same dataset provided by the EIA, we calculated the average hours in service of power plants that utilize the same cooling technology. As depicted in Supplementary Table 11, the difference in hours in service of once-through cooling systems and cooling towers is, on average, 2.2% and thus considered small. Therefore, based on the results presented in Supplementary Tables 10 and 11, the use of the same value of full load hours for all types of cooling of a given type of power plant in a given region is appropriate.

At subsequent stages, we calculated the total water footprint and the freshwater footprint with different scopes: at the global level, for the 145 regions of the LUT model, for 148 countries and for major rivers. Results were obtained for the LTS and BPS scenarios for the period 2015–2050. The 'Water demand per region' sheet in Supplementary Data 3 gives more information on water demand development for each region, based on the BPS.

GIS analysis and water source for cooling identification. To link the thermal power plants with water bodies, we deployed a method of GIS analysis based on the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG)[49] as a source of a high-resolution geography dataset that includes global coastlines, lakes, rivers and political borders.

A literature review showed that there is a wide range of assumptions concerning seawater use for cooling purposes of power plants. These assumptions are based on the relative position of the given power unit and its distance to the closest coastline, starting from 5 km and up to 100 km (refs [15,50]). There are reported cases of water transported up to a distance of 70 km in Phoenix, Arizona[51]. These distances may vary for different locations depending on different factors (as discussed by Behrens et al.[1]). Thus, we assumed that all the thermal power plants located within 20 km of a coastline use seawater for cooling purposes as recommended in a study by Greenpeace[13].

The results of the GIS analysis on seawater cooling highlight the strong alignment of the derived results of this research with the reported data on seawater cooling in the Middle East and North Africa region with a deviation of less than 5% (ref. [17]). Then, we also took into account reported numbers stating that 50% of the coal power plants in China and 85% of those in India located within 20 km of the coastline use seawater for their cooling[13]. The analysis revealed for India that 85% of the power plants are located within 7.88 km of the coastline. Thus, we labelled all the thermal power plants in India located within a distance of 7.88 km from the coastline as seawater cooled. In the case of China, 50% of all the thermal power plants located within 20 km of the coastline are even within 0.49 km. Therefore, all the thermal power plants in China located within 0.49 km from the coastline were assigned as seawater cooled. All other thermal power plants were assumed to use freshwater for cooling purposes. This analysis was conducted only for India and China because of the lack of similar information concerning other countries.

The applied assumption of 20 km might lead to an underestimation of the freshwater use in the world[13]. To assess the deviation of the freshwater demand that results from the choice of the seawater cooling buffer zone, we performed a sensitivity analysis (Supplementary Table 12). The results of the analysis show that reducing the sea cooling range from 20 km to 4 km results in a smooth increase of global freshwater consumption and withdrawal. For instance, if the sea cooling range is reduced to 12 km, the difference in freshwater consumption and withdrawal is below 2% compared to the 20 km assumption. Assuming a sea cooling range of 2 km, a difference of 12.3% for freshwater consumption and 8.6% for freshwater withdrawal is estimated, compared to the assumed 20 km for this study. The difference can be explained by the fact that thermal power plants tend to be located closer to the coastline (Supplementary Figs. 9 and 10).

The power plants were assumed to have a direct freshwater source for cooling if they are located within 5 km of rivers and lakes. We used the GSHHG database for the GIS analysis as it provides the location of about 25,960 rivers worldwide in high resolution. Facilities with an intake or discharge of cooling water to a smaller stream, or those that use groundwater, cannot be matched using GIS analysis. In our research, it was not possible to determine with certainty the exact source of water of 9.9% of the total active capacity presented in our filtered database. Further information provided by electricity generation companies proved that those power plants use ground water for their cooling purposes (an example is given in Groves et al.[52]), so these results were added to the freshwater consumption and water withdrawal numbers.

In more than half of the reported cases concerning cooling technology presented in the GlobalData dataset, the type of water used for cooling purposes is specified (seawater or water from rivers or lakes). We used the reported data for individual power plants to compare our results for the identification of the water type (Supplementary Table 6). Moreover, we used data provided by the EIA for the United States[44] to compare our results for the identification of the water type. As depicted in Supplementary Table 7 and Supplementary Data 2, the proposed method shows a high accuracy for the determination of the water type (93% of cases demonstrate a correctly identified water type), which clearly indicates that it can be used for regional and global studies. However, we acknowledge that to obtain a higher accuracy for the results at the plant level, it is necessary to consider data directly reported by power generation companies for each specific power plant unit.

Transition scenarios. We performed our analysis of the water footprint development in five-year time steps in a full hourly resolution, focusing on the transition period for the years from 2015 to 2050. Two scenarios were considered: LTS and BPS.

The main idea of the LTS is that the stock of thermal power plants is assumed to operate until the point of decommissioning. We follow the reasoning of Farfan and Breyer[33], who calculated the expected year of decommissioning as the reported year of commissioning of a power plant plus the average technical lifetime of the power plant by fuel type. Thus, we assumed that the average technical lifetime for gas- and oil-fired power plants is 34 years, and for coal-fired and nuclear power plants 40 years[53]. However, the database used contains power plants that were active in 2015 that should have been decommissioned before that year (these plants were highlighted as 'very old'). In addition, those power plants in the database for which the commissioning year is unknown were marked as power plants with 'unknown year'. The unknown year category represents 123.92 GW, or 3.0%, of the total thermal capacity. The very old power plants that are still operating represent 748.87 GW, or 17.9%, of the thermal power plant capacity. We assumed that the above-mentioned two categories of power plants are gradually decommissioned between 2015 and 2025, 10% of their initial capacity per year. The BPS was constructed on the basis of the LUT Energy System Transition model[21]. According to this model, the operation of the power sector is cost optimized and the full load hours of coal-, gas- and oil-fired power plants are a part of the optimization and can decrease or cease during the transition period, as shown in the data presented by Bogdanov et al.[21]. Opposed to that, the specific utilization of nuclear power plants does not allow a change of the baseload over time due to security issues, so the continuous utilization of the existing capacity until the end of its technical lifetime was assumed (except for Germany, where partly an earlier decommissioning is forced by law). Hence, the outcome of the applied scenario is a time series of full load hours of power generation facilities for each of the 145 regions. The model tolerates the role of gas power plants during the transition period due to lower greenhouse gas emissions and, in particular, the possibility to substitute the currently used natural gas by biomethane or power-to-gas in these plants at later time periods. Thereby, according to the outcomes of the applied scenario, 1,797 GW of gas-fired capacities will be installed globally from 2015 to 2050, whereas 2,077 GW are still active in 2050 and used by a global average of 483 full load hours. We determined and assigned to the new capacities the most common gas generator type during the past 15 years for each of the 145 regions. The cooling technology was assigned as indicated in the Dataset on thermal power plants section. The changes in the water footprint of new commissioned plants as well as of the existing operating gas power plants were calculated in the same way as for coal- and oil-fired power plants using the full load hours generated by the LUT Energy System Transition model. We followed the logic of the power plant decommissioning process described in the LTS.

Supplementary Note 6 contains the equations that underlie the calculation of water demand of power plants in the LTS and BPS.

Analysis of water footprint of power plants on global rivers. For the river analysis we required a river database that also contained names of rivers. Commonly, the rivers are given a certain identity number rather than their respective names, and thus we chose to use the river database from Natural Earth[54].

Initially, the database contained 1,454 rivers and river sections. For rivers with missing or misspelled names, these were investigated and corrected manually. Separate sections of rivers that belong together were merged. Using GIS analysis, we identified rivers with power plants located within 5 km of the river's corridor. As a result, we obtained 354 unique rivers for further analysis.

We calculated the water consumption and water withdrawal of power plants separately for each of these 354 rivers, as well as the projected values for the period 2015–2050 with five-year intervals using the baseline of the BPS. To make the results of this work useful to local policy makers, we assigned to each of the given rivers the corresponding continent and ocean of discharge and the country with the highest impact on its flow.

Data availability

The data that support the findings of this study are available from GlobalData[26], but restrictions apply to the availability, which was used under license for this study. The database encompasses over 170 fields of information, which include the names of power generators, owners, operators, generator manufacturers and so on. An extract of the extensive list of thermal power plants that exceed 50 MW, which contains fuel type, country, active capacity, generation type, location and type of cooling technology, is available as Supplementary Data 1. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

Example Matlab scripts used in the production of this analysis are available at https://github.com/WaterEnergyWork/FreshwaterDemand.git

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References

1. Behrens, P., van Vliet, M. T. H., Nanninga, T., Walsh, B. & Rodrigues, J. F. D. Climate change and the vulnerability of electricity generation to water stress in the European Union. *Nat. Energy* **2**, 17114 (2017).
2. Ganguli, P., Kumar, D. & Ganguly, A. R. US power production at risk from water stress in a changing climate. *Sci. Rep.* **7**, 11983 (2017).
3. *Water Energy Nexus* WEO-2016 Special Report (International Energy Agency, 2016); https://doi.org/10.1021/es903811p
4. van Vliet, M. T. H. et al. Vulnerability of US and European electricity supply to climate change. *Nat. Clim. Change* **2**, 676–681 (2012).
5. Roehrkasten, S., Schaeuble, D. & Helgenberger, S. *Secure and Sustainable Power Generation in a Water-Constrained World* (Institute for Advanced Sustainability Studies, 2015).
6. McDermott, G. & Nilsen, O. Electricity prices, river temperatures, and cooling water scarcity. *Land Econ.* **90**, 131–148 (2014).
7. Boogert, A. & Dupont, D. The nature of supply side effects on electricity prices: the impact of water temperature. *Econ. Lett.* **88**, 121–125 (2005).
8. Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H. & Marks, D. H. The water consumption of energy production: an international comparison. *Environ. Res. Lett.* **9**, 105002 (2014).
9. Kenny, J. F. et al. *Estimated Use of Water in the United States in 2005* Circular 1344 (US Geological Survey, 2009); https://doi.org/10.3133/cir1405
10. Luo, T., Krishnaswami, A. & Li, X. *A Methodology to Estimate Water Demand for Thermal Power Plants in Data-Scarce Regions using Satellite Images* Technical Note (World Research Institute, 2018); https://www.wri.org/publication/methodology-estimate-water-demand-thermal-power-plants-data-scarce-regions
11. Diehl, T. H., Harris, M. A., Murphy, J. C., Hutson, S. S. & Ladd, D. E. *Methods for Estimating Water Consumption for Thermoelectric Power Plants in the United States* Scientific Investigations Report 2013–5188 (US Geological Survey, 2013); https://doi.org/10.3133/sir20135188
12. Flörke, M. et al. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. *Glob. Environ. Change* **23**, 144–156 (2013).
13. Biesheuvel, A., Witteveen+Bos, Cheng, I., Liu, X. & Greenpeace International. *Methods and Results Report: Modelling Global Water Demand for Coal Based Power Generation* (Witteveen + Boss, Greenpeace, 2016).
14. Macknick, J., Newmark, R., Heath, G. & Hallett, K. C. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environ. Res. Lett.* **7**, 045802 (2012).
15. van Vliet, M. T. H., Wiberg, D., Leduc, S. & Riahi, K. Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Change* **6**, 375–380 (2016).
16. Vassolo, S. & Döll, P. Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resour. Res.* **41**, 1–11 (2005).
17. Siddiqi, A. & Anadon, L. D. The water–energy nexus in Middle East and North Africa. *Energy Policy* **39**, 4529–4540 (2011).
18. *GWSP Global Water System Project Digital Water Atlas* (Global Water System Project, 2008); http://atlas.gwsp.org/
19. Maulbetsch, J. & Stallings, J. Evaluating the economics of alternative cooling technologies. *Power Eng.* **116**, 120–128 (2012).
20. Masson-Delmotte et al. *Global Warming of 1.5 °C* Special Report (IPCC, 2018).
21. Bogdanov, D. et al. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nat. Commun.* **10**, 1077 (2019).
22. Jacobson, M. Z. et al. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. *Renew. Energy* **123**, 236–248 (2018).
23. Creutzig, F. et al. The underestimated potential of solar energy to mitigate climate change. *Nat. Energy* **2**, 17140 (2017).
24. Sgouridis, S., Csala, D. & Bardi, U. The sower's way: quantifying the narrowing net-energy pathways to a global energy transition. *Environ. Res. Lett.* **11**, 094009 (2016).
25. Teske, S. *Achieving the Paris Climate Agreement Goals* (Springer International, 2019).
26. *GlobalData Power* (GlobalData Ltd, accessed 20 November 2015); http://power.globaldata.com/Home.aspx
27. *Tracking Clean Energy Progress 2017* (International Energy Agency, 2017); https://www.iea.org/etp/tracking2017/
28. *World Nuclear Performance Report* (World Nuclear Association, 2016).
29. *Global Energy Transformation: A Roadmap to 2050* (IRENA, 2019); https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf
30. Hansen, K., Breyer, C. & Lund, H. Status and perspectives on 100% renewable energy systems. *Energy* **175**, 471–480 (2019).
31. *Form EIA-923 Detailed Data with Previous Form Data (EIA-906/920)* (US Energy Information Administration, accessed 29 June 2019); https://www.eia.gov/electricity/data/eia923/
32. Diehl, T. H. & Harris, M. A. *Withdrawal and Consumption of Water by Thermoelectric Power Plants in the United States, 2010* Science Investigation Report 2014-5184 (US Geological Survey, 2014); https://doi.org/10.3133/sir20145184
33. Farfan, J. & Breyer, C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *J. Clean. Prod.* **141**, 370–384 (2017).
34. Wong, C., Williams, C., Pittock, J., Collier, U. & Schelle, P. *World's Top 10 Rivers at Risk* (WWF, 2007); http://d2ouvy59p0dg6k.cloudfront.net/downloads/worldstop10riversatriskfinalmarch13_1.pdf
35. Biggs, E. M. et al. Sustainable development and the water–energy–food nexus: a perspective on livelihoods. *Environ. Sci. Policy* **54**, 389–397 (2015).
36. Greenpeace, GWEC & SolarPower Europe. *Energy [R]evolution: A Sustainable World Energy Outlook 2015* (Greenpeace International, 2015).
37. Brown, T. W. et al. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renew. Sustain. Energy Rev.* **92**, 834–847 (2018).
38. *Clean Water and Sanitation: Why It Matters* (United Nations, 2016); https://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/6_Why-it-Matters_Sanitation_2p.pdf
39. *World Electric Power Plants Database* (S&P Global Platts, 2016).
40. *Renewable Energy Capacity Statistics 2015* (IRENA, 2015).
41. Lehner, B. et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ.* **9**, 494–502 (2011).
42. Gerlach, A., Werner, C., Gerlach, A., Breyer, C. & Orlandi, S. In *Proc. of the 31st European Photovoltaic Solar Energy Conference* (eds Rink, S., Helm, P & Taylor, N.) 2965–2973 (WIP Renewable Energies, 2015).
43. Schaap, D. M. A. & Lowry, R. K. SeaDataNet—Pan-European infrastructure for ocean and marine data management. *Int. J. Digit. Earth* **3**, 50–69 (2010).
44. *Form EIA-860 detailed data with previous form data (EIA-860A/860B)* (Energy Information Administration, accessed 29 June 2019); https://www.eia.gov/electricity/data/eia860/
45. Morton, V. & Echeverri, D. P. *Electric Power Plant Water Use in North Carolina: Forced Evaporation and Emission Controls*. MSc Thesis, Duke Univ. (2010).
46. Feeley, T. J. et al. Water: a critical resource in the thermoelectric power industry. *Energy* **33**, 1–11 (2008).
47. *Statistics. Global Energy Data at your Fingertips* (International Energy Agency, 2018).

48. *Electric Power Monthly* (US Energy Information Administration, accessed 29 June 2019); https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01
49. Wessel, P. & Smith, W. H. F. A global, self-consistent, hierarchical, high-resolution shoreline database. *J. Geophys. Res. Solid Earth* **101**, 8741–8743 (1996).
50. Zhou, Y. & Tol, R. S. J. Evaluating the costs of desalination and water transport. *Water Resour. Res.* **41**, 1–10 (2005).
51. Cooling Power Plants (World Nuclear Association, accessed 1 November 2017); http://www.world-nuclear.org/information-library/current-and-future-generation/cooling-power-plants.aspx
52. Groves, J., Krankkala, T. & Nigent, G. Afton combined cycle with hybrid cooling. *Power Engineering* **114**, 56–60 (2010).
53. Farfan, J. & Breyer, C. Aging of European power plant infrastructure as an opportunity to evolve towards sustainability. *Int. J. Hydrog. Energy* **42**, 18081–18091 (2017).
54. *Rivers + lake centerlines* (Natural Earth, 2016); https://www.naturalearthdata.com/downloads/50m-physical-vectors/50m-rivers-lake-centerlines/

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Author contributions
A.L. designed the study and performed the analysis, collected data on cooling technology and water use and drafted the manuscript. J.F. collected the data on existing power plants globally, and assisted with the methodology development and the results analysis. U.C. assisted with the methodology development and literature review. C.L. assisted with the sensitivity analysis and gave support for the paper writing. C.B. assisted with the analysis and initiated, supervised, reviewed and coordinated the work.

Competing interests
The authors declare no competing interests.

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Publication II

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Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system

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Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system

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ABSTRACT

The transition towards a 100% renewable energy system may be an opportunity to resolve the water-energy nexus. However, deployment of some technologies might impose additional strain on water ecosystems. An energy-system-wide analysis of water demand in Europe was performed for the period 2015–2050 using the LUT Energy System Transition model for two scenarios: Area (with electricity interconnections) and Regions (without). For fossil-fuelled power plants, the water footprint in 20 European regions may decrease considerably until 2050, by 28.3% in the 'Area scenario' and 24.2% in the 'Regions scenario'. However, total water demand in the Area scenario increases in 5 regions on average by 14%, from 7% (Balkan-West countries) to 24% (Sweden). Further, Turkey, Norway and Sweden may have the largest water demands in Europe due to the commissioning of new hydropower plants. Results indicate discussions on the sustainability of energy transition scenarios should be expanded to include water footprint.

1. Introduction

Currently, a large share of Europe's power generation relies heavily on water availability. Considerable amounts of water are used in hydropower generation, and thermal power plants require water for cooling purposes. The electricity sector of the European Union is on average responsible for approximately 55% of the total water withdrawal [1]. The researchers note that without a radical improvement of the water resource management in the power sector, the power plants' demand for water might surge considerably in the future [2]. This rising water demand might lead to a further depletion of water resources and aggravation of water-related risks, especially in regions which are already suffering severely from water stress [2].

In the annual report released by the World Economic Forum [3], "water crisis" is listed in the top-10 global risks in terms of both likelihood and impact for the year 2020. According to the data presented in the Water Resources Institute (WRI) Aqueduct Atlas, about 142 million Europeans are currently living in areas exposed to high or extremely high baseline water stress [4]. The river Danube, which flows through 19 European countries and passes 47 cities and 4 national capitals, was listed by the World Wide Fund for Nature (WWF) as one of the ten rivers at risk in the world [5].

Water constraints, droughts and heatwaves have already compromised power generation in Europe [2]. For instance, the heatwave of 2015 induced a reduction of coal power generation in Germany and Poland [6,7]. Previously in 2006, the temperature rise in river water forced French, German and Spanish nuclear plants to reduce or even halt power generation [8]. According to the European Environment Agency report [9], water availability is projected to further decrease as a side effect of climate change [10]. This holds especially true in southern parts of Europe, affecting thermal power plants, hydropower, bioenergy potential and fuel transport on rivers.

The adaptation to climate change represents challenges and opportunities for the implementation of a defossilised energy system in Europe [9]. In general, renewable energy technologies are known to consume considerably less water compared to conventional fossil-nuclear fuelled power plants. For instance, solar PV and wind generation require only marginal quantities of water (if any) for occasional cleaning of PV modules and wind turbine blades [11]. However, some other types of renewable energy technologies (for instance, hydropower and bioenergy) could consume water more

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intensively than the fossil-based systems they replace [12,13]. Thus, a more careful assessment of energy-based water consumption will add another layer in the discussion of the sustainability of 100% renewable energy systems, which are extensively discussed in recent years, in particular, for the case of Europe [14–17].

Studies of the water-energy nexus exist for several regions of the world, such as the Middle East and North Africa [18], China [19], the UK [20], as well as globally [21]. However, studies on Europe as a whole are lacking in the literature. In addition, water-energy nexus studies have not been completed on a European level that account for projections of the transition towards higher shares of renewable energy in the future. Furthermore, the European Council has set a target to strengthen the energy interconnection between the countries [22] in order to increase the European Union's security of electricity supply and to achieve higher penetration of renewable energy technologies into its energy markets. The economic consequences of establishing such interconnections have been the focus of recent research articles [16,23]. However, there is a lack of research analysing the potential changes in water usage in electricity production. Given that Europe is reported to have the highest energy-related water footprint in the world [24], projections of future water use in the energy sector can provide a basis for effective water policy and planning.

To address the above-mentioned concerns, this study aims to: (1) assess the current water demand of Europe's power sector from the perspective of water consumption, (2) evaluate the potential impact of establishing high voltage power transmission interconnections between the regions of Europe on the water demand estimates, (3) project the development of water consumption until 2050 for the example case of two energy transition scenarios, and (3) identify potential bottlenecks on the pathway towards a zero greenhouse gas (GHG) emission renewable energy system when conducting the comparison of the two scenarios.

2. Methods

2.1. Data gathering and database compilation

2.1.1. Compilation of the power plant dataset

The main source of power plant data for the research was the GlobalData dataset [25]. The dataset was later complemented and corrected with the information presented in other databases [26–28], and the results of the global power plant structure were published by Farfan and Breyer [29]. The presented dataset provides comprehensive information on existing power plants (name, capacity, type of generator, fuel type, commission date, country and region, etc. were reported for each specific power plant). However, the dataset did not include the locations in high spatial resolution of the power plants, or the source and the amount of water used for power generation, which are required for the water footprint determination and analysis.

The aim of this study was to put an emphasis on the European energy system-wide analysis. Therefore, the initial dataset was narrowed down to contain only active power plant units exceeding 50 MW located in Europe. Countries presented as part of the analysis are the EU-27 member states, Albania, Bosnia and Herzegovina, Iceland, Kosovo, Macedonia, Moldova, Norway, Serbia, Switzerland, Turkey, Ukraine and the United Kingdom.

The limitation of 50 MW originates from the inability to identify the location and the cooling system of such power plants using satellite imagery. This selected cut-off seems appropriate for the study due to the following reasons: (1) thermal power plants of low capacity require a relatively low amount of water for cooling purposes due to their small size; (2) thermal power plants of low capacity are typically equipped with dry cooling systems, which demand less water than other cooling systems [13]; (3) thermal power plants of low capacity are often combined heat and power (CHP) plants, which have relatively low water abstractions for waste heat discharge [30]. As for renewable energy technologies, it is challenging to identify the location of small-scale generation units since the names of such units are typically not available in the commonly used power plants databases.

In contrast to the previous study by Lohrmann at al. [31], which was focused only on thermal power plants, this research aims to assess the water footprint of other water-intensive non-thermal power technologies. As a result, 3276 power plants with a total active power plant capacity of 845 GW were presented for the analysis, of which 895 units (27.3%) are gas power plants, 852 (26.0%) are coal-fired, 835 (25.5%) are hydropower, 302 (9.2%) are oil-fired, and 150 (4.6%) are nuclear power plants. Other technologies, such as biomass and biogas power plants, solar photovoltaic (PV) and concentrated solar thermal power (CSP) plants, together account for less than 7.4% of the total amount of the units presented for the analysis.

This research does not encompass the assessment of geothermal plants since their share in the current European energy system is negligible (less than 0.3% of the total energy generated in 2015). However, it is important to remark that geothermal power plants, depending on the cooling type, might be the second most water demanding power generation technology (after hydropower), consuming up to 19.48 m^3 per MWh [13]. This extensive water consumption might have a considerable impact on the local water systems. In contrast to geothermal technology, the share of wind power in the current energy system is high (16% of the total installed capacity higher than 50 MW). In addition, according to both scenarios considered in this study, this share is projected to increase by 2050. However, no water is being abstracted in the process of wind power generation. Thus, the water footprint of wind power generation was not assessed in this study. In addition, pumped hydro energy storage technology was left out of the scope of the research since no water footprint factors were available in Macknick et al. [13].

2.1.2. Identification of location and coupling power plants with water bodies

To estimate the type of water used for cooling purposes (sea or freshwater), the exact location of individual power plants needs to be pinpointed. The exact geographical coordinates of thermal power plants were previously identified and reported by Lohrmann et al. [31]. For this study, the locations of other types of power plants presented for the analysis (hydropower, biomass, CSP) were identified based on the information presented in the initial database (name of the specific power plant, fuel type and capacity, region and town of its location) using satellite imagery in Google Earth, Bing and Yandex.Maps. Fig. 1 presents the location of water-intensive power generation facilities identified for this study, thus, excluding solar PV power plants.

To link individual power plants with water bodies, the method of Geographic Information System (GIS) analysis was implemented. The Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) [32] was used as a source of a high-resolution data for ocean coastlines, lakes and rivers. Power plants were assumed to have a direct freshwater cooling source if they are located within 5 km of rivers and lakes. In contrast to that, power plants located within 20 km of the ocean coastline, were assumed to use seawater for cooling purposes, as it was shown by Biesheuvel et al. [33] and later implemented and validated on global level by Lohrmann et al. [31], where power units with unknown water source were assumed to use underground freshwater for cooling.

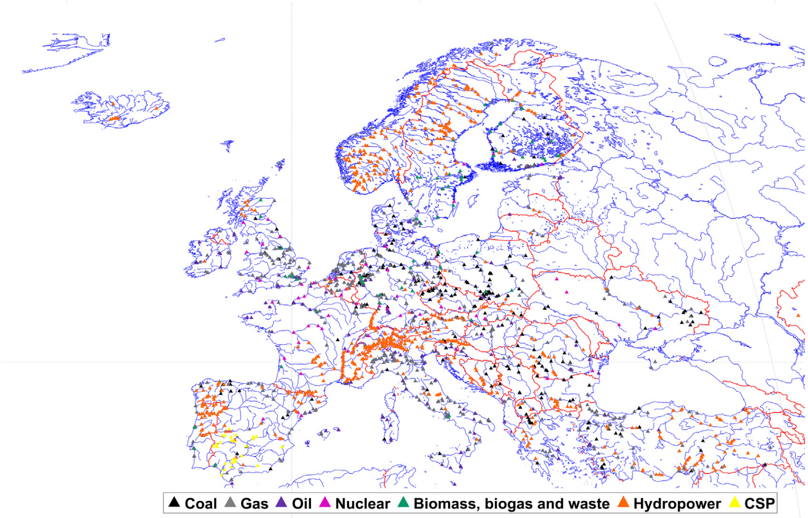

Fig. 1. Identification of the exact location of power plants exceeding 50 MW in Europe. The blue lines on the map represent water bodies: rivers, lakes, ponds, channels, and coastlines. The borders of the countries are marked in red colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.1.3. Cooling system identification

Knowing the cooling system of individual thermal power plants is crucial for the assessment of their water footprint on river ecosystems. However, the initial dataset provided by GlobalData [25] contained almost no information on the installed cooling technology at an individual power plant level. Therefore, the subset of the European power plants used in this research was complemented with the cooling technology data gathered and reported by Lohrmann et al. [31] for the case of coal, gas, nuclear and oil power plants. In subsequent steps, the type of cooling technology was identified for individual CSP, biomass and biogas power plants.

The method of cooling system identification in biomass and biogas power plants applied in this research was previously reported by U.S. Geological Survey [34] and Luo et al. [35] and tested on a global level by Lohrmann et al. [31]. For the case of the US power plant fleet, Luo et al. [35] achieved a precision level of 90% for the cooling technology identification. Their method is based on the manual identification of the cooling technologies of individual thermal power plants using satellite imagery provided by Google Earth, Bing and Yandex.Maps. In total, five types of cooling technologies were considered: dry cooling (or so-called air cooling, direct and indirect), once-through cooling (or open loop cooling), recirculating tower cooling systems (which is typically subdivided into natural draft towers, mechanical induced-draft towers and mechanical forced-draft towers), recirculating pond cooling and inlet cooling systems of gas power plants.

The main limitations of the applied method were discussed by Luo et al. [35]. In this research, the cooling system identification method did not allow identification of the cooling technology in several cases. Firstly, the method appeared to be ineffective for biomass power plants that were located within large industrial complexes (e.g. pulp and paper facilities) where several types of cooling technologies were utilised. In this case, the allocation of cooling technology should be performed by specialists familiar with the particular industrial complex. Secondly, the identification of several once-through power plants was not feasible using satellite imagery due to the fact that their intake or outlet facilities were submerged. Thirdly, in many cases, it was not possible to identify the cooling system of low-capacity power plants due to their small size. Thus, the size emerged as the primary reason for selecting a 50 MW capacity as the limit for this study. Moreover, the precision of cooling system identification appeared to be strongly dependent on the image resolution and timing of the satellite shot. Finally, the assignment of cooling technology was not possible for power plants belonging to the category "aggregated capacities". This category was added to the initial GlobalData database [25] by Farfan and Breyer [29] to match the capacities presented in the database with the statistical information on power generation provided by governmental institutions and international organisations for all countries in the world. These capacities cannot be assigned to specific power plants or units. Therefore, by definition, this method applied in the research cannot be used for their cooling system identification. The amount of thermal power plants which cannot be assigned any cooling technology using this method is rather low (for instance, the "aggregated capacities" represent 135 entries in the database, which account for about 4.1% of all power units presented for the analysis). They represent only 16.1% of the total power plant capacity in the database. Thus, the choice of missing value treatment for the cooling technology is crucial for the analysis of local freshwater-deficit regions.

In order to "fill in the gaps" in the cooling technology data, a simple statistical analysis was performed. The analysis was based on historical data (year, capacity, fuel and combination of the generator type and cooling technology of individual power plants) available in the database. The selected method of missing value imputation might impact the water consumption estimates. In order to assess the variability of the water consumption estimates resulting from the choice of the cooling technology for the "aggregated capacities", a sensitivity analysis was performed. The results of the sensitivity analysis are discussed in the Supplementary Materials (Note 1).

2.2. Analytical approach for the assessment of the current water footprint

2.2.1. Individual power plant − level

Typically, the assessment of the energy-based water footprint is conducted from the perspective of water withdrawal and water consumption. Water withdrawal is defined as the total amount of water taken from the water source to meet the demand of the power generation process. In contrast to that, water consumption represents the difference between water withdrawal and the amount of water returned to the source. From another viewpoint, if water is seen as a common good for industrial, agricultural and domestic use, then water withdrawal can be treated as the amount of water "used" by the economy. In contrast to that, water consumption can be defined as the amount of water "used" by the technological process since it describes how much water is "lost" during the process of power generation. The focus of this study is on water consumption since it illustrates the direct impact of power generation on water availability. In particular, this water is disposed from the immediate water environment, for instance, by means of evaporation.

Water consumption (or so-called "water footprint") of power plants was calculated using Equation (1) presented below.

$$Water\ footprint = Active\ capacity \times FLH \times WUI \tag{1}$$

where the *Active capacity* is given in MW; *FLH* − full load hours of power generation − in hours; *WUI* − water use intensity factor − in m^3 per MWh. For the assessment of the current (2015) water footprint, the FLH were obtained from the International Energy Agency (IEA) statistics [36]. The FLHs were assigned to individual power plants according to their generation type (coal, gas, hydropower, solar PV, etc.) and location (country).

Table 1 in the Supplementary Material contains information concerning the WUI factors used in this study, which were derived by Macknick et al. [13]. For different types of power plants, depending on the installed generator type and cooling technology, different WUI factors were applied. As highlighted in Table 1 of the Supplementary Material, a few types of power plants do not require cooling for the process of power generation (solar PV and hydropower). In the case of solar PV, the WUI factors were available only for utility-scale plants. This is one of the limitations of this study, and residential solar PV plants were left out of the scope. For hydropower plants, the WUI factors were only reported for in-stream plants and reservoirs, thus, the other types (e.g. pumped hydro energy storage) were filtered out from the final database. A discussion concerning the selection of the WUI factors for CHP power plants is presented in Note 2 of the Supplementary Material.

Although the approach of using WUI factors is an effective and widely applied method for water demand estimations in the power generation sector, it is associated with uncertainty (since different factors will lead to different estimates). As mentioned previously, for this study, the values of water use intensities were derived from Macknick et al. [13]. Whilst these factors were reported for the United States, Macknick et al. suggest that they can also be used for water demand estimations for other geographic regions (including Europe) [13]. Consequently, many studies which focused on water demand estimations for European power plants (e.g. Ref. [37]) have reported using WUI factors from Macknick et al. [13]. However, any variations in water management and cooling technology utilization between the United States and Europe might result in differences in the water consumption estimates [38]. In order to address this concern, the WUI factors (median values and min-max intervals), which were applied in this study [13], were compared to the WUI factors that were used in other studies on Europe (see Note 3 of the Supplementary Material).

2.2.2. Region- and country − level

The country-specific total water consumption was calculated as the sum of the water consumption of all power generation facilities located in these countries. In addition, the aggregated water footprint was calculated for all Europe's twenty sub-regions presented in the LUT Energy System Transition model [16,39]. The LUT Energy System Transition model optimises the projected energy systems in full hourly resolution. The dataset of the real weather conditions, which is implemented in the model, has a $0.45^\circ \times 0.45^\circ$ spatial and hourly temporal resolution. Hence, the (local) variability of renewables and their impact on the future energy system design is considered in greater detail, compared to other studies. This step was taken in order to match and compare the estimated current water footprint with the projected values by the 'Regions scenario' and the 'Area scenario' until 2050. These twenty regions, their location and specifications are presented in Fig. 2. Additional information concerning the countries assigned to each specific region is provided in Table 1.

2.3. Scenarios

The Regions scenario assumes that each of the defined 20 regions of Europe is an independent energy system with no exchange of electricity. At the same time, it was recognised in Ref. [16] that some natural areas of energy cooperation exist within the European context while constructing the individual regions. In most cases, regions are national energy systems. However, many regions are combinations of national systems that have shown high levels of energy cooperation in the past, especially the exchange of electricity. The Area scenario establishes high voltage power transmission interconnections between the regions of Europe. The basis of the scenario is established by known capacities of HVAC and HVDC connections in winter 2010/2011 as developed by ENTSO-E [40] and supplemented by further information from Refs. [41–43]. Interconnections were determined on an individual basis between each region and observed known border crossing points as well as routes of undersea cables. To account for varying topography, an additional 10% was added to interconnection distances. In some cases where accurate information could not be found, straight lines between the main centres of electricity demand were drawn. New undersea cables were assumed to be HVDC cables, as is the norm in Europe. New additions on land were assumed to be comprised of 70% underground cables and 30% overhead lines to account for possible social resistance to visible lines overhead. In both scenarios, no analysis of transmission or distribution infrastructure within regions was attempted, although internal transmission line losses were accounted as a function of electricity consumed, as documented in Ref. [44]. A full description of scenario parameters and methods is found in Ref. [16].

2.4. Estimation of the power sector's water footprint in 2016–2050

The results of the Regions and Area scenarios determine the power capacities that should be commissioned during the transition period from 2016 to 2050. However, since the location of these new power capacities was not defined, this study assumes that all new thermal capacities will consume freshwater for cooling purposes.

The scenarios were applied to project the development of the

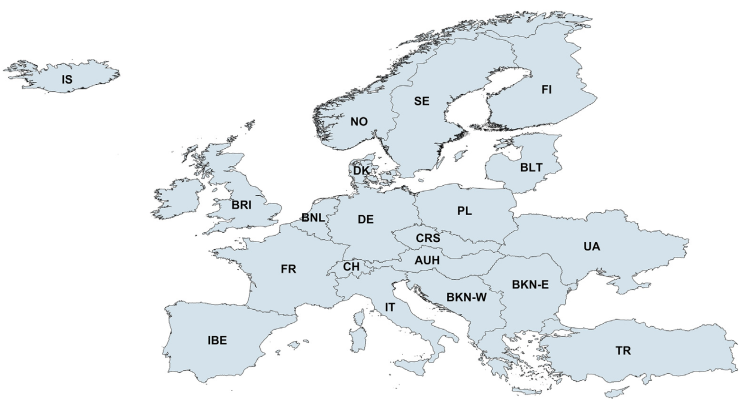

Fig. 2. Geographical regions used in this study [39].

Table 1
Median, minimum and maximum values of water consumption estimates and specific water consumption per region in 2015.

Region	Countries	Median, [km^3]	Minimum, [km^3]	Maximum, [km^3]	Specific water consumption, m^3/MWh (based on median values)
NO	Norway	1.89	0.60	7.56	15.47
DK	Denmark	0.02	0.01	0.02	0.55
SE	Sweden	1.20	0.41	4.49	7.66
FI	Finland	0.32	0.13	1.07	4.22
BLT	Baltic: Estonia, Latvia, Lithuania	0.05	0.02	0.14	1.74
PL	Poland	0.32	0.26	0.57	2.07
IBE	Iberia: Portugal, Spain, Gibraltar	1.34	0.70	4.13	3.74
FR	France, Monaco, Andorra	2.40	1.79	4.81	4.23
BNL	Belgium, Netherlands, Luxembourg	0.28	0.22	0.33	1.31
BRI	British Isles: Ireland, United Kingdom, Isle of Man, Guernsey, Jersey	0.52	0.36	0.98	1.33
DE	Germany	1.13	0.95	1.99	2.04
CRS	Czech Republic, Slovakia	0.42	0.29	0.71	3.70
AUH	Austria, Hungary	0.80	0.34	3.11	8.55
BKN-W	Balkan-West: Slovenia, Croatia, Bosnia & Herzegovina, Serbia, Kosovo, Montenegro, Macedonia, Albania	0.69	0.29	2.41	6.94
BKN-E	Balkan-East: Romania, Bulgaria, Greece	0.62	0.30	1.95	3.87
IT	Italy, San Marino, Vatican	0.43	0.17	1.50	1.40
CH	Switzerland, Liechtenstein	0.67	0.26	2.42	10.24
TR	Turkey, Cyprus	1.71	0.69	6.12	5.41
UA	Ukraine, Moldova	0.46	0.31	0.92	2.79
IS	Iceland	0.23	0.07	0.93	13.19

water footprint of Europe's power sector from 2016 to 2050. Equation (2) below was used to estimate the Aggregated water consumption (AWC) of the power sector in each of the twenty regions presented for the analysis. The results were obtained for 5-year intervals and cover water consumption of fossil-based, nuclear and renewable energy technologies.

$$\mathrm{AWC}_t = \sum_{i=1}^{n} \left(Previously installed capacity_{i,t} \times ProjectedFLH_{i,t} \times WUI_i\right) + \sum_{i=1}^{n} \left(Projected new capacity_{i,t} \times ProjectedFLH_{i,t} \times WUInew_i\right) \quad (2)$$

where i denotes the specific type of power generation (coal, gas, hydropower, solar PV, etc.), t the analysed year. *Projected new capacity* (in MW) and *Projected FLH* (in hours) were obtained from Ref. [16] as part of the results of the simulation of the Regions scenario and the Area scenario.

'*Previously installed capacity*' was calculated as the difference between active power plants in 2015 and power plants that are scheduled for decommissioning by the year t. The projected lifetime for different types of power plants was obtained from Farfan and Breyer [45], who report on the average technical lifetime of 40 years for coal and nuclear power plants, 34 years for gas and oil, and 100 years for hydropower plants.

To compute the water footprint of newly installed thermal power plants, a simple statistical analysis was performed. We determined the most common generator type during the last 15 years for all twenty regions and assigned it to the new capacities in these regions. The cooling technology was selected premised on a similar logic used in the section 'Cooling system identification', which also considers that the cooling system technology should correspond to the generator type and the fuel used at the power plant. Using this approach, *WUI new* factors were assigned.

3. Results

3.1. Current water consumption of the Europe's power sector

In 2015, the total water consumption of Europe's power plant fleet was estimated at a level of 15.54 km^3. The highest amount of water was consumed by hydropower plants (in-stream and reservoirs), which accounted for 61.5% or 9.55 km^3 of the annual water loss. Nuclear and coal-fired power plants consumed 19.4% and 15.5%, respectively. Other technologies (gas-, oil-, biomass- and biogas-fired power plants, CSP and solar PV plants) together were responsible for less than 3.6% of the total water consumption.

According to the IEA statistics [36], the share of hydropower plants in European power generation was about 13.9% in 2015. As mentioned previously, the estimated share of consumed water by hydropower plants is much higher (61.5%). This difference can be explained by the fact that hydropower plants have the largest reported water consumption factors among all power technologies, which, according to Macknick et al. [13], can be up to 68 m^3 per MWh. This value represents the higher limit of the minimum−maximum (min−max) interval for water consumption estimates, which is 21 times higher than the corresponding value for nuclear power plants equipped with cooling towers. Thus, hydropower plants consume up to 21 times more than nuclear plants with cooling towers for the generation of the same amount of electricity.

In contrast to that, gas-fired power plant contribution to the Europe's generation mix was 15.4% in 2015, while their share in the total water consumption was estimated at 2.5%. Compared to other technologies (hydropower, nuclear and other fossil-based plants), Europe's gas power plants have a relatively low water consumption per unit of generated energy. These "water savings" are mostly caused by the commonly used dry cooling systems, which, according to the findings of this study, equip up to 21% of the Europe's gas power plants that exceed 50 MW.

In this study, all hydropower plants, CSP and solar PV plants were assigned to freshwater sources. Thus, the GIS analysis was conducted for thermal power plants presented in the database. The results of the GIS analysis highlighted that about 37.6% of the total active thermal capacity is located within 20 km of the sea coastline. Thus, following the approach described in the study by Biesheuvel et al. [33] and also implemented by Lohrmann et al. [31], it was assumed that these power plants might use seawater for cooling purposes. The use of seawater for cooling represents a "more sustainable" solution, especially for coastal regions with high freshwater scarcity. The share of the assumed seawater-cooled capacities varies in different regions. The results show that regions with the highest shares are Norway, Denmark and Sweden, where the proportion of potentially seawater-cooled thermal capacities was higher than 93%.

As illustrated in Fig. 3, the water consumption for electricity generation is not distributed evenly in Europe either. The "leader" in total (sea- and fresh-) water consumption was France, consuming about 2.39 km^3 annually. Nuclear power plants (mostly equipped with cooling towers), which contributed as much as 77.5% to the final generation mix in 2015 [36], accounted for 64.5% of the total water consumption. Hydropower, the second-largest power generation technology in France in 2015, consumed about 33% of water related to the country's power sector. About 32.4% of the thermal capacity exceeding 50 MW was assumed to be potentially seawater-cooled, thus, freshwater consumption of the country was estimated at the level of 1.83 km^3 annually.

In 2015, the second place of total water consumption was taken by Norway with 1.89 km^3 of water "loss" annually, of which 99.7% was consumed by hydropower. Water consumption of thermal power plants was dominated by gas power plants located at the coastline. Thus, the above-mentioned water consumption value represents losses of freshwater. Therefore, Norway had the largest consumption of freshwater for power generation in Europe.

The results of the analysis highlight that Europe's region with the lowest water demand was Denmark. Total water consumption was 0.02 km^3, of which only 16% was abstracted from freshwater sources (i.e. rivers and lakes).

The specific water demand per 1 MWh of generated electricity reflects the influence of the power generation mix on the average water consumption. The analysis shows that Europe's "leader" was Norway with estimated 15.5 m^3/MWh. The lowest specific water consumption was in Denmark with 0.6 m^3/MWh. Information about other regions presented for the analysis is given in Table 1. This table also includes median, minimum and maximum estimates of water consumption per region.

Figs. 3 and 4 depict the values of the total water consumption in all twenty regions selected for the analysis. The values presented are the estimated median values and min-max intervals for the year 2015. It is crucial to remark that the presented values for Iceland's total water consumption might appear lower than its actual water consumption in 2015. This difference can be explained by the fact that geothermal technology, which represents the second main power generation technology of the country and is contributing 28.8% to the generation mix, was left out of the scope of this research.

3.2. Projected water consumption in 2050

In the case that the Area scenario is implemented, the annual total water consumption is estimated at the level of 11.14 km^3 in 2050. Thus, the total water consumption was projected to decrease by about 28.3% by 2050, compared to the 2015 level. In contrast to that, if the Regions scenario is pursued, the annual total water consumption in Europe will decrease to 11.77 km^3 by the end of 2050. Compared to the 2015 level, this will result in a 24.2% decrease in water consumption. Fig. 5 illustrates the projected annual water consumption on a regional level for both scenarios. As highlighted in the figure, the projected "leaders" in total water consumption are Turkey, Norway and Sweden due to their high shares of hydropower in the final generation mix. In 2050, these three countries are projected to be responsible for about 47.5% of Europe's total water consumption according to the Area scenario, and for 44.8% according to the Regions scenario, respectively. Both scenarios project Turkey's power sector to have the highest water demand in Europe in 2050 with 1.91 km^3 of water consumed annually.

As shown in Fig. 6A, the largest decrease in annual water consumption is projected during the period from 2015 to 2030. This decrease can be explained by the large defossilisation of the power sector, which, according to these scenarios, is scheduled during 2015−2030 [16]. In particular, fossil-fuel power plants are projected to consume about 35.3% of the total amount of water used by the Europe's power sector in 2020. According to the Area scenario, this share is estimated to consistently decrease to 13.9% in 2030, to 4.5% in 2040 and to about 1.6% in 2050. In contrast to that, the Regions scenario projects a slightly higher share of 2.0% for fossil-fuel power plants in the total water consumption by the end of 2050. Thus, both scenarios project an almost full elimination of the water footprint of fossil-fuelled power plants.

3.3. Comparison of the Area and Regions scenarios

A suitable scenario should ensure better mitigation strategies for water use in the power generation sector during the whole

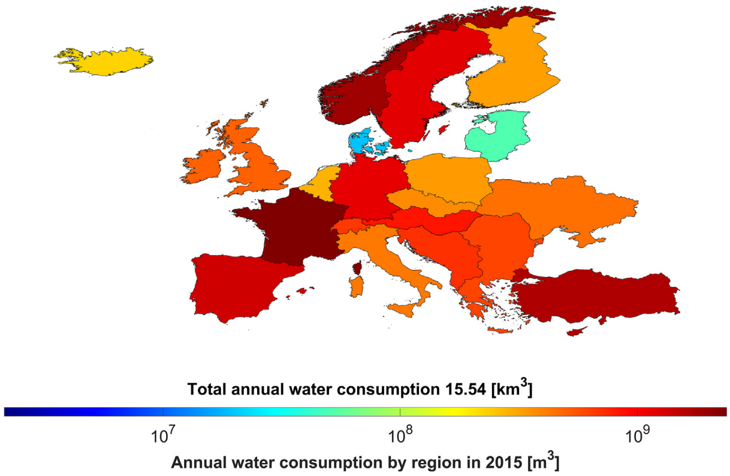

Fig. 3. Total water consumption (median values) of the Europe's power sector in 2015, in m^3.

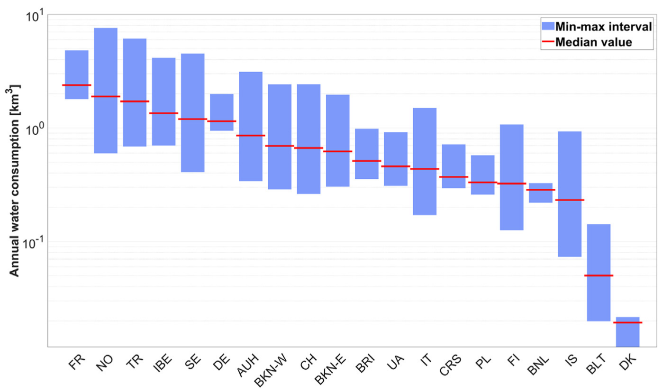

Fig. 4. Total water consumption of power sector in 2015, per region. Y-axis is given in logarithmic scale.

transition period. The results of the study show that the total annual water consumption projected for both scenarios in 2050 differs only marginally (0.64 km^3 per year or 5.4%). Another way to evaluate and compare the scenarios is to use the metric of cumulative difference introduced by Lohrmann et al. [31].

The cumulative difference represents the amount of water that could be excluded from power generation in the case that the Area scenario is implemented instead of the Regions scenario. In other words, the cumulative difference illustrates the "savings" of water, which are aggregated for the entire transition period from 2015 to 2050.

In this study, the cumulative difference was calculated using Equation (3). This equation determines the area between the curves in Fig. 6A, which represents the annual water consumption for both scenarios.

$$Cumulative\ diff = \int_{2015}^{2050} \left(AWC(t)_{Regions} - AWC(t)_{Area}\right) dt \quad (3)$$

where *AWC* denotes the Aggregated water consumption of the power sector, in m^3, and *t* the analysed year.

The results of the calculations are illustrated in Fig. 6B, which illustrates that the Area scenario allows to gradually save up to 18.09 km^3 of water during the 35-year transition period, compared to the situation when the Regions scenario is selected for implementation.

3.4. Identification of potential bottlenecks of the energy transition

The next step of the study was to evaluate the potential impact

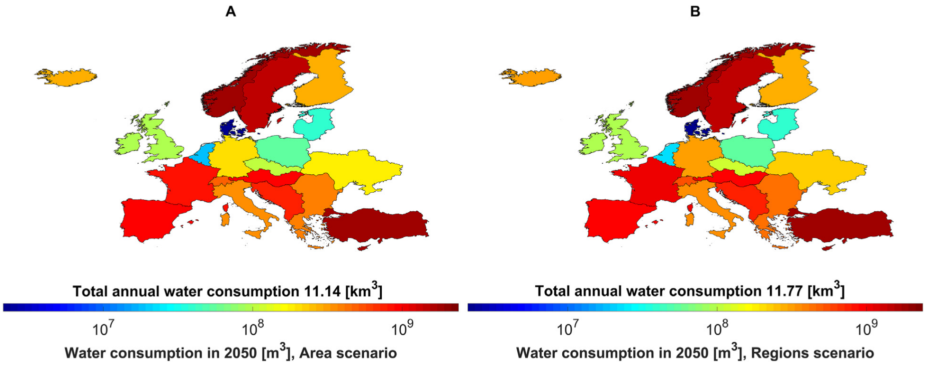

Fig. 5. Projected total water consumption (median values) of Europe's power sector in 2050, in m^3, according to the Area scenario (A) and the Regions scenario (B).

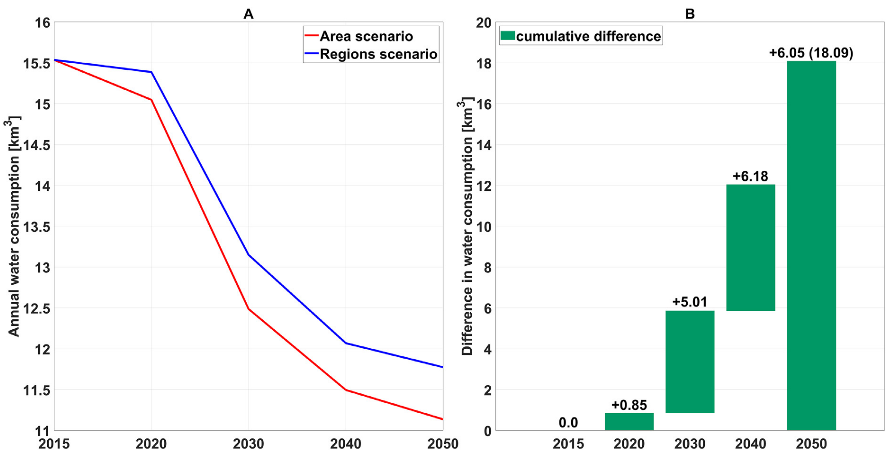

Fig. 6. Comparison of the Area and Regions scenario. Changes in total annual water consumption from 2015 to 2050, in m^3, according to the Area scenario and the Regions scenario (A). Cumulative difference in water consumption (B).

of the energy transition on the regional level. Fig. 7 highlights the development of the water consumption in 2015–2050 on the regional level for the Area scenario (Fig. 7A) and the Regions scenario (Fig. 7B). As shown in the figure, in Europe as a whole as well as in most of Europe's regions, the total water consumption of the power sector is projected to decrease by the end of 2050 (marked in green colour). This projected decrease in the annual total water consumption reflects the projected decommissioning of old fossil-fired power plants and their replacement by less water consuming renewable energy technologies [16].

However, in five out of twenty regions an increase in the annual total water consumption of up to 24% is projected during 2015–2050. In Fig. 7, these regions are marked with red colour.

The results show that an increase of 7% is projected in Austria and Hungary (AUH region), another 7% in the Balkan-West countries, 11% in Turkey, 21% in Iceland and 24% in Sweden. Thus, the estimated average increase for these regions is 14%. According to the Area scenario, during the transition period 2015–2050, the commissioning of new hydropower plants or expansion of capacity is projected in 19 of Europe's regions (with the exception of Finland) presented for the analysis. However, in the case of the five above-mentioned regions, the share of these new hydro capacities is high: compared to 2015, on average, an increase of 29.4% of the hydropower capacities is projected in 2050. Thus, the “savings” of water achieved by the decommissioning of old thermal power plants could not compensate for the “additional” water consumption of the increased hydropower capacities.

4. Discussion

Sustainability aspects of the Area and Regions scenarios were discussed in previous studies [16,39]. On the one hand, it was shown that both scenarios are consistent with the targets imposed by the Paris Agreement [46]. In particular, Child et al. [16] reported that a complete defossilisation of the European energy system could be achieved by 2035 in the Area, and by 2045 in the Regions

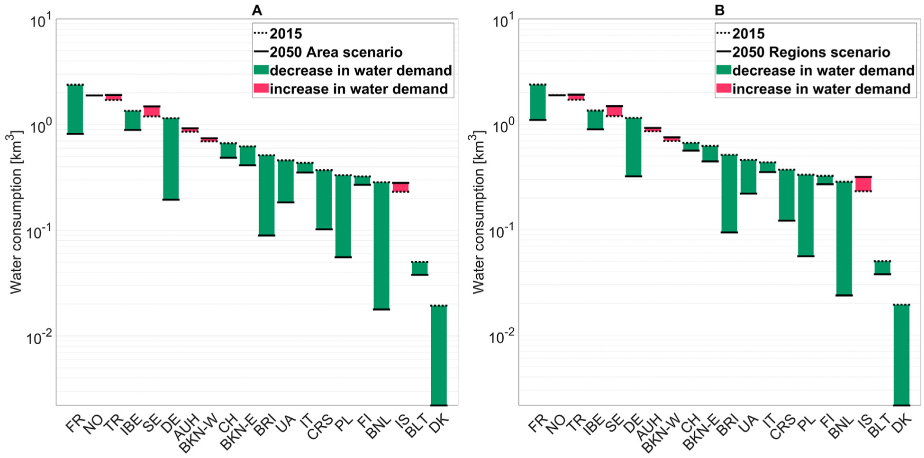

Fig. 7. Changes in total annual water consumption (median values) from 2015 to 2050, in m^3, according to the Area scenario (A) and the Regions scenario (B). The y-axis is given in logarithmic scale.

scenario. On the other hand, the economic feasibility of the presented scenarios was assessed. Child et al. [16] projected the decrease of the levelised cost of electricity (LCOE) from the current 69 €/MWh to 51 €/MWh in the Area scenario and to 56 €/MWh in the Regions scenario. In addition, the technical feasibility and governmental policies were taken into account in their research.

In contrast to that, this study focuses on the assessment of the water footprint of the European power sector, which is not always included in modelling studies. The results of this study indicate that the water demand of power plants should not be neglected in the discussion on the sustainability of energy transition scenarios.

In particular, the results show that in the case that the Area scenario is implemented, the total water demand (of fossil-based and renewable energy technologies) for Europe as a whole can be decreased by up to 28.3% during the transition period until 2050. In eight regions, the implementation of a zero GHG electricity system will lead to a reduction in water consumption in the power sector exceeding 60%. However, in five out of twenty regions the total water demand is projected to increase between 7% (Balkan-West countries) to 24% (Sweden), with an average ascent of 14%, according to the Area scenario. The projected increase in water demand is on account of the extensive implementation of new hydropower capacities, which are scheduled for commissioning during 2015–2050. Thus, even if these regions possess large hydropower potentials, they require a more careful assessment of water resources before the implementation of these scenarios. Such an assessment is pivotal, as the consumed water represents the “lost” water by means of evaporation and, thus, would not return to the local water systems.

The results of this transition show several potential impacts related to water footprints. First, the reduction in thermal power plant capacity can result in an increase in water quality and availability at a local level in some locations, especially for the Area Scenario. Some cooling systems in thermal plants extract water at a lower temperature than it is returned, thereby affecting water quality through thermal pollution [18]. In addition, cooling may result in evaporative losses that displace water over long distances. The reduced water footprint shown in this transition may then contribute to the achievement of the United Nations Sustainable Development Goal (SDG) 6 – Clean Water and Sanitation, which aims to increase water quality and reduce withdrawals as a proportion of the total water resources. In addition, SDG 12 calls for the responsible consumption and production through reductions in materials' footprints (including water). It is estimated that the current increasing trend of water scarcity could lead to the displacement of approximately 700 million people even by 2030 [18].

A diminished need for water in energy systems may increase water security in a broader sense. This may make water available to increase such provisioning services as agriculture. Also, retaining water in ecosystems may sustain various cultural services, such as recreation, spirituality, science and art. A reduction in water scarcity in some regions may also contribute to a decreased potential for conflict as well as reduce inequalities [47]. Failure to establish an effective balance between water and energy security can have potential social, economic and environmental consequences [21]. Also, it has been argued that the nexus can be expanded to include food, land use and climate, suggesting a complex system affecting many areas of life [48].

According to the WRI Aqueduct Atlas [4], four out of five regions with the projected increases in water consumption (except for Turkey) are reported to have low baseline water stress, which is indicative of a high availability of renewable water resources. However, Turkey, which is projected to increase its energy-based water consumption by 11% and, thus, to become the largest water consumer in Europe, is characterised by high baseline water stress [4]. In addition, the agricultural sector of Turkey is reported to dominate the country's water demand with a 75% share of the total water consumption [49] (compared to an average of 44% for Europe [50]). It is projected that all larger regions of Turkey even require access to desalination to guarantee freshwater supply [51], which is also driven by demand for irrigation [52]. Thus, the projected implementation of a high share of hydropower might impose an additional stress on Turkey's water resources and create a higher competition for water resources with the pivotal agricultural sector. Therefore, a further systematic analysis is required to evaluate the effect of the implementation of these scenarios for the case of Turkey.

According to Gleick [53], losses from hydropower plants vary greatly and are affected by such factors as regional climate, average annual flow of the water body, dam height, gross static head, reservoir area and volume, drainage area characteristics, installed capacity of the hydropower plant, type of power plant and average annual energy production. The authors conclude that the relationship between gross static head and dam height may be better indicators of evaporative water loss and other sustainability concerns than power production. This may be particularly important when considering the difference between run-of-river hydropower and large dams. In addition, many large dams and reservoirs have been constructed for multiple purposes that may result in larger reservoirs than would otherwise be needed for electricity generation. This could exaggerate statistics related to evaporative losses for hydropower in some cases and Gleick [53] recommends that this key distinction be taken into account in any overall environmental assessment. Likewise, Torcellini et al. [54] also indicate that there is no easy way to disaggregate the end uses of hydropower dams and reservoirs, which makes an assessment of evaporative losses per unit of electricity generated problematic. For the case of Turkey, the rather high level of estimated consumption from hydropower may produce benefits greater than those measured by electricity generation alone (e.g. flood control, consistent water supply for irrigation and recreational use).

Therefore, the provided values of specific water consumption per 1 MWh of generated electricity represent rough estimates that may even seem “ambiguously formulated” for the case of hydropower in certain cases according to Gleick [53]. Given the wide-ranging geography of different parts of Europe, appropriate caution in interpreting results is advised. In order to obtain more accurate projections, a life-cycle assessment of the entire energy system should be conducted.

The choice of 2015 as a representative year for this analysis merits further comments. As stated previously, heatwaves in parts of Europe caused temporary reductions in coal power generation [6,7]. In addition, 2015 was at the end of a 5-year trend of decreasing wholesale electricity prices in Europe. Some regions of Europe even saw the lowest wholesale electricity prices in more than a decade [55]. As thermal power plant operation is related to wholesale prices, one could surmise that thermal plant full load hours may have been lower than normal during 2015. This could mean that initial estimations of water consumption for power production in Europe (15.5 km^3) may have been somewhat lower than a truly representative year, making projections of water savings presented here rather conservative. At the same time, changes in European electricity generation sources due to increasing impacts of variable renewable energy had already resulted in a decreasing trend in full load hours for thermal power plants over the preceding decade [56]. Therefore, selection of a representative year for comparisons within such a context of change is inherently problematic.

5. Conclusions

The study addresses the problem of extensive energy-based water use in Europe. In particular, the current water footprint of 3276 power generation units exceeding 50 MW was estimated and aggregated on a per region and country level.

Using the results of the Area and Regions scenarios computed with the LUT Energy System Transition model, the water demand of the European power sector was projected for the time period from 2015 to 2050. The results of the study reveal that the transition to a 100% renewable electricity system might lead to a decrease of up to 28.3% for Europe's energy-based water consumption by 2050, compared to the 2015 level. As the result of defossilisation, the water footprint of thermal power plants is projected to decrease to the negligible amount of 1.6% in 2050 according to the Area scenario. In addition, the study highlights the potential bottlenecks of the future energy transition, where the change of the energy system might lead to an increase in energy-based water consumption. As a consequence, this change of the energy system can become an additional factor contributing to the already existing water stress in a region. The impacts of new hydropower capacity in particular should be viewed within specific geographical and operational contexts to best determine if related consumption would contribute to greater water stress or other environmental harm.

The results of the study demonstrate water-related benefits of establishing power transmission interconnections between the regions of Europe. During the investigated period from 2015 to 2050, the additional savings of water (due to power interconnections) are estimated to reach 18.09 km^3 of water.

Therefore, the results of the study could potentially support Europe-wide and regional policymaking by providing another dimension to the discussion of the sustainability of the energy transition scenarios.

Non-English speaking authorsfinalization of the manuscript

The second author, Michael Child, who is a native English speaker, has conducted proofreading of the article.

Data availability

The data that support the findings of this study are available from GlobalData [25].

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Alena Lohrmann: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft. **Michael Child:** Resources, Validation, Writing - Review & Editing. **Christian Breyer:** Writing - Review & Editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121098.

References

[1] Eurostat. Water use in industry. http://ec.europa.eu/eurostat/statisticsexplained/%0Aindex.php/Water_use_in_industry; 2014.
[2] Roehrkasten S, Schaeuble D, Helgenberger S. Secure and sustainable power generation in a water-constrained world. Potsdam: Institute for Advanced Sustainability Studies (IASS); 2015. https://www.iass-potsdam.de/sites/default/files/files/iass_2015_powergenerationinawaterconstrainedworld.pdf.
[3] World Economic Forum (WEF). The global risks report 2020. fifteenth ed. Switzerland: Cologny; 2020. https://www.weforum.org/reports/the-global-risks-report-2020.
[4] Water Resources Institute (WRI). Aqueduct Atlas - baseline water stress country rankings. 2020. Washington, DC, https://www.wri.org/applications/aqueduct/country-rankings/.
[5] Wong C, Williams C, Pittock J, Collier U, Schelle P. World's top 10 rivers at risk. WWF International. Gland; 2007. https://assets.panda.org/downloads/worldstop10riversatriskfinalmarch13_1.pdf.
[6] Polskie Sieci Elektroenergetyczne (PSE) S.A.. Information on the situation in the Polish power system. http://www.pse.pl/index.php?dzid=32&did=2516; 2015.
[7] STEAG. Transparency data STEAG GmbH. 2015. http://transparenz.steag.com/%0At-s-home.html.
[8] Guardian The. Heatwave shuts down nuclear power plants. 2006. https://www.theguardian.com/environment/2006/jul/30/energy.weather. [Accessed 18 March 2020].
[9] European Environmental Agency (EEA). Adaptation challenges and opportunities for the European energy system. Building a climate-resilient low-carbon energy system. 2019. https://doi.org/10.2800/227321. Luxembourg.
[10] Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, et al. Trajectories of the Earth system in the anthropocene. Proc Natl Acad Sci Unit States Am 2018;115:8252–9. https://doi.org/10.1073/PNAS.1810141115.
[11] Meldrum J, Nettles-Anderson S, Heath G, Macknick J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ Res Lett 2013;8:015031. https://doi.org/10.1088/1748-9326/8/1/015031.
[12] European Commission. In-depth analysis in support of the commission communication COM. Brussels: 2018 2018;773. https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf.
[13] Macknick J, Newmark R, Heath G, Hallett KC. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett 2012;7. https://doi.org/10.1088/1748-9326/7/4/045802.
[14] Löffler K, Burandt T, Hainsch K, Oei P-Y. Modeling the low-carbon transition of the European energy system - a quantitative assessment of the stranded assets problem. Energy Strateg Rev 2019;26:100422. https://doi.org/10.1016/J.ESR.2019.100422.
[15] Pleßmann G, Blechinger P. How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050. Energy Strateg Rev 2017;15:19–32. https://doi.org/10.1016/J.ESR.2016.11.003.
[16] Child M, Kemfert C, Bogdanov D, Breyer C. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew Energy 2019;139:80–101. https://doi.org/10.1016/J.RENENE.2019.02.077.
[17] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/J.ENERGY.2019.03.092.
[18] Siddiqi A, Anadon LD. The water-energy nexus in Middle East and North Africa. Energy Pol 2011;39:4529–40. https://doi.org/10.1016/j.enpol.2011.04.023.
[19] Wu XD, Chen GQ. Energy and water nexus in power generation: the surprisingly high amount of industrial water use induced by solar power infrastructure in China. Appl Energy 2017;195:125–36. https://doi.org/10.1016/j.apenergy.2017.03.029.
[20] Byers EA, Hall JW, Amezaga JM. Electricity generation and cooling water use: UK pathways to 2050. Global Environ Change 2014;25:16–30. https://doi.org/10.1016/j.gloenvcha.2014.01.005.
[21] Holland RA, Scott KA, Flörke M, Brown G, Ewers RM, Farmer E, et al. Global impacts of energy demand on the freshwater resources of nations. Proc Natl Acad Sci Unit States Am 2015;112:E6707–16. https://doi.org/10.1073/PNAS.1507701112.
[22] European Commission. Electricity interconnection targets. Brussels, Belgium. https://ec.europa.eu/energy/topics/infrastructure/electricity-interconnection-targets_en; 2016.
[23] Victoria M, Zhu K, Brown T, Andresen GB, Greiner M. Early decarbonisation of the European energy system pays off. Nat Commun 2020;11:6223. https://doi.org/10.1038/s41467-020-20015-4.
[24] Mekonnen MM, Gerbens-Leenes PW, Hoekstra AY. The consumptive water footprint of electricity and heat: a global assessment. Environ Sci Water Res Technol 2015;1:285–97. https://doi.org/10.1039/C5EW00026B.
[25] GlobalData Ltd. GlobalData power. Database. London. 2014. http://power.globaldata.com/Home.aspx.
[26] Platts. World. Electric power plants database. S&P Glob. London; 2016.
[27] IRENA. Renewable. Energy capacity statistics 2015. Abu Dhabi 2015;75:44. https://doi.org/10.1016/j.renene.2014.09.059.
[28] Lehner B, Liermann CR, Revenga C, Vörömsmarty C, Fekete B, Crouzet P, et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front Ecol Environ 2011;9:494–502. https://doi.org/10.1890/100125.
[29] Farfan J, Breyer C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. J Clean Prod 2017;141:370–84. https://doi.org/10.1016/j.jclepro.2016.09.068.
[30] ECOFYS. Geo-localised inventory of water use in cooling processes, assessment of vulnerability and of water use management measures. 2014. Utrecht, Netherlands, https://ec.europa.eu/environment/archives/water/adaptation/pdf/InventoryCoolingWaterUse.pdf.
[31] Lohrmann A, Farfan J, Caldera U, Lohrmann C, Breyer C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. Nat Energy 2019;4:1040–8. https://doi.org/10.1038/s41560-019-0501-4.
[32] Wessel P, Smith WHF. A global, self-consistent, hierarchical, high-resolution shoreline database. J Geophys Res Solid Earth 1996;101:8741–3. https://doi.org/10.1029/96JB00104.
[33] Biesheuvel A, Witteveen+Bos, Cheng I, Liu X, Greenpeace International. Methods and results report: modelling global water demand for coal based power generation. 2016. Amsterdam, http://www.greenpeace.org/international/Global/international/briefings/climate/2016/Coal-Water/Technical-Report-Coal-Water-Methods-Results.pdf.
[34] Diehl TH, Harris MA, Murphy JC, Hutson SS, Ladd DE. Methods for estimating water consumption for thermoelectric power plants in the United States. 2013. https://doi.org/10.3133/sir20135188.
[35] Luo T, Krishnaswami A, Li X. A methodology to estimate water demand for thermal power plants in data-scarce regions using satellite images. Washington, DC: Technical note. World Resources Institute; 2018. https://www.wri.org/publication/methodology-estimate-water-demand-thermal-power-plants-datascarce-region.
[36] International Energy Agency. Statistics. Global energy data at your fingertips. 2018. Paris.
[37] Medarac H, Magagna D, Hidalgo Gonzalez I. Projected fresh water use from the European energy sector. 2018. https://doi.org/10.2760/30414. Luxembourg.
[38] Larsen MAD, Drews M. Water use in electricity generation for water-energy nexus analyses: the European case. Sci Total Environ 2019;651:2044–58. https://doi.org/10.1016/j.scitotenv.2018.10.045.
[39] Child M, Bogdanov D, Breyer C. The role of storage technologies for the transition to a 100% renewable energy system in Europe. Energy Procedia 2018;155:44–60. https://doi.org/10.1016/J.EGYPRO.2018.11.067.
[40] ENTSO -E. TYNDP 2016 scenario development report. 2016. Brussels.
[41] ABB. HVDC. References. Zürich. https://new.abb.com/systems/hvdc/references. [Accessed 12 January 2018].
[42] Siemens AG. High-voltage direct current transmission. Munich, https://www.energy.siemens.com/co/pool/hq/power-transmission/HVDC/HVDC-Classic/HVDC-Classic_Transmission_References_en.pdf. [Accessed 12 January 2018].
[43] France-Angleterre Interconnexion. Assets. 2018. London, http://ifa1interconnector.com/about-us/assets/. [Accessed 12 January 2018].
[44] Sadovskaia K, Bogdanov D, Honkapuro S, Breyer C. Power transmission and distribution losses – a model based on available empirical data and future trends for all countries globally. Int J Electr Power Energy Syst 2019;107:98–109. https://doi.org/10.1016/J.IJEPES.2018.11.012.
[45] Farfan J, Breyer C. Aging of European power plant infrastructure as an opportunity to evolve towards sustainability. Int J Hydrogen Energy 2017;42:18081–91. https://doi.org/10.1016/j.ijhydene.2016.12.138.
[46] UNFCCC. Conference of the parties (COP). Adoption of the Paris agreement. Proposal by the president. Paris 2015;21932. https://doi.org/FCCC/CP/2015/L.9/Rev.1.
[47] United Nations Department of Economic and Social Affairs. Sustainable development goals. https://sdgs.un.org/.
[48] Sušnik J, Masia S, Indriksone D, Brēmere I, Vamvakeridou-Lydroudia L. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. Sci Total Environ 2021;775:145827. https://doi.org/10.1016/j.scitotenv.2021.145827.
[49] OECD. Agricultural water pricing: Turkey. 2010. Ankara, Turkey.
[50] European Commission. European Commission reaffirms the importance of sustainable usage of water in agriculture. Brussels. https://ec.europa.eu/info/news/sustainable-usage-water-agriculture_en; 2017.
[51] Kilickaplan A, Bogdanov D, Peker O, Caldera U, Aghahosseini A, Breyer C. An energy transition pathway for Turkey to achieve 100% renewable energy powered electricity, desalination and non-energetic industrial gas demand sectors by 2050. Sol Energy 2017;158:218–35. https://doi.org/10.1016/J.SOLENER.2017.09.030.
[52] Caldera U, Breyer C. Assessing the potential for renewable energy powered desalination for the global irrigation sector. Sci Total Environ 2019;694:133598. https://doi.org/10.1016/J.SCITOTENV.2019.133598.
[53] Gleick PH. Environmental consequences of hydroelectric development: the role of facility size and type. Energy 1992;17:735–47. https://doi.org/10.1016/

0360-5442(92)90116-H.
[54] Torcellini P, Long N, Judkoff R. Consumptive water use for U.S. Power production. United States; 2003. https://doi.org/10.2172/15005918.
[55] European Commission. Energy prices and costs in Europe. 2020. Brussels, Belgium.
[56] de Groot M, Crijns-Graus W, Harmsen R. The effects of variable renewable electricity on energy efficiency and full load hours of fossil-fired power plants in the European Union. Energy 2017;138:575−89. https://doi.org/10.1016/j.energy.2017.07.085.

Publication III

Lohrmann A., Farfan J., Lohrmann C., Kölbel J., and Pettersson F.

Troubled waters: Estimating the role of the power sector in future water scarcity crises

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Troubled waters: Estimating the role of the power sector in future water scarcity crises

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Abstract

One of the effects of climate change is on freshwater availability. The widespread drought in the summer of 2022 impeded access to freshwater, putting into question the reliability of the current and future energy generation and evoking concerns of competition of different industries for water. In response to climate change, energy transition scenarios represent pathways to a more sustainable energy system, but often overlook the water footprint of the energy sector. Therefore, this study uses machine learning for the identification of thermal power plants' cooling systems to estimate the water footprint of the current and future energy system using six energy transition scenarios. It is built on published data on thermal power plants announced globally, with a total capacity of 3,277 GW, which are planned to be installed between 2020 and 2050. The results demonstrate that the water consumption of the global power sector may increase by up to 50% until 2050, compared to the 2020 level. The findings also emphasize that every new thermal power plant installed in the future will be associated with a higher average water demand per unit of generated electricity. Hence, the rising stress on water systems becomes another argument supporting the transition towards renewables.

Keywords

Power plants; Water consumption; Cooling technology; Water criticality; Machine learning

Highlights

1. Specific water consumption of thermal plants will increase to 1.7 m^3/MWh by 2050
2. Specific water consumption of the global energy sector reaches 3.04 m^3/MWh by 2050
3. Water consumption of the global power sector may increase by up to 50% by 2050
4. Water consumption criticality merges water availability and power sector water use
5. Countries with a high level of water consumption criticality were highlighted

1. Introduction

Climate change is also a water change, because the effects of climate change are strongly felt through changes in freshwater availability, its disrupted supplies, and exacerbated water scarcity [1,2]. Since 2012, "water crisis" was constantly included in the Top-5 Global Risks by

Impact in the yearly Global Risks Report released by the World Economic Forum (WEF) [3]. Even according to very modest estimates, already in 2017 about 47% of the global population (or 3.6 billion) lived in areas that suffer from water scarcity at least one month every year [4]. This is the result of a constantly increasing demand for water, food, and energy of a growing population as well as the economy, and the depletion of water resources [5]. The global power sector is currently the second largest consumer of freshwater resources after agriculture. In particular, a considerable amount of water is consumed (evaporated) in hydropower generation, and in thermal power plants (coal-, gas-, oil-fired and nuclear) for cooling. According to some estimates, the energy-related water demand can reach a level as high as 40% of the total water demand in a country [6].

Despite the environmental concerns reflected in various reports and countries' obligations to reduce carbon emissions in the power sector to tackle climate change, according to the information provided in the GlobalData dataset there are plans to commission at least 2.6 TW of new thermal power plant capacities worldwide by 2050 [7]. This projected increase in thermal power capacities globally will result in an increase in water demand for power generation. This may impose an additional pressure on the areas already suffering from high or extremely high water stress and worsen the competition for the already limited freshwater resources with other vital sectors such as agriculture and housing.

Generally, energy transition scenarios aim to demonstrate a pathway towards a more sustainable renewable energy system from a carbon emissions perspective. Yet, the water footprint of the current and future energy system in many transition scenarios is often overlooked [8,9]. Therefore, water scarcity and water demand should be taken into account while designing transition scenarios.

Several previous studies have approached this problem from different perspectives, timeframes and geographical scales. A wide range of studies exist for the United States [10], China [11], the United Kingdom [12], South Africa [13] and India [14]. On a regional level, studies exist for the European continent [15] and Middle East and North Africa (MENA region) [16]. A handful of studies project the future water demand on a global scale [17]. Some studies are focused on the estimation of the operational water use in the energy sector (when water is mainly used for cooling purposes or cleaning) [14], other studies [11,16] employ a lifecycle assessment (LCA) approach which, in addition to the operational water use, considers water use associated with the foreground and background processes of the energy production (e.g., extraction of the fuel). However, the results of this LCA analysis should be treated with caution because an accurate allocation of the calculated water demand to water bodies may be challenging unless the extraction of the fuel, its treatment and its power generation processes are located in the same geographical area.

Studies that aim to predict the future water demand of the energy sector typically use aggregated capacity data for the water footprint projections (for instance, the study by Terrapon-Pfaff et al. [8]). However, this approach has two main drawbacks. First, it is difficult to quantify the uncertainty of the estimated values (due to their aggregated nature). Second, similarly to the results of the LCA approach, the water demand predicted using this method can neither be allocated to a specific power plant nor to a specific water body to analyze the potential consequences of the energy-related water abstractions on the availability of freshwater resources on the local-level.

Thus, the current knowledge gap is the lack of information on the current and future water demand on the individual power plant level and the future water demand on the level of the power sector as a whole. This gap implies that current water footprint analyses may be restricted by impeding the ability to trace the water demand to its origin, to track its development over time (inability to track the operation and decommissioning of power plant units), as well as to capture the uncertainty of the results based on the cooling technology of individual power plants and the estimation model. Apart from that, the availability of information regarding the current water demand of specific power plants is essential for designing future sustainable energy systems, especially in areas with significant water scarcity coupled with elevated power demand.

Hence, to address this information gap, in contrast to previously conducted studies, this study aims to assess the future water demand of the energy sector using the reported data on individual, announced and planned power plants globally. The water demand assessment is conducted from the perspective of water consumption and water withdrawal, with a special emphasis on the freshwater consumption and on the water consumption per unit of generated electricity. The estimates are presented for the time period from 2020 to 2050 for the entire power sector and for the global thermal power plant fleet separately. A focus of this study is on thermal power plants since they, in addition to a high water demand, have a large environmental footprint and, thus, should be phased out in the near future. In the study, we deploy a machine learning algorithm using the available historical power plant data to identify the most probable cooling technology of each individual future power plant unit, and, subsequently, to estimate its future water footprint.

This paper shows that currently planned power plants not only significantly delay a successful low-carbon transition, but they also significantly increase water consumption by the power sector. In addition, taking into consideration the geographically distributed water stress provides a clearer view of the impact of the power sector on the water systems at a local level. Therefore, the results of this study address two areas of research: Firstly, the projections of the total water demand add another dimension to the discussion of the sustainability of the energy transition scenarios. Secondly, they may provide a basis for enabling an effective water policy and planning on a country-level and globally.

The rest of the paper is structured as follows. Chapter 2 goes through the methods deployed over the course of this study, and Chapter 3 presents its' results. The study concludes with the discussion in Chapter 4, which puts the obtained results into the context of the global water crisis, and Chapter 5, where the conclusions are drawn.

2. Methods

2.1 Power plant data

The main source of power plant data for this study was the power plant database obtained from Lohrmann et al. [18]. This database contains information on 13'863 active thermal power plant units (coal, gas, nuclear and oil) exceeding 50 MW, which were installed globally from 1923 to 2015. In order to complement it with power plants that were installed during 2016-2020 and to obtain information concerning future power plants, we used the GlobalData database [7] to add 4'289 "future" power plants, which correspond to 3.3 TW of thermal power capacity. More information regarding the power plant data compilation process is provided in Section A of Supplementary Materials.

Many power plants in the compiled dataset (corresponding to 1.9 TW of thermal capacity) did not have information concerning their future commission year. However, this information is crucial for the assessment of the future water footprint of the thermal power generation. Thus, the next step was to assign commission years to individual power plants for which this information was missing in the initial database [7]. Section B of Supplementary Materials discusses the approach to assign commission years to individual power plants for which this information was missing in the initial database. Sections C and D of Supplementary Materials demonstrate the potential impact of this step on the presented water footprint estimates on the example of the results obtained for the Bloomberg New Energy Finance (Bloomberg NEF) scenario.

2.2 Cooling technologies of announced plants

Since the power plant database did not contain any information concerning the cooling systems installed in the announced power plants, the type of cooling needs to be determined. In this study, the projection of the cooling technologies utilized for individual power plants is based on a method deploying machine learning, which was developed and tested in a previous study [19]. Previous research highlighted the existing wide application of machine learning in water management [20].

The method applied in this study uses information on the technical characteristics of individual power plants to assign the cooling technology to each individual power plant. The variables *"Power plant capacity (total active)", "Fuel used in power plant", "Year Online", "Type of boiler"* are available from the power plant database for each specific power plant, *"Seawater-cooling"* was assigned to each specific unit, as discussed in Section 2.4 and the remaining information was obtained from open sources that corresponds to their specific location (such as "*Freshwater total, per country*", "*Seasonal water variability, per country*", *"Agricultural water withdrawal as percent of total renewable water resources of the country, per country"* – all obtained from [21], "*Water stress score, province*" from [22], *"Days of warm weather"* from [23], and other country-level socio-economic variables, such as the "*Corruption perception index*" – from [24], "*GDP per capita of the country*" – from [25], and "*Prices for electricity*" – from [26]. The selection of these variables for the cooling type assignment was based on a literature review of previous water-energy nexus studies and of reports on local factors influencing the cooling systems selection [32,33]. For example, some previous studies relied on the ratios of cooling system types in the region / country found in various literature sources [27, 29]. Other studies identified cooling technologies using satellite images [28]. However, the majority of studies identified the type of installed cooling system based on power plants' proximity to large water bodies: to major rivers [30] and sea / ocean coastline [17, 31].

The cooling technology assignment method combines the filter method (Pearson) correlation and the differential evolution feature selection (DEFS) wrapper method [34] to select features that are relevant for the cooling technology identification. It is a sophisticated approach for the selection of relevant variables that has demonstrated high accuracies for the assignment of cooling technologies in the previous study [19]. Next, the selected features are used in a K-nearest neighbor (KNN) classifier to assign cooling technologies to individual power plant units. The classifier was trained and cross-validated using the power plant database [18], which contains information on active thermal power plant units commissioned before the year 2015 globally, and using additional information. The training data was initially divided into a separate data set per fuel type to train fuel-specific models in order to achieve a better classification accuracy. Both the 5-fold cross-validation and the holdout split were applied with stratified random sampling to ensure that the training, validation and test sets all contain similar shares of the cooling technology classes (dry, inlet cooling, once-through cooling, cooling tower and pond cooling). Figure 1 illustrates the flow chart of the classification model.

The set of features selected by the model for the cooling technology prediction using the KNN classifier as well as the calculated test set accuracies are presented in Section E of Supplementary Materials. The obtained test set accuracies are considerably higher than the reported accuracies of other previously used approaches for the missing value imputation of the cooling technology, which use aggregated capacity data and pre-determined shares of cooling technologies for the water footprint projections [35].

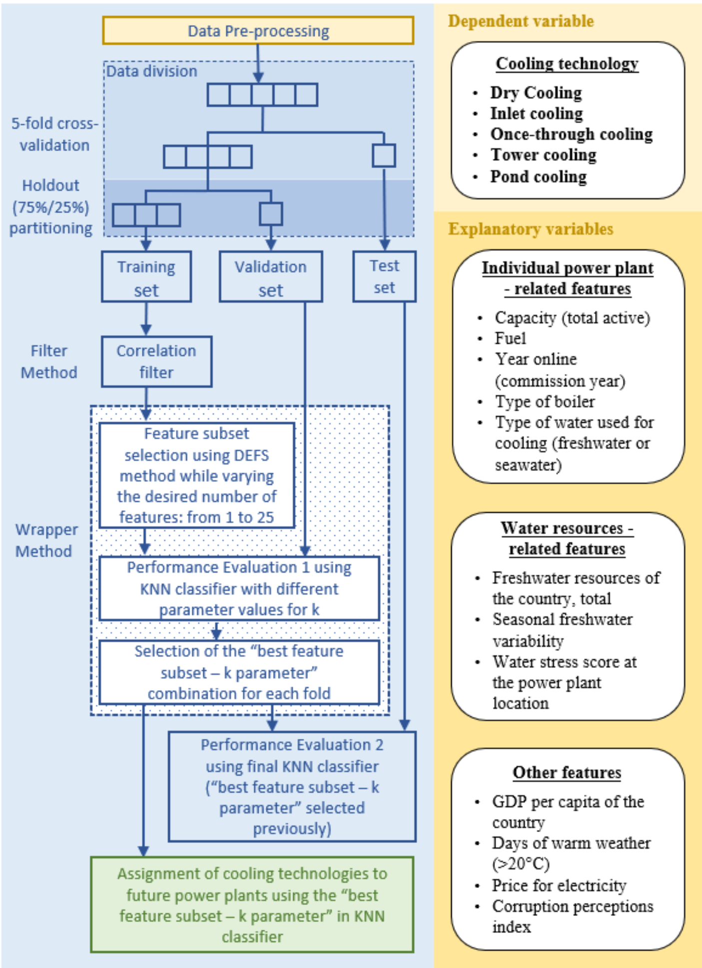

Figure 1. Model for cooling technology identification using K-nearest neighbor (KNN) classifier, from [19].

2.3 Type of water for cooling

The selection of cooling technologies (and their optimal design) implemented in individual power plants is influenced by the type of water (freshwater or seawater) available for cooling purposes [32]. Typically, power plant databases do not contain information concerning the type of water used for cooling. This information is usually available from the reports issued by the power plants operators for individual power plants. However, collecting this information from plant operators, especially for future (planned) power plants and on the global scale, is highly impractical, and for many of the power plants in non-transparent states becomes impossible. The GlobalData dataset [7] contains neither information concerning the type of water used by future (planned) power plants nor their exact location. To overcome this data limitation, in this study, the type of water for cooling was assigned to individual power plants using the current shares of seawater-cooled thermal power capacities obtained from Lohrmann et.al. [18]. These shares were calculated using the results of a Geographic Information Systems (GIS) analysis performed in the study and represent the percentage of the country's current active thermal capacity that uses seawater for cooling purposes. Although this approach may add uncertainty to the results of the study, it was selected for several reasons. First, the shares of the seawater-cooled power plants in the generation mix of each specific country will likely remain unchanged in the future. This is based on the fact that thermal power plants are typically closely linked to the population / industrial centers (large power consumers), whose location (in regard to the nearest water bodies) will not considerably change in the next decades. Secondly, previous studies deployed this approach of applying coefficients of the seawater use in thermal power generation (for instance, in Davies et al. [17]).

2.4 Assessment of the water footprint

The water footprint (WF) of individual power plants for each specific year was calculated using Equation 1.

$$\mathrm{WF} = \mathrm{WUI} \times \mathrm{Cap} \times \mathrm{FLH} \tag{1}$$

where WUI – water use intensity factor, in m^3 of water per MWh of generated electricity, Cap - active capacity of individual power plants, it is given in megawatts, and FLH – full load hours of power generation in hours. In subsequent steps, the calculated annual water footprint of individual power plants was aggregated on country-, region-, and global-levels.

The assessment of the water footprint of individual power plants was conducted through the calculation of their water withdrawals and water consumption. Water withdrawal refers to the total amount of water that is taken from a water source, and water consumption is the difference between water withdrawal and the amount of water returned to the water source. It is noteworthy that the WUI factors vary for water withdrawal and water consumption.

The use of WUI factors for the water footprint estimation in the power sector is an effective and a widely used approach. For this study, we applied the WUI factors from Macknick et al. [36]. Although these factors were initially derived using empirical data records of the water use in the United States, Macknick et al. [36] suggest that they could also be applied for water demand estimation for power plants located in other geographic regions [36]. Lohrmann et al. [9] demonstrated that these factors can be used for power plants in Europe. The authors of this study, however, acknowledge that any differences in cooling water management in individual power plants across the globe may result in minor variations in the water demand estimates.

The WUI factors are assigned using information concerning the type of fuel used by individual power plant, its generation technology and the installed cooling system. Since the WUI factors are not available for oil-fired power plants [36], we grouped oil and gas power plants at this stage, as it was done in previous studies [28,37]. It is crucial to mention that oil power plants may, in general, have a higher water dependency than gas plants. This assumption, however, will not impact the accuracy of our estimates considerably, since, as mentioned earlier, the share of future oil power plants in the database is negligible and represents only 1.4% of the thermal power capacities with an announced installation year and 2.9% of power capacities with an unknown installation date.

For the full load hours (FLH) of the future thermal power plant generation we used the forecast by the U.S. Energy Information Administration (EIA) annual energy outlook 2021 [38] and Bloomberg NEF 2020 [39]. Specific FLH for a country or region are applied when available. In case no distributed data is available, global averages are applied for the thermal power plants, as is the case in the Bloomberg NEF scenario. Although, in principle it is potentially inaccurate to use global numbers for power plants across regions, this approach has been selected using the following logic. The current variations in the generation behaviors between countries or regions with different energy system compositions will be reduced in the future. This is because regions that currently use controllable generation (such as gas, oil and, to some extent, coal) for the totality or majority of their generation, will be forced to shift from constant generation to balancing of higher shares of renewables, which follow similar patterns across the globe. According to the EIA, by 2050 all scenarios predict between 53% and 58% of generation by renewables, from which up to 76% is expected to come from wind and solar PV, while Bloomberg NEF forecasts 69% generation from renewables. Therefore, thermal generation will have to adapt to more irregular production schemes of fluctuating renewables, which is expected to become the norm.

3. Results

3.1 Water consumption of global energy sector

The water footprint of the global energy system was investigated from the perspective of the water consumption. The results for the years 2020, 2030, 2040 and 2050 are presented in Table 1. The table presents the median water consumption estimates for all six scenarios considered in this study. The table contains both, the projected annual water consumption of the global power sector and the corresponding annual water consumption of the thermal power generation (given in brackets).

In 2020 the median annual water consumption of the global energy sector was estimated at the level of 88 cubic kilometers of water. If the development of the global energy system will follow the scenarios projected by Bloomberg, the water consumption may increase to about 104 cubic kilometers of water annually. When following the EIA scenarios, the annual water footprint ranges from 119 (in EIA Low Oil Price Scenario) to 132 cubic kilometers of water (in EIA High Oil Price Scenario). This implies an increase between 35% to 50% of the annual water consumption, compared to the 2020 level.

Table 1. Projections of the annual water consumption of the global power sector, in cubic kilometers. Values in brackets depict the projected values of the water consumption of the global thermal power sector, in cubic kilometers.

Estimate [km^3]	**2020**		**2030**		**2040**		**2050**	
Bloomberg NEF	87.80	(20.8)	91.99	(19.3)	97.96	(20.1)	104.22	(21.2)
EIA Reference case	88.12	(19.5)	103.16	(19.1)	113.10	(23.9)	124.30	(29.0)
EIA High Oil Price			105.70	(19.8)	117.14	(24.0)	132.07	(29.6)
EIA Low Oil Price			101.52	(18.9)	110.89	(23.2)	118.76	(28.2)
EIA High Economic Growth			105.58	(20.0)	116.89	(24.5)	131.96	(30.0)
EIA Low Economic Growth			101.61	(18.6)	110.90	(23.0)	118.67	(27.8)

While the largest share of the energy-related water consumption is related to hydropower plants, thermal power generation is currently responsible for about 22% of the total water consumption of the global energy sector. Depending on the scenario, by 2050 thermal power generation's share is projected to constitute 20-24% of the total water consumption.

3.2 Water footprint of thermal power plants

In 2020, the total water consumption of the global thermal power plant fleet was estimated between 19.5 cubic kilometers (in EIA scenarios) and 20.8 cubic kilometers (in Bloomberg NEF). The slight difference (of about 6%) between these estimates is caused by the difference in the FLH projections reported by Bloomberg and EIA for 2020. It was estimated that about 78% of the consumed water was taken from local freshwater sources, such as rivers and lakes, while the remaining 22% was seawater.

As shown in Figure 2, the United States, China, India and Russia had the largest water consumption of the thermal power sector in 2020, consuming annually 5, 4.1, 2.1, 1.4 cubic kilometers of water, respectively. These four countries are currently responsible for about 60% of the water consumed by thermal power plants globally. Aside from the large thermal power capacities located in these four countries, their high water consumption is influenced by the wide use of cooling towers, which is a prevailing cooling technology in the thermal power sectors of these countries, and which consumes a considerable amount of water per unit of generated electricity, compared to other cooling technologies.

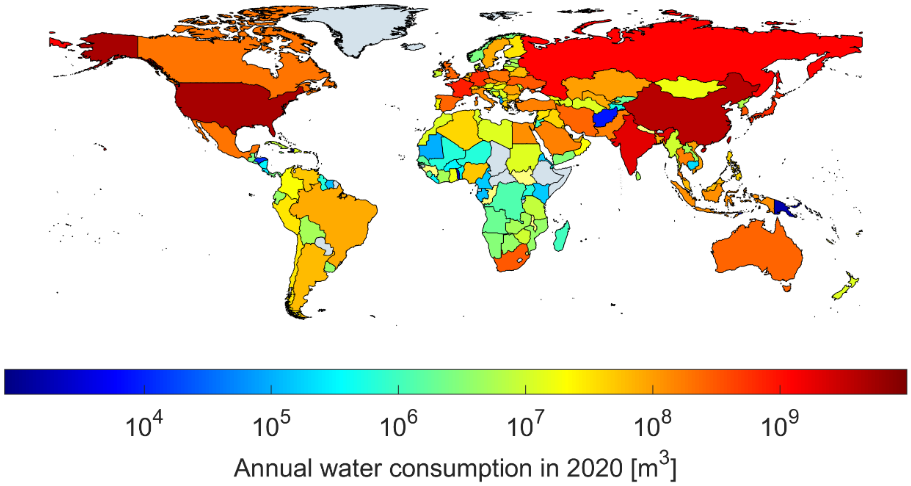

Figure 2. Annual water consumption of thermal power generation in 2020, per country, in cubic meters. The presented map is for illustrative purposes only and does not imply the expression of any opinion concerning the legal status of any country or territory or concerning the political delimitation of borders.

In the same year, the global total water withdrawal of thermal power plants was projected to be between 820.3 cubic kilometers (in the EIA scenarios) and 861.9 cubic kilometers (in Bloomberg NEF). Unsurprisingly, the share of abstracted seawater in the total global water withdrawal is considerable: it constitutes about 57% of the projected global total water withdrawal. This could be explained by the fact that power plants equipped with once-through cooling systems (which withdraw large amounts of water during operation) tend to be located close to the ocean's coastline.

The countries associated with the largest water withdrawal are China (159.8 cubic kilometers), the United States (152.8 cubic kilometers), Japan (94 cubic kilometers) and Russia (56.8 cubic kilometers). About 95% of Japan's thermal power sector is equipped with once-through cooling systems, which results in the country's high water withdrawals. However, it is worth mentioning that 96% of Japan's thermal capacity is projected to be seawater-cooled, therefore having a rather inconsequential effect on the country's freshwater resources.

The results for both the annual water consumption and water withdrawal for the reference year 2020 and the projections until 2050 are illustrated in Figure 3. The figure presents the projected median values for the six scenarios and the minimum-maximum interval of these projections. By 2050, the global thermal power sector is projected to consume between 21.2 cubic kilometers of water (according to Bloomberg NEF scenario) and 28.9 cubic kilometers of water (average of EIA scenarios) and withdraw between 507.9 cubic kilometers of water (in Bloomberg NEF scenario) and 865.6 cubic kilometers of water (average of EIA scenarios). It can be noted that in the case of water consumption, the min-max interval for the year 2050 is considerably wider than the min-max interval for 2020, which highlights the difference in the FLH projections for the power generation technologies associated with a high water consumption, such as nuclear power plants.

As depicted in the figure, the projected increase in thermal power capacities from 2020 to 2050 is estimated to result in an average increase of 48% in the total water consumption of the thermal power sector if following EIA scenarios, and a negligible change if Bloomberg NEF scenario will be implemented. Only a minor change in the total water withdrawal is projected in the EIA scenarios: by 2050, median withdrawal values increase by, on average, 6%. In contrast to that, according to Bloomberg NEF scenario, the total water withdrawal will decrease by 11% by 2050, compared to the 2020 level. These projections correspond to the current global trend to increase the installations of tower cooling systems and to decrease the use of once-through cooling systems, which indicates a development towards the reduction of water withdrawals for cooling purposes in power generation.

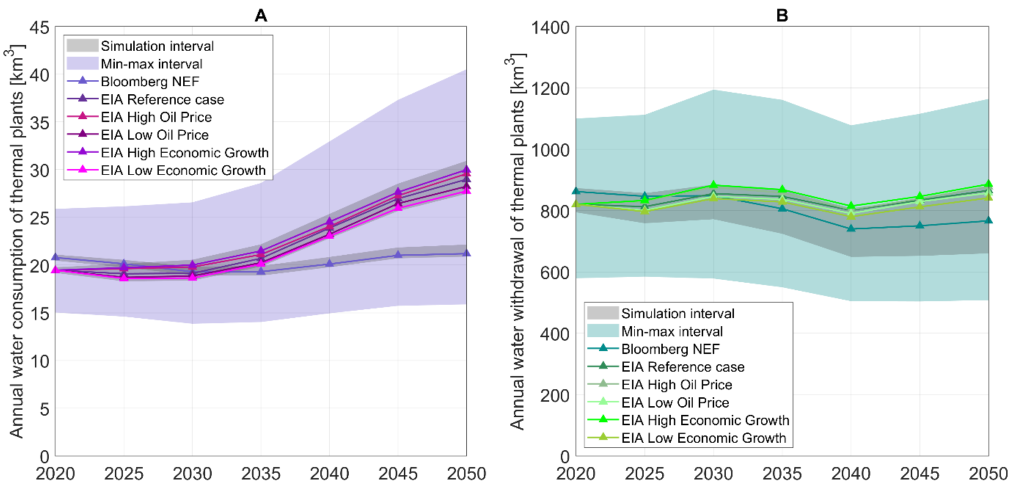

Figure 3. Projections of annual water consumption (A) and water withdrawal (B) of thermal power plants globally, in cubic kilometers, from 2020 to 2050. The figure presents median estimates for each scenario, min-max interval of these estimates (purple shade in A, green shade in B), based on min-max WUI coefficients – see Macknick et al. [36]. and the simulation interval (gray shade) reflecting the cooling technology classification model's plausible variation of results.

The lines in Figure 3 represent the estimate of the median total water consumption and withdrawal of thermal power plants according to the classification models used in this study. Acknowledging the possibility of error for the assignment of the cooling technology for some power plants, the impact of plausible misclassifications on the consumption and withdrawal estimates is presented in Figure 3 as grey areas. The results are based on a simulation approach (10'000 runs) using the fuel type-specific error rates of the models (see Section E of Supplementary Materials) and the confusion matrices of these models to simulate possible errors in number and type that may occur for the assignment of the cooling technology to each future power plant. The corresponding results show that for consumption the estimates only vary up to 1.8% below (in 2025) and 3.6% above (in 2050) the presented projected median annual water consumption, with most intervals showing variations of less than 3% around the median estimate. For withdrawal, the estimates vary up to 13.5% below (in 2050) but only 1.5% above (in 2020) the projected median annual water withdrawal.

To put the aforementioned findings into perspective, Table SM2 of the Supplementary Materials shows the share of freshwater withdrawals of the power sector in each country to the total freshwater withdrawals in that country, and the corresponding water stress score. Among the countries characterized by high and extremely high water stress, for a few countries the estimated share of the total freshwater withdrawals allocated for the thermal power generation is over 5% (incl. Azerbaijan, Belgium, Italy, Spain and the United States), and for three countries this share even exceeds 10% (China, Israel, and Kuwait). High shares of water withdrawals dedicated to only the thermal power sector (excluding hydropower) in countries with a considerable water stress highlight the need for a careful consideration of the potential increase in the water intensity of thermal power for managing regional water stress.

3.3 Specific water consumption

The specific water demand per unit of generated electricity (in this study – per MWh) describes the influence of the power generation mix on the average water demand of the power sector. This measure is widely used in LCA studies to estimate the energy-related water content of various products [11].

The projected development of the specific water consumption for the global energy sector is presented in Figure 4A. As illustrated, the projected changes in the power generation mix will lead to a decrease of the specific water consumption: from an average of 3.74 cubic meters per MWh in 2020 to about 3.04 cubic meters per MWh by 2050. Although all scenarios suggest a drastic increase of renewable and low water-demanding capacities such as solar and wind energy (from about 10% of the total generation mix in 2020 to 56.1% by 2050 according to the Bloomberg NEF scenario and to 40.5% in the EIA Reference scenario), it only leads to a 20% decrease of the specific water consumption in the energy sector by 2050. This is because of the hydropower generation, which, due to its high water use intensity, keeps the specific water consumption relatively constant during the investigated time period. This highlights the urge to increase the share of low water-demanding technologies, such as wind and solar PV, in the global power generation mix.

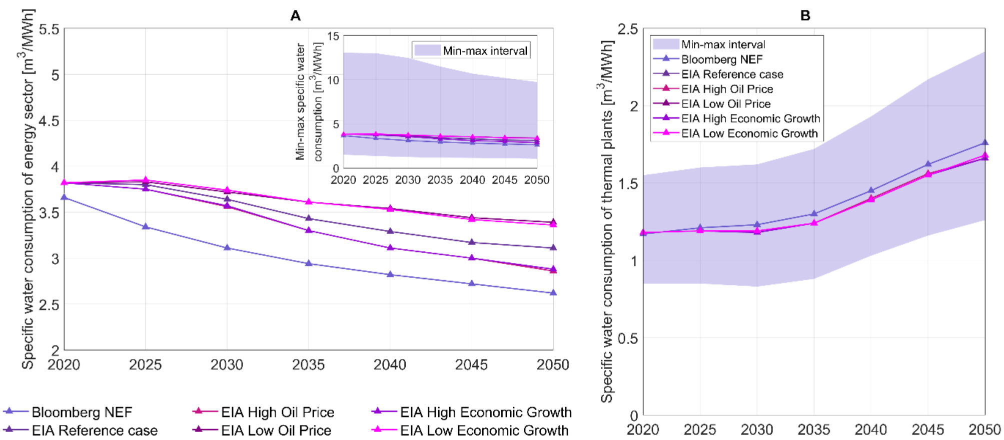

Figure 4. Projections of the specific water consumption of the global energy sector (A) and of the global thermal power plants (B), in cubic meters per MWh of generated electricity, from 2020 to 2050. The shaded area presents median values and min-max interval (based on min-

max WUI coefficients – see Macknick et al. [36]). More information concerning this min-max interval is given in Section F of Supplementary Materials.

Although the specific water consumption of the entire global energy sector is projected to decline over time, the specific water consumption of thermal power generation is expected increase, as demonstrated in Figure 4B. According to the results of the analysis, in 2020 the specific water consumption of thermal power plants was at the level of 1.2 cubic meters per MWh. By 2050 it may reach the value of 1.7 cubic meters per MWh.

This increase could be explained by the following consideration. The average size of announced thermal power plants in the database tends to increase over time. In particular, according to the database used in this study, the average size of the power plant in 2020 was about 800 MW, and power plants that are planned for commissioning in 2050 have an average size of about 1700 MW. The size of a power plant is important, as larger power plants can use technologies like super-critical and ultra-critical boilers which have higher fuel efficiency than subcritical boilers, however resulting in an overall reduction of the water efficiency of the system as found by Macknick et al. [36]. Macknick et al. [36] report that super-critical boilers consume about 3% more water than subcritical boilers per MWh of electricity produced, while using the same cooling system. Consequently, as thermal capacities are replaced by more fuel-efficient (and yet more water-demanding) power plants, the overall specific water consumption of the thermal power plant fleet is expected to increase.

In order to restrain the rising water demand of the power sector, the installation of new thermal power plants should be limited in the future. In this regard, there are several strategies, which should be implemented in the future:

(1) to offset the growth of thermal power capacities by more water-efficient technologies,
(2) to increasingly replace future thermal power plants with renewable energy technologies, such as solar PV and wind,
(3) to ensure that water-intensive thermal is done only in areas with abundant water resources (low water stress level).

3.4 Water consumption criticality

The next step is the analysis of the development of the water consumption in different countries to highlight geographical locations that are potentially critical from the perspective of water resource availability for energy-related water consumption. Figure 5 illustrates the total capacity, freshwater consumption, specific water consumption and water stress score in 2020 and their corresponding projected change (relative and absolute) until 2040.

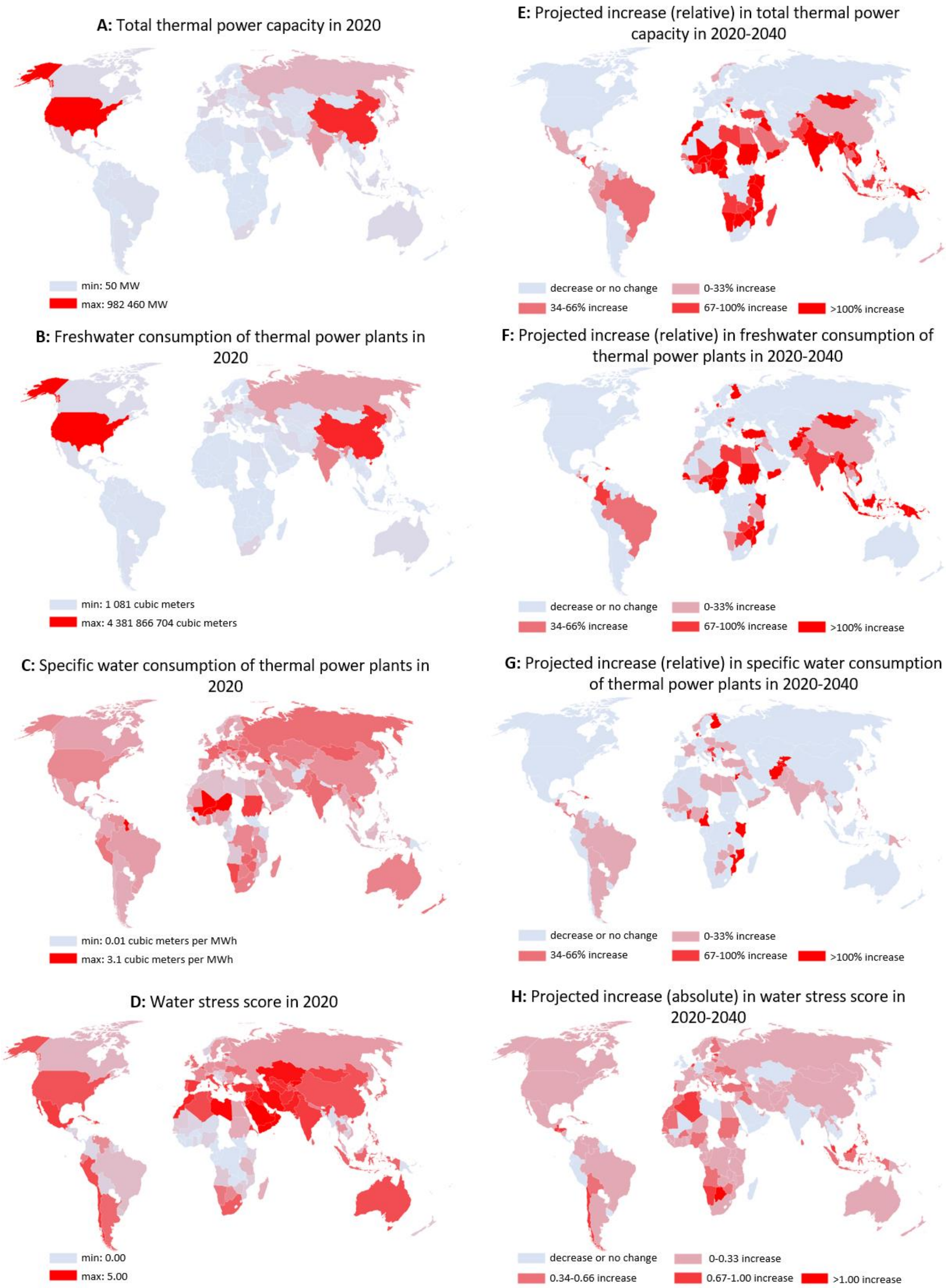

Figure 5. Components of the water consumption criticality in 2020 (A-D) and their corresponding projected increase (relative and absolute) until 2040 (E-H). A, E: total thermal power capacity. B, F: freshwater consumption of thermal power plants. C, G: specific water consumption of thermal power plants. D, H: water stress score (as reported by [22]). The presented map is for illustrative purposes only and does not imply the expression of any opinion

concerning the legal status of any country or territory or concerning the political delimitation of borders.

To examine potential implications of the projected development for the global thermal power sector, we introduce and deployed the water consumption criticality (WCC) matrix. WCC matrix considers in the X-axis each country's specific water consumption of the thermal power plants (which, in turn, takes into account the types of cooling technologies used in the country), on the Y-axis the freshwater consumption for the thermal power sector, and whether this freshwater consumption is projected to increase by 2040 (arrow). In this study, the WCC analysis includes only power plants with known geographical location that are currently active and which are announced by the authorities to be commissioned in the upcoming decades. In future studies, the analysis of WCC can also include other forms of power generation, such as hydropower plants, if the exact location of the future hydropower capacities is known.

Figure 6 displays the WCC matrix for the year 2020. The figure contains only countries, which are characterized by high and extremely high water stress in 2020, which indicates a high competition for freshwater resources [22]. Hence, although some countries were assigned to the group of Low WCC (green color in Figure 6), in this classification they represent the countries of high concern.

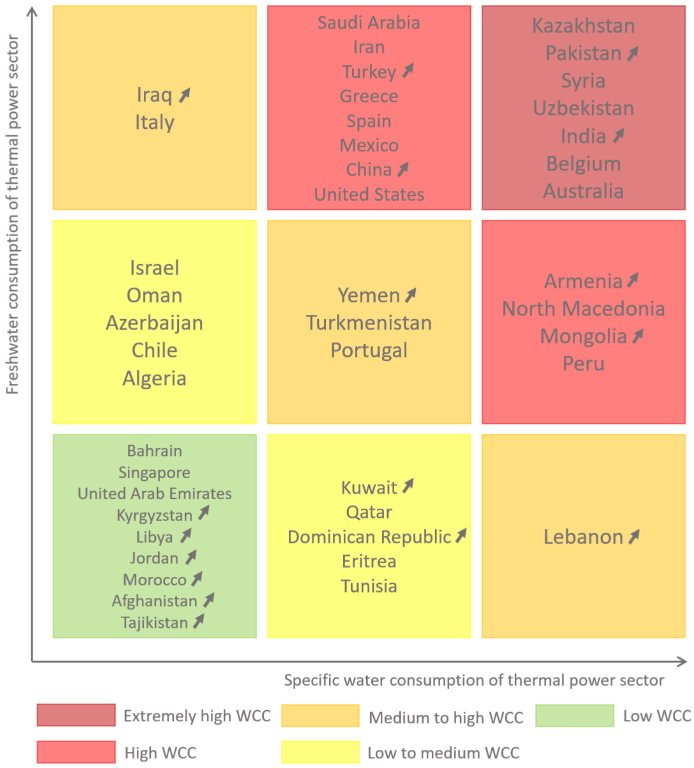

Figure 6. Water consumption criticality (WCC) in 2020. The countries are arranged in descending order based on their water stress score. The arrows indicate that the freshwater

consumption of the country will increase by 2040, compared to 2020 level (based on the data on the planned and announced thermal power plants).

According to our estimates, Kazakhstan, Pakistan, Syria, Uzbekistan, India, Belgium and Australia are assigned to the extremely high WCC category since these countries have a high specific water consumption, a high freshwater consumption and were in 2020 considered countries with already high to extremely high water stress. Saudi Arabia, Iran, Turkey, Greece, Spain, Mexico, China, the United States, Armenia, North Macedonia, Mongolia and Peru are characterized by high WCC. Large thermal power capacities, which are located in these countries, and which have a high freshwater dependence, should be monitored closely. Among the above-mentioned countries, Armenia was estimated to have a considerably high specific water consumption for the thermal power generation in 2020 (about 2.3 cubic meters per MWh in 2020, which is considerably higher than the estimated global average of 1.2 cubic meters per MWh – as shown in Figure 4A).

The ongoing climate change and the extensive water use by other sectors of the economy as well as the growing population are estimated to reduce the availability of water resources in the future, compared to the current levels [1]. As demonstrated in Figure 5H, the water stress level is projected to worsen in most countries of the world over the upcoming decades. For some countries (for instance, Saudi Arabia, Oman, Yemen, Libya, Kazakhstan, etc.), the water stress score remains unchanged due to the fact that these countries are already facing the highest level of water stress.

In this regard, Turkey embodies a country of growing concern. First, the country's water stress is predicted to worsen from high to extremely high by 2040. Second, based on our results, the water consumption of Turkey's thermal power sector is projected to increase by 130% by 2040, compared to the 2020 level, and the specific water consumption of the country's thermal power plant fleet is projected to grow during the investigated time period. Taking into account the plans of the country to install more hydropower capacities in the near future [40], the sustainable use of freshwater resources by the energy sector in Turkey might be compromised. A similar situation is expected in Pakistan and India, both characterized by a high competition for water resources, where the water consumption of thermal plants is projected to increase by about 61% and 84%, respectively, and the specific water consumption is expected to grow as well. This increased water demand for the energy generation may put an additional strain on the local freshwater resources and, simultaneously, may reduce the freshwater availability for the energy sector of these countries, as it has already happened before in several countries in the world [41].

In general, the effects of climate change will be different across the globe. WRI investigates these effects from the perspective of seasonal variability, which describes variation in water supply between months of the year, flood occurrence, which reflects the number of floods, and drought severity, which indicates the average length of droughts and the dryness of the droughts around the globe [22]. In this regard, using a water stress score as the only indication of the effects of climate change might appear as a simplification of a more complex phenomenon.

The results presented for 2040 in this section should be viewed as an optimistic scenario since they were only based on the information that is currently available in the GlobalData dataset, which, in turn, may not contain all power plants that will be installed globally by 2040.

4. Discussion

The relationship between water and energy is not new, and the term "water–energy nexus" has been in use for more than a decade [16,42]. However, this relationship and its implications are rather complex and constantly evolving along with the development of technologies for electricity production and storage, as well as developments in other sectors such as agriculture and urban infrastructure, and different approaches to the study of this relationship are constantly being developed. For example, one study [43] investigated several individual energy–water nexus links between rural, urban and infrastructure settings around some of the most populated and economically active regions of China; Beijing, Hebei and Tianjin. Another example, also in China, investigates the water–energy–carbon nexus at the delta of the Yangtze River and populations surrounding it [44]. Similarly, very geographically specific studies have recently been conducted for Romania [45] and India [46], addressing also the connections of water and energy with land and food respectively. However, to the best of the authors' knowledge, there has been no study that, at a global level, takes into account the currently announced–future energy developments as well as the specific geographical water stress. The contribution of this study is to present estimates for the water demand of the future power sector according to several energy transition scenarios.

Climate change is making water resources increasingly unreliable, contributing to the need and utility of estimates for the water demand of the future power sector as an instrument for water planning and policy. To illustrate the depth of the issue, just during the summer of 2022, the water levels of the main European tributaries such as the Rhine, Rhône and Garonne rivers have been severely affected by drought, lowering their levels to the point where their transport and cooling capabilities for power plants are being thwarted, and it can still get worse [47,48]. A considerable increase in drought intensity was reported during the last decades in France [49]. This has caused a decrease in the cooling power of rivers (low river flows and increased temperature of water), which has resulted in interruptions in the power generation process [50] and has affected electricity prices [51]. In the middle of an ongoing energy crisis, France is being forced to take water out of hydroelectric reservoirs to maintain other economic activities in the Garonne River basin, at the cost of millions of euros and for the first time in over 30 years [48]. Severe droughts like the currently ongoing one, are more likely to become increasingly common, due to climate change. Considering the ongoing scenarios, research has been performed that proposes the reduction of water use for other economic activities, for example agriculture [52] and mining [53], in order to have more water available for the electricity production.

However, the increasing uncertainty of water resources should be taken into account when designing the future global power system, and a low water–dependence for the electricity production may prove to be the best strategy going forward. For example, the abovementioned case of hydropower reservoirs being drained in order to keep river flows in France is only one side of the story. Just as other economic sectors are competing for water, thermal power production is also struggling to keep operating, as nuclear power plants are forced to reduce their output due to water shortages for cooling [54].

In view of recent energy and water crises, it becomes clear that water–resiliency should become one of the deciding factors for the planning and management of the current and future power infrastructure. It appears that politicians, decision-makers, energy system planners and modelers are currently disregarding the impact that the power sector has on water resources (and vice versa) while focusing on emissions, as even the most optimistic or realistic scenarios implies higher water consumption in comparison to today's level. A failure to carefully account for the future water demand and future potential water availability variations could prove to be catastrophic. Thus, it becomes another solid argument for the acceleration of a transition to a power system deeply based on, or entirely constituted by, renewable energy such and wind and solar. In this regard, knowledge on the impact of the current power sector on water availability is vital for moving forward toward sustainability.

5. Conclusions

Energy transition scenarios typically overlook the water footprint of the future energy system. As shown in this study, the water consumption of the power sector will continue to grow, despite the expected increase of "water-free" solar and wind installations. As estimated in this study, the global energy sector in 2050 will consume at a minimum around 102 km^3 of freshwater (coming from the more progressive Bloomberg NEF scenario), out of which 16.5 km^3 are freshwater commitments to thermal power plants not yet in operation today. Problematically, an increase in freshwater consumption associated with the planned and announced thermal power generation is projected to occur in at least 39% of the countries that have already high or extremely high water stress by 2040, suggesting that energy policy in those countries is neglecting water demand aspects.

While the specific water demand per unit of generated electricity of the global power sector is projected to decline (due to the higher shares of solar and wind in the power generation mix), the specific water consumption of thermal power plants is going to increase from 1.2 cubic meters per MWh in 2020 to 1.7 cubic meters per MWh in 2050. Hence, in order to ensure a (more) sustainable use of water resources in the future, both, the total capacity of highly water-dependent thermal power generation and its share in the global power generation mix, should decrease.

In 2020 Iran, India, Saudi Arabia, Ukraine, Kazakhstan, China, United States, South Africa, Pakistan, France, Armenia, Australia and Mexico are associated with a very high WCC. The water demand of the local energy systems of these countries may become an additional factor contributing to the already existing water stress. By 2040, Turkey, Pakistan and India embody countries of increasing concern due to the estimated considerable growth of energy-related water demand. The potential consequences of this projected growth and its impact on the local water systems should be studied in a greater detail within a specific geographical context.

From the analyzed energy transition scenarios, it is shown that Bloomberg NEF strikes a better balance of water resource use and emissions. According to the Bloomberg NEF 2020 scenario, a reduction by more than 40% of the emissions from the power sector is expected by 2050. However, the freshwater demand during the same period is increasing by almost 20%. Other, more progressive energy transition scenarios are occasionally presented in the academic literature (for instance [55]), which could potentially further decrease the water consumption of the power sector. However, these scenarios were not considered for this study, as they do not take into account the thermal power plants that are currently announced, planned and under construction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Alena Lohrmann: Conceptualization, Resources, Methodology, Software, Investigation, Visualization, Validation, Writing - Original Draft. **Javier Farfan:** Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing. **Christoph Lohrmann:** Methodology, Software, Visualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Julian Fritz Kölbel:** Resources, Writing - Review & Editing. **Frank Pettersson:** Investigation, Validation, Writing - Review & Editing.

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Code availability

Matlab scripts used in the production of this analysis are available from the corresponding author upon request.

References

[1] Caretta MA, Mukherji A, Arfanuzzaman M, Betts RA, Gelfan A, Hirabayashi Y, et al. Water. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, et al., editors. Clim. Chang. 2022 Impacts, Adapt. Vulnerability, Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022, p. 551–712. https://doi.org/10.1017/9781009325844.00.

[2] UNICEF. Water and the global climate crisis: 10 things you should know 2022. https://www.unicef.org/stories/water-and-climate-change-10-things-you-should-know (accessed September 1, 2022).

[3] World Economic Forum (WEF). The Global Risks Report 2021: 16th Edition. 2021. https://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf

[4] United Nations World Water Assessment Programme (WWAP), UN-Water. The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO); 2018. www.unwater.org/publications/world-water-development-report-2018/

[5] Boretti A, Rosa L. Reassessing the projections of the World Water Development Report. Npj Clean Water 2019;2:15. https://doi.org/10.1038/s41545-019-0039-9.

[6] Dieter CA, Maupin MA, Caldwell RR, Harris MA, Ivahnenko TI, Lovelace JK, et al. Estimated use of water in the United States in 2015. U.S. Geological Survey. Reston,

VA: 2018. https://doi.org/10.3133/cir1441.

[7] [database] GlobalData Plc. GlobalData Power plant database 2020. https://www.globaldata.com/ (accessed May 10, 2021).

[8] Terrapon-Pfaff JC, Ortiz W, Viebahn P, Kynast E, Flörke M. Water Demand Scenarios for Electricity Generation at the Global and Regional Levels. Water 2020;12. https://doi.org/10.3390/w12092482.

[9] Lohrmann A, Child M, Breyer C. Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system. Energy 2021;233:121098. https://doi.org/https://doi.org/10.1016/j.energy.2021.121098.

[10] Lee U, Chou J, Xu H, Carlson D, Venkatesh A, Shuster E, et al. Regional and seasonal water stress analysis of United States thermoelectricity. J Clean Prod 2020;270:122234. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.122234.

[11] Wu XD, Ji X, Li C, Xia XH, Chen GQ. Water footprint of thermal power in China: Implications from the high amount of industrial water use by plant infrastructure of coal-fired generation system. Energy Policy 2019;132:452–61. https://doi.org/https://doi.org/10.1016/j.enpol.2019.05.049.

[12] Murrant D, Quinn A, Chapman L, Heaton C. Water use of the UK thermal electricity generation fleet by 2050: Part 1 identifying the problem. Energy Policy 2017;108:844–58. https://doi.org/https://doi.org/10.1016/j.enpol.2017.05.011.

[13] Thopil GA, Pouris A. A 20 year forecast of water usage in electricity generation for South Africa amidst water scarce conditions. Renew Sustain Energy Rev 2016;62:1106–21. https://doi.org/https://doi.org/10.1016/j.rser.2016.05.003.

[14] Srinivasan S, Kholod N, Chaturvedi V, Ghosh PP, Mathur R, Clarke L, et al. Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. Appl Energy 2018;210:673–84. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.04.079.

[15] van Vliet MTH, Yearsley JR, Ludwig F, Vögele S, Lettenmaier DP, Kabat P. Vulnerability of US and European electricity supply to climate change. Nat Clim Chang 2012;2:676–81. https://doi.org/10.1038/nclimate1546.

[16] Siddiqi A, Anadon LD. The water-energy nexus in Middle East and North Africa. Energy Policy 2011;39:4529–40. https://doi.org/10.1016/j.enpol.2011.04.023.

[17] Davies EGR, Kyle P, Edmonds JA. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv Water Resour 2013;52:296–313. https://doi.org/10.1016/J.ADVWATRES.2012.11.020.

[18] [database] Lohrmann A, Farfan J, Caldera U, Lohrmann C, Breyer C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. Nat Energy 2019;4:1040–8. https://doi.org/10.1038/s41560-019-0501-4.

[19] Lohrmann A, Lohrmann C, Luukka P. Global and regional models for identification of

cooling technology in thermal power generation for water demand estimations in water-energy nexus studies. J Clean Prod 2022;380:134842. https://doi.org/10.1016/J.JCLEPRO.2022.134842.

[20] Fu G, Jin Y, Sun S, Yuan Z, Butler D. The role of deep learning in urban water management: A critical review. Water Res 2022;223:118973. https://doi.org/https://doi.org/10.1016/j.watres.2022.118973.

[21] [database] Food and Agriculture Organization of the United Nations (FAO). AQUASTAT Main Database 2021. http://www.fao.org/aquastat/statistics/query/index.html;jsessionid=6C067D308754D4DA7FEF0D86786A4BAB (accessed October 5, 2021).

[22] [database] Water Resources Institute (WRI). AQUEDUCT Water Risk Atlas 2021. https://www.wri.org/applications/aqueduct/water-risk-atlas (accessed March 18, 2020).

[23] [database] Sadovskaia K, Bogdanov D, Honkapuro S, Breyer C. Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally. Int J Electr Power Energy Syst 2019;107:98–109. https://doi.org/10.1016/J.IJEPES.2018.11.012.

[24] [database] Transparency International. Corruption Perceptions Index 2019 2019. https://www.transparency.org/en/publications/corruption-perceptions-index-2019.

[25] [database] The World Bank. GDP (current US$) - All Countries and Economies 2020. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD (accessed October 5, 2020).

[26] [database] GlobalPetrolPrices. Electricity prices 2020. https://www.globalpetrolprices.com/electricity_prices/ (accessed January 20, 2021).

[27] Larsen MAD, Petrovic S, Engström RE, Drews M, Liersch S, Karlsson KB, et al. Challenges of data availability: Analysing the water-energy nexus in electricity generation. Energy Strateg Rev 2019;26:100426. https://doi.org/https://doi.org/10.1016/j.esr.2019.100426.

[28] Luo T, Krishnaswami A, Li X. A mehodology to estimate water demand for thermal power plants in data-scarce regions using satellite images. Technical note. Washington, DC: 2018. www.wri.org/publication/water-power-methodology

[29] Spang ES, Moomaw WR, Gallagher KS, Kirshen PH, Marks DH. The water consumption of energy production: An international comparison. Environ Res Lett 2014;9. https://doi.org/10.1088/1748-9326/9/10/105002.

[30] Vassolo S, Döll P. Global-scale gridded estimates of thermoelectric power and manufacturing water use. Water Resour Res 2005;41:1–11. https://doi.org/10.1029/2004WR003360.

[31] Larsen MAD, Drews M. Water use in electricity generation for water-energy nexus analyses: The European case. Sci Total Environ 2019;651:2044–58. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.10.045.

[32] EcoFys BV. Pilot project on availability, use and sustainability of water production of

nuclear and fossil energy. Geo-localised inventory of water use in cooling processes, assessment of vulnerability and of water use management measures 2014. https://ec.europa.eu/environment/archives/water/adaptation/pdf/InventoryCoolingWaterUse.pdf.

[33] California Energy Commission, Electric Power Research Institute (EPRI). Comparison of Alternate Cooling Technologies for California Power Plants. Economic, Environmental and Other Tradeoffs 2002. https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1167.pdf (accessed December 18, 2021).

[34] Khushaba RN, Al-Ani A, Al-Jumaily A. Feature subset selection using differential evolution and a statistical repair mechanism. Expert Syst Appl 2011;38:11515–26. https://doi.org/https://doi.org/10.1016/j.eswa.2011.03.028.

[35] Lohrmann A, Lohrmann C, Luukka P. A Region-Based Approach for Missing Value Imputation of Cooling Technologies for the Global Thermal Power Plant Fleet Using a Decision Tree Classifier BT - Intelligent Systems and Applications in Business and Finance. In: Luukka P, Stoklasa J, editors., Cham: Springer International Publishing; 2022, p. 93–125. https://doi.org/10.1007/978-3-030-93699-0_5.

[36] Macknick J, Newmark R, Heath G, Hallett KC. Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. Environ Res Lett 2012;7. https://doi.org/10.1088/1748-9326/7/4/045802.

[37] Feeley TJ, Skone TJ, Stiegel GJ, McNemar A, Nemeth M, Schimmoller B, et al. Water: A critical resource in the thermoelectric power industry. Energy 2008;33:1–11. https://doi.org/10.1016/j.energy.2007.08.007.

[38] U.S. Energy Information Administration (EIA), U.S. Department of Energy. International energy outlook 2021. Washington, DC, USA: 2021. https://www.eia.gov/outlooks/ieo/pdf/IEO2021_Narrative.pdf

[39] Bloomberg New Energy Finance (Bloomberg NEF). New energy outlook 2020. New York, NY, USA: 2020. https://about.bnef.com/new-energy-outloo

[40] Renewable Energy World. Powering Up Turkey with Hydropower 2014. https://www.renewableenergyworld.com/baseload/powering-up-turkey-with-hydropower/#gref (accessed August 31, 2022).

[41] Roehrkasten S, Schaeuble D, Helgenberger S. Secure and sustainable power generation in a water-constrained world, Potsdam: Institute for Advanced Sustainability Studies (IASS); 2015.

[42] Scott CA, Pierce SA, Pasqualetti MJ, Jones AL, Montz BE, Hoover JH. Policy and institutional dimensions of the water–energy nexus. Energy Policy 2011;39:6622–30. https://doi.org/https://doi.org/10.1016/j.enpol.2011.08.013.

[43] Wang S, Chen B. Unraveling energy–water nexus paths in urban agglomeration: A case study of Beijing–Tianjin–Hebei. Appl Energy 2021;304:117924. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.117924.

[44] Liang MS, Huang GH, Chen JP, Li YP. Energy-water-carbon nexus system planning: A case study of Yangtze River Delta urban agglomeration, China. Appl Energy 2022;308:118144. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.118144.

[45] Tudose NC, Cheval S, Ungurean C, Broekman A, Sanchez-Plaza A, Cremades R, et al. Climate services for sustainable resource management: The water—energy—land nexus in the Tărlung river basin (Romania). Land Use Policy 2022;119:106221. https://doi.org/https://doi.org/10.1016/j.landusepol.2022.106221.

[46] Kholod N, Evans M, Khan Z, Hejazi M, Chaturvedi V. Water-energy-food nexus in India: A critical review. Energy Clim Chang 2021;2:100060. https://doi.org/https://doi.org/10.1016/j.egycc.2021.100060.

[47] Connolly K. Low water levels mean Rhine is days from being shut for cargo. Guard 2022. https://www.theguardian.com/world/2022/aug/05/rhine-low-water-levels-shut-cargo

[48] Mizzy S. Drought: in Toulouse, the Garonne has never been so low for 30 years. Europe-Cities 2022. https://europe-cities.com/2022/08/18/drought-in-toulouse-the-garonne-has-never-been-so-low-for-30-years/

[49] Vidal J-P, Martin E, Kitova N, Najac J, Soubeyroux J-M. Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios. Hydrol Earth Syst Sci 2012;16:2935–55. https://doi.org/10.5194/hess-16-2935-2012.

[50] Toreti A, Bavera D, Acosta Navarro J, Cammalleri C, de Jager A, Di Ciollo C, et al. Drought in Europe August 202. Luxembourg: 2022. https://doi.org/10.2760/264241.

[51] Azevedo Rocha P, Mathis W. European Power Hits Record as Extreme Heat, Drought Parch Europe. Bloomberg 2022. https://www.bloomberg.com/news/articles/2022-08-02/german-power-prices-hit-fresh-record-as-consumer-costs-mount

[52] Zhang T, Tan Q, Zhang T, Yang J, Wang S. A nexus approach engaging water rights transfer for addressing water scarcity in energy and food production under uncertainty. J Environ Manage 2022;316:115163. https://doi.org/https://doi.org/10.1016/j.jenvman.2022.115163.

[53] Araya N, Ramírez Y, Cisternas LA, Kraslawski A. Use of real options to enhance water-energy nexus in mine tailings management. Appl Energy 2021;303:117626. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.117626.

[54] Kar-Gupta S, Crellin F, Lough R, Harvey J. France tweaks rules to keep nuclear plants running during heatwav. Reuters 2022. https://www.reuters.com/world/europe/frances-asn-nuclear-regulator-adapts-hot-water-discharge-rules-light-heatwave-2022-08-08/

[55] Gulagi A, Ram M, Bogdanov D, Sarin S, Mensah TNO, Breyer C. The role of renewables for rapid transitioning of the power sector across states in India. Nat Commun 2022;13:5499. https://doi.org/10.1038/s41467-022-33048-8.

Publication IV

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Environmental benefits of circular economy approach to use of cobalt

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Environmental benefits of circular economy approach to use of cobalt

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ABSTRACT

Cobalt is an important critical material and a constituent of a broad range of products such as batteries, electronics, superalloys, and hard metals. Effective recycling of cobalt is considered one of the most pivotal processes in alleviating its criticality. In this paper, using the dynamic modelling of material, energy, and water flows in cobalt supply chain, we show that by 2050 around 25% of the total demand for cobalt could be supplied by recycling. Our results indicate that, compared to the primary production of cobalt, its recycling might lead to a reduction of energy consumption by 46% associated with the global cobalt supply chain and the corresponding fall in the use of water by 40%. In addition, recycling of cobalt is estimated to mitigate around 59% of the total emissions of greenhouse gases and 98% of the total emissions of sulfur oxides. Finally, we present the regionally distributed projections of cobalt-related energy and water use from 2020 to 2050.

1. Introduction

Sustainable supply of cobalt (Co) is essential for a number of industrial applications such as batteries, superalloys, hard metals integrated circuits, cemented carbides, diamond tools, pigments, chemical catalysts, and magnets (Kovacheva-Ninova et al., 2018). Cobalt has been identified as an important critical material mainly because of its high economic importance, supply risk, scarcity of natural resources and high demand (Campbell, 2019; EU Commission, 2017; Ober, 2018). Moreover, the forecasted market balance for cobalt projects a small surplus in 2020 (EU Commission, 2014) and a very high level of risk of cobalt shortage by 2050 (Sun et al., 2019). One of the drivers for the projected cobalt shortage is the expected increase in penetration of electric vehicles and their related lithium-ion batteries. Demand in this area only may require cobalt supplies exceeding the globally known cobalt reserves (Alves Dias et al., 2018; Lebedeva et al., 2017).

Several factors, such as large annual growth rate of global demand for cobalt (about 6–11 %) and high price volatility as well as the dependency on a close-to single supply country – Democratic Republic of Congo (DRC) which supplies around 60 % of the globally produced cobalt – cause reasonable concerns regarding supply and demand for cobalt (Nkulu et al., 2018). To address those issues, one of the possible solutions is to promote closing the material flow loop by recycling end-of-life products containing cobalt (Ferron, 2013; Golroudbary et al., 2019a). Hence, the policy measures adopted within the framework of the circular economy (increased recycling rates and waste reduction of critical raw materials) should mitigate not only future potential supply risks of these materials, but also the environmental impact associated with their life cycle (Elia et al., 2017; EU Commission, 2015; Golroudbary et al., 2019b). From this perspective, there is a global trend towards improved recovery of cobalt from recycled end-of-life products (Mudd et al., 2013; Pagnanelli et al., 2016; Tkaczyk et al., 2018). It has been demonstrated that an improvement of the cobalt recycling (technology development and management strategies) and a global co-operation for recycling of cobalt in waste streams are urgently required (Glöser-Chahoud and Schultmann, 2019; Sun et al., 2019).

Considering the constantly increasing significance of cobalt recycling, its environmental performance, including energy consumption, water use, greenhouse gas (GHG) and sulfur oxides (SO_x) emissions, is one of the most important criteria in the assessment of overall sustainability of the cobalt supply chain (Dai et al., 2019; Golroudbary et al., 2019a; Graedel et al., 2011). High amounts of energy consumption and water use in different processes of cobalt production have been highlighted by several studies (Ahmed et al., 2017; Huang et al., 2015), as well as high levels of GHG emissions as discussed by Dunn et al. (2015) and Romare and Dahllöf (2017). Moreover, Dunn et al. (2015) have

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shown that the production of cathode containing cobalt generates high SO_x emissions. However, there is still lack of a systematic quantitative analysis of all stages of cobalt supply chain to better understand its environmental impact.

The main objective of our study is to address three key issues regarding environmental sustainability of cobalt supply chain. The first goal is to understand whether there are savings of energy and water thanks to the recycling of cobalt in its supply chain. The second one is to analyze whether recycling contributes to the reduction of GHG and SO_x emissions throughout cobalt life cycle. Finally, the third goal is to study what is the global impact of cobalt consumption and its supply from primary and secondary sources on selected environmental indicators by 2050. The presented comprehensive environmental assessment of cobalt supply chain provides an insight into the key question of whether supplying cobalt from available secondary sources is a sustainable solution.

2. Materials and methods

2.1. Model of the global cobalt supply chain

Several approaches have been applied to analyze global cobalt flows in order to determine the dynamic interactions among various components of the system under investigation (Chen et al., 2019; Sun et al., 2019; Sverdrup et al., 2017). However, there is a lack of a systematic environmental analysis of sustainability of cobalt global supply chain. Fig. 1 gives an overview of the proposed dynamic cobalt model. The model consists of cobalt flows, the respective resource use and emissions. The cobalt flow can be divided into three main stages: industrial phase which includes mining and processing; production phase; and recycling stage which consists of the collection and recycling processes. Environmental impacts of its energy consumption, water use, GHG and SO_x emissions are considered in the model.

The first step is the industrial stage, where Co-containing minerals are extracted, then processed and produced into chemicals such as cobalt oxide – Co_3O_4, cobalt sulfate – $CoSO_4$, cobalt nitrate – $Co(NO_3)_2$, and cobalt chloride – $CoCl_2$. Cobalt is mainly extracted as by-product of nickel mining (about 55 %), copper mining (about 35 %) and other platinum group metals (about 8 %) (Sverdrup et al., 2017). Potential mines where cobalt could be recovered as a main product (about 2 %) require processing of arsenic-rich ores, leading to significant environmental issues, and thus have to be managed carefully (Mudd et al., 2013). Furthermore, the rates of cobalt recovery as byproduct vary, mainly depending on type of deposit. Some studies indicate that the mining industry might continue to receive interest from investors due to the essential role of cobalt in several manufacturing applications (Tisserant and Pauliuk, 2016).

The second step corresponds to the production stage, where cobalt is present in various manufacturing streams, e.g. batteries and electronics – lithium cobalt oxide (LCO), lithium nickel cobalt manganese oxide (NCM), lithium nickel cobalt aluminum oxide (NCA), nickel metal hydride battery (NiMH), nickel–cadmium battery (NiCd) and electrodes; alloys – superalloys, magnetics alloys, and mixed metallic alloys; hard materials – cemented carbides, diamond tools, pigments, chemical catalysts, magnets; and other industrial applications.

Finally, the third step corresponds to the collection of waste containing cobalt and its recycling processes. To address the gap between cobalt supply and demand, the significance of recycling of Co-containing end of life products and a comprehensive overview of different processes of recycling have been presented in many studies (Chagnes and Swiatowska, 2015; Ordoñez et al., 2016; Palanivel and Natarajan, 2012; Swain, 2017; Wang, 2006; Zeng et al., 2014). It is also worth mentioning that there are losses of cobalt along its supply chain, especially in applications such as pigments, tire adhesives, ceramics, and paint dryers. The main waste streams for cobalt recycling are batteries, alloys, catalysts, magnets, and cemented carbides (Alves Dias et al., 2018).

The dynamic model includes 172 variables: 60 flows, 32 stocks and 80 auxiliary variables. We divided the variables of the dynamic model into two groups including endogenous and exogenous variables to

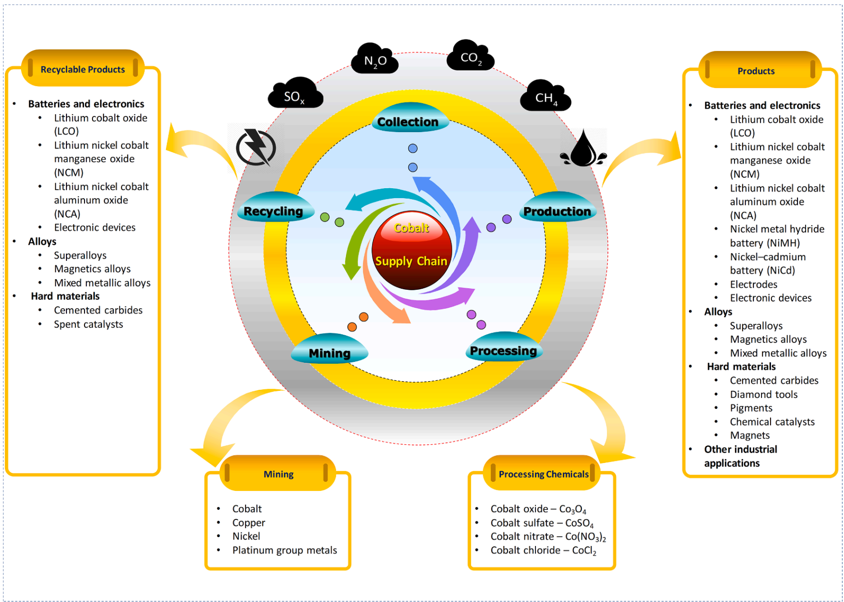

Fig. 1. Conceptual model of the global supply chain of cobalt.

further specify a model boundary. Endogenous variables affect and are affected by other system components and parameters, while exogenous variables are not directly affected by the system. The group and type of all variables are specified in Supplementary Table 1.

2.2. Mathematical formulation of the cobalt stock and flow

We used dynamic modelling to simulate the global supply chain of cobalt. All required data to run the model is presented in Supplementary Table 2. The GREET-2018 software (Wang et al., 2018) was used as the main data source for environmental input variables. Below, we present the main formulas used in calculating material, energy, water, GHG and SO_x flows. All equations and the details of the model are given in Supplementary Table 3.

There are two types of equations in the model, which represent the flow of mass, energy, water, GHG and SO_x: stock equations (state equations) and flow equations (rate equations). The results of the model are then used as inputs of geographical distribution equations.

The stocks assumed in the material flows of the model are: mined cobalt, processed chemical cobalt, batteries and electronics, alloys, inks and pigments, cemented carbide, catalyst, tire adhesives and paint tire, lithium-ion batteries, LCO, NCM, NCA, NiMH, NiCd, electronics, superalloys, magnetic alloys, mixed metallic alloys, hard metal, other applications, collected waste, recycling of end of life products, energy consumption, water use, GHG emissions, and SO_x emissions.

The behavior of stock ($S(t)$) in the time period "t_0-t", where "t_0" is the initial year and "t" is the final year (Equation (1)), is given by a time integral of the net inflows of input rate ($I_R(t)$) minus the net outflows of output rate ($O_R(t)$) (Equation (2)). From Equation (2), $V(t)$ is an auxiliary variable in time "t", and P represents constant input parameters (All parameters are presented in Supplementary Table 2).

$$S(t) = \int_{t_0}^{t} (I_R(t) - O_R(t))dt + S(t_0) \tag{1}$$

$$I_R(t) = f(S(t), V(t), P); O_R(t) = f(S(t), V(t), P) \tag{2}$$

2.3. Regionally distributed projections of cobalt demand

The assumption for the distribution of cobalt demand is linked to the projected development of GDP and population until 2050 created by Toktarova et al. (2019), using the geographical distribution used by Bogdanov et al. (Bogdanov et al., 2019). These projections are in turn used in conjunction with the cobalt utilization factor modelled by Equation 3 and the factors presented in Table 1, to produce the distribution of cobalt across GDP per capita. These assumptions represent only one of several possible detailed scenarios for future development. Due to their scope, the results given by Toktarova et al. (2019) have been used in this work. However, one should remember that it is possible to use other models, based on the different assumptions, for long-term GDP per capita projections. More specifically, the data used as basis for the calculations presented in this work can be found in the Supplementary Data 6 file from Toktarova et al. (2019). For additional reference, the aforementioned population projections fall within the latest UN projections range of 95 % confidence prediction interval (United Nations Department of Economic and Social Affairs, 2019).

Moreover, the assumption that cobalt demand is only linearly proportional to GDP is too simplistic. It is observed that the cobalt demand at the reference year (2014) was already not linearly proportional to GDP. To show this, in Fig. 2 there is displayed the cobalt consumption of European countries in 2014 (Huisman et al., 2017).

In Fig. 2, examples of EU and Schengen countries are shown in ascending order of GDP per capita. In 2014, Bulgaria had a GDP per capita of 12,300€ as the lowest value of the group, while Luxembourg had 68,700€. The red line represents cobalt consumption per unit of GDP, while the blue one indicates cobalt consumption per capita. It can be observed from the graph that cobalt consumption per unit of GDP continues to increase in parallel with the cobalt per capita line, considering the fluctuation for the first part of the graph (GDP per capita of around 32,100€ in 2014). The use of cobalt per unit of GDP starts to decline for countries with consumption higher than that of the Netherlands (GDP per capita of 34,400€), while the consumption of cobalt per capita continues to rise for these countries.

In order to model the aforementioned phenomena, the cobalt utilization factor ($CoF_{(x)}$) is introduced. The cobalt utilization factor, designed in MS Excel, adopts values between "0″ and "1", where "0" represents negligible cobalt demand for GDP per capita below 2,000€, and "1" represents the maximum cobalt demand for the GDP per capita of and above 40,000€. This factor is therefore introduced to compensate for the lower impact of GDP per capita into the cobalt demand above the level of 40,000€.

The $CoF_{(x)}$ curve is modelled by Equation 3 for the range of GDP per capita of 0–105,000€. The equation is derived using the Curve Fitter APP of MATLAB, taking advantage of the interactive nature of the app to test different functions such as polynomial, exponential, Gaussian and Fourier functions, where the amount of terms can also be experimented with. A five term Fourier fitting function, with the parameters presented in Table 1 as returned by the Curve Fitter APP of MATLAB, was found to represent best our $CoF_{(x)}$ assumption curve with a coefficient of determination R^2 of 0.9998.

$$\begin{aligned} CoF(x) = a_0 + a_1{*}\cos(x{*}w) + b_1{*}\sin(x{*}w) + a_2{*}\cos(2{*}x{*}w) + b_2{*}\sin(2{*}x{*}w) \\ + a_3\cos(3{*}x{*}w) + b_3{*}\sin(3{*}x{*}w) + a_4\cos(4{*}x{*}w) + b_4\sin(4{*}x{*}w) \\ + a_5{*}\cos(5{*}x{*}w) + b_5{*}\sin(5{*}x{*}w) \end{aligned} \tag{3}$$

As seen in Fig. 3, the $CoF_{(x)}$ curve shows that the demand for cobalt below the 4,500€ GDP per capita level (roughly the GDP per capita of Nigeria in 2014) is quite small, growing thereafter up to reaching the maximum at around 40,000€ (roughly the GDP per capita of Norway in 2014). The idea is that as GDP grows, the population gets access to more devices that require cobalt, but from the 40,000€ point of GDP the demand per capita for cobalt does not further grow as the quantity of devices using cobalt remains constant, but rather the quality and cost of the devices increase. The second distribution factor is calculated with Equation (4) and adjusts the total demand to match the stock $S_{(t)}$ at different time steps of 2020, 2030, 2040 and 2050.

$$S_{a(t)} = \frac{S_{(t)}}{\sum_{a=1}^{i}(P_{a(t)} \times GDP_{a(t)} \times CoF_{a(t)})} \tag{4}$$

where $S_{a(t)}$ shows stock of cobalt for region "a" in year "t"; $S_{(t)}$ corresponds to total global projected stock of cobalt in year "t"; "t" represents year (2020, 2030, 2040 or 2050); "a" is a region or a country; $P_{a(t)}$ shows projected population of a region "a" in year "t"; $GDP_{a(t)}$ represents projected GDP of region "a" in year "t"; $CoF_{a(t)}$ corresponds to

Table 1
Coefficients of the cobalt utilization factor curve over GDP per capita.

Variable	GDP per Capita [0–105,000€]
CoF(x)	Cobalt utilization factor where "x" represents GDP per Capita
a_0	$2.737e^{+7}$
a_1	$-4.289e^{+7}$
b_1	$-1.596e^{+7}$
a_2	$1.997e^{+7}$
b_2	$1.724e^{+7}$
a_3	$-4.839e^{+6}$
b_3	$-8.802e^{+6}$
a_4	$3.339e^{+5}$
b_4	$2.255e^{+6}$
a_5	$4.847e^{+4}$
b_5	$-2.293e^{+5}$
W	$6.624e^{-6}$

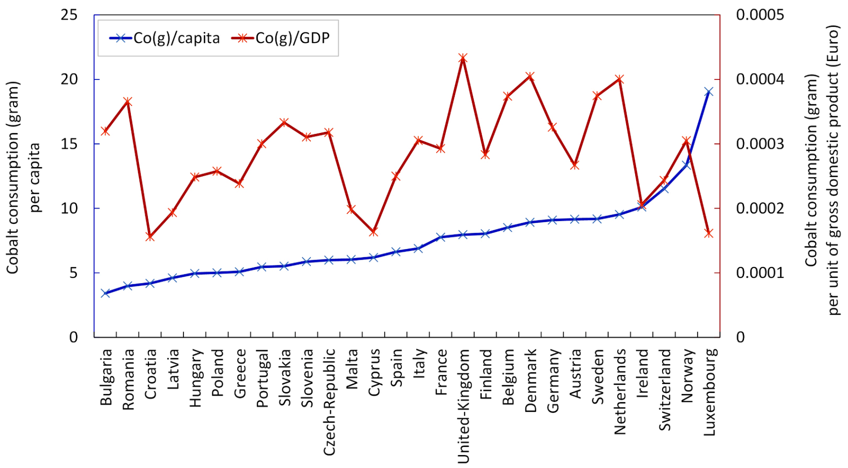

Fig. 2. Behaviour of cobalt consumption in 2014 for example countries.

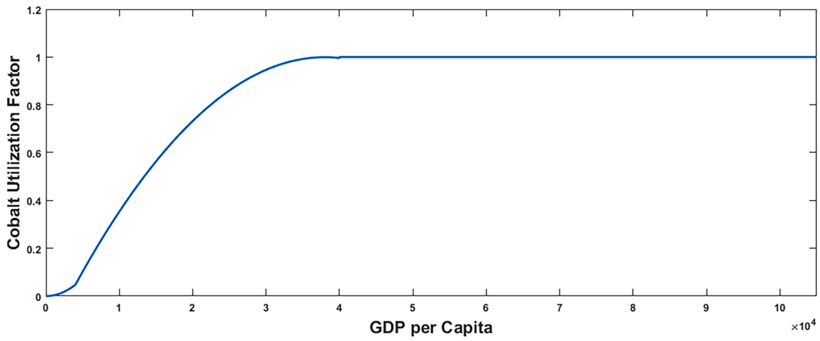

Fig. 3. Cobalt utilization factor as a function of GDP per capita.

cobalt intensity coefficient for region *"a"* in year *"t"*; and *"i"* is the total number of analyzed regions.

Finally, cobalt-related energy demand allocated to each region ($EPCo_{a(t)}$) is calculated in Equation (5). In Equation (5), $EPCo_{a(t)}$ stands for the amount of energy required for primary cobalt processing, $PCoF_{(t)}$ represents the projected share of primary cobalt from the total cobalt projected to be processed globally in year *"t"*. $RSCo_a$ stands for the share of the global primary cobalt allocated to country *"a"* according to Supplementary Table 4, which is the share of the total global for the countries in the list, or an equivalent distribution of the remaining 12.3 % among the other countries. Finally, PCo_{eF} is the primary cobalt energy intensity factor, in MJ per ton of cobalt.

$$EPCo_{a(t)} = S_{a(t)} \times PCoF_{(t)} \times RSCo_a \times PCo_{eF} \quad (5)$$

For secondary cobalt processing, local recycling is assumed, meaning that each territory recycles cobalt already present in the territory after operational lifetime using Equation (6). In Equation (6), $ESCo_{a(t)}$ stands for the amount of energy required for secondary cobalt processing, $SCoF_{(t)}$ refers to the share of secondary cobalt from the total cobalt used in year *"t"*, and SCo_{eF} is the secondary cobalt energy intensity factor.

$$ESCo_{a(t)} = S_{a(t)} \times SCoF_{(t)} \times SCo_{eF} \quad (6)$$

2.4. *Connecting energy use with regional cobalt processing*

Every stage in the cobalt supply chain consumes energy, obtained from different sources. During the mining of cobalt, energy consumption is mainly associated with the use of mining machines and equipment. In the production stage, the manufacturing of products containing cobalt is analyzed separately. In the recycling stage, our study is limited to the analysis of energy demand related to the recycling of cobalt from waste streams coming from used products such as LCO, NCM, NCA, electronic devices, alloys, cemented carbides, and spent catalysts. Total cumulative energy consumption and the annual amount of energy consumption in each stage are calculated by equations Equation (7) and (8).

$$E_{T-i}(t) = \int_{t_0}^{t} E_i(t)\mathrm{d}t + E_i(t_0) \quad (7)$$

$$E_i(t) = C_i(t) \times \sum_{n=1}^{8} \lambda_{i,n} \tag{8}$$

In Equation (7), $E_{T-i}(t)$ corresponds to the total cumulative amount of energy consumption in stage *"i"* in the year *"t"* for the period 2000–2050, *i*= *1,2,…,13* represent primary and secondary production stages of the cobalt supply chain (considered recycled Co sources (*CRCoS*): batteries, electronics, alloys, inks and pigments, cemented carbides, catalysts, tire adhesives, and paint tire). $E_i(t_0)$ is energy consumption in stage *"i"* in the initial year "t_0". *In* Equation (8), $E_i(t)$ is energy consumption in stage *"i"* in the year *"t"* for the period 2000–2050, $C_i(t)$ is the amount of material in stage *"i"* in the year *"t"*, and $\lambda_{i,n}$ is the energy required per one tonne of cobalt flow in stage *"i"* from each energy source*n* = *1,2,…,8* which represent all sources of energy: fossil fuel, natural gas, petroleum, coal, non-fossil fuel, nuclear, renewables, and biomass.

However, the distribution of energy consumption cannot be distributed like the demand for cobalt. First, according to the results of the simulation, the cobalt stock $S_{(t)}$ is primarily distributed between primary and secondary cobalt use. For the period of 2020 to 2050, primary cobalt covers around three quarters of the global cobalt use. Despite cobalt use being considered relative to GDP per capita, in reality primary cobalt processing is limited to a few countries, which carry out the major part of global cobalt processing. Most of the primary cobalt processing is done in China representing 43.2 % of the global primary cobalt refining, followed by Japan and South Korea with 10.6 % each, and the USA with 8.8 % (Sun et al., 2019). In total, the top 9 countries processing cobalt accounted for 87.7 % of the global cobalt primary production in 2014 (Sun et al., 2019). The remaining 12.3 %, in the absence of more specific information, is evenly distributed among the rest of the territories using Equation (5), and the total distribution of primary production of cobalt is shown in Supplementary Table 4.

2.5. Relation between water use and cobalt regional processing

The total amount of water consumed in primary and secondary production of cobalt can be investigated from the perspective of "direct" and "indirect" water use. In this study, the direct water use, meaning the direct water consumption, was defined as the amount of water directly linked to the processing of cobalt. In general, it could be measured at the processing location as the difference between the total amount of water taken from the source to meet the demand for cobalt production and the amount of water that is returned to the environment.

Here, we estimate the total direct water consumption of the cobalt supply chain for the period 2000–2050 using Equation 9. In Equation 9, $Wd_{T-i}(t)$ is the total direct water consumption in stage *"i"* (with*i* = *1,2, …,13*), where *"i"* represents the primary and secondary production stages of the cobalt supply chain (CRCoS), and *"t"* denotes the year. $Wd_i(t_0)$ represents the direct water use in stage *"i"* in the initial year *"t_0"*.

$$Wd_{T-i}(t) = \int_{t_0}^{t} Wd_i(t)\mathrm{d}t + Wd_i(t_0) \tag{9}$$

In contrast to that, the indirect water use, meaning the indirect water consumption, represents the "hidden" part of cobalt production, which is directly linked and strongly influenced by the sources of energy used at the processing location. In order to accomplish a higher accuracy when estimating this quantity, the local energy mix at the location of processing is used. To calculate the indirect water consumption, we deploy the metric of the specific water utilization, which reflects the influence of regional power generation mix on the average water consumption. Initially, we estimated the regional energy-based water consumption by applying the bottom-up approach presented in Lohrmann et al. (2019). In this approach, water consumption of individual power plants was estimated using the water use intensity factors reported by Macknick et al. (2012) and then aggregated on the region-level. In subsequent steps, using the global energy systems evolution projections of Bogdanov et al. (2019) and the method applied in Lohrmann et al. (2021) for the case of Europe, the specific water utilization per 1 MJ of generated electricity was calculated for each region included in our analysis. Finally, the indirect water use was calculated for each specific region using Equation (10).

$$Wid_{i,a}(t) = E_i(t) \times SWD_a \tag{10}$$

where $Wid_{i,a}(t)$ is the amount of indirect water consumed in stage *"i"* in region *"a"* in the year *"t"*, $E_i(t)$ is energy consumption in stage *"i"* in region *"a"* in the year *"t"*, and SWD_a is the specific water utilization per one joule of energy calculated for each specific region.

2.6. GHG and SOx emissions of the global supply chain of cobalt

Air pollution, such as GHG and SO_x emissions, has both acute and chronic effects on animal and human health. GHG and SO_x emissions are driven by dynamic interactions between physical and human systems as climate change alters the frequency or severity of extreme climate events (for example, heat waves, drought, and heavy precipitation). Human activities, such as the burning of fossil fuels, are increasing the levels of GHG in the atmosphere (Golroudbary et al., 2022; Rahimpour Golroudbary et al., 2019). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the main greenhouse gases negatively affecting the environment (Golroudbary et al., 2019b). The life-cycle GHG intensities of energy sources are adapted from the GREET model (Wang et al., 2018), using IPCC AR5 100-year Global Warming Potential values (Stocker et al., 2013) of 1 (CO_2), 36 (CH_4), and 298 (N_2O).

We applied Equations (11) and (12) to estimate the total and annual GHG and SO_x emissions of each life cycle stage of the cobalt supply chain. In Equation (11), $T_{G-i}(t)$ is the total cumulative GHG or SO_x emissions in stage *"i"* in the year *"t"* for the period 2000–2050, *i*= *1,2, …,13* represent primary and secondary production stages of the cobalt supply chain (CRCoS). Then,$G_i(t_0)$ is the GHG or SO_x emissions in stage *"i"* in the initial year *"t_0"*. In Equation (12), $G_i(t)$ is the GHG or SO_x emissions in stage *"i"* in the year *"t"*, $E_i(t)$ is energy consumption in stage *"i"* in the year *"t"*, and $\delta_i(t)$ is the amount of CO_2 equivalent (CO_2 eq) emitted in stage *"i"* in the year *"t"* (for the case of GHG emissions) or the amount of SO_x emitted in stage *"i"* in the year *"t"* (for the case of SO_x emissions).

$$T_{G-i}(t) = \int_{t_0}^{t} G_i(t)\mathrm{d}t + G_i(t_0) \tag{11}$$

$$G_i(t) = E_i(t) \times \delta_i(t) \tag{12}$$

3. Results and discussions

The need for a systematic analysis of the cobalt supply chain has been presented in several studies, e.g. Nkulu et al. (2018), Sun et al. (2019), Tisserant and Puliuk (2016), and Nansai et al. (2014). In this paper, we try to address this call by assessing the key environmental concerns such as energy consumption, water use, GHG and SO_x emissions at different stages of the global cobalt supply chain using system dynamics modelling (Forrester, 1997). The analysis presented in this paper covers a 50-year time horizon, from 2000 to 2050. The reason for the selection of this time interval is the need to explore future global environmental impacts of cobalt mining, processing, and recycling. Also, we consider challenges of the cobalt supply and consumption from the near future and until 2050. Some studies project a fourfold increase of the cobalt demand by 2050 (Nansai et al., 2014; Tisserant and Pauliuk, 2016), which might be triggered by the growth of the global demand for several products containing cobalt, such as batteries and superalloys (Monge and Gil-Alana, 2019).

3.1. Trends in cobalt production

Historical data for the global mine production of cobalt are available for the period between 1990 and 2016 from the United States Geological Survey (USGS) data sources (Shedd, 2016). Therefore, the model duration corresponds to two periods, the historical (1990–2016) and the future period (2016–2050). Growth rate of the estimated primary production of cobalt is based on future demand (on average 5–8 % per annum) by 2050 (Hagelüken, 2014; Tisserant and Pauliuk, 2016). Supplementary Fig. 1 presents geographical distribution of cobalt primary and secondary production in 2020 and 2050. Results show that the total global primary production of cobalt increases from 129.27 thousand tonnes in 2020 to 284.58 thousand tonnes in 2050. The total global secondary cobalt production increases from 38.67 thousand tonnes in 2020 to 97.00 thousand tonnes in 2050.

The analysis of mass flows shows a significant potential of supplying cobalt from secondary sources up to 25 % by 2050. In the recycling stage, one of the most important factors is the delay between the production phase and waste collection. Considering the high hoarding percentage and the low collection rate of end of life products, which mainly occurs because waste products including cobalt are disposed as municipal waste, the analysis shows that waste separation technologies will play a major role in the development of the cobalt industry. The efficiency of waste separation technologies is, naturally, one of the most influential factors of cobalt recovery. Detailed calculations show that every 1 % of improvement on the efficiency of waste separation technologies represents roughly a 4 % increase of material recovery by 2050.

3.2. Trends in environmental impacts of cobalt supply chain

In this study, the dynamic model is used to evaluate different cobalt flows and their global environmental impacts in the years 2000–2050. The total annual energy consumption and direct water use in primary and secondary cobalt production as well as the trend in GHG and SO_x emissions from the global supply chain of cobalt are illustrated in Fig. 4. Trends in energy and water demand as well as in GHG and SO_x emissions are affected by the projected continuous increase in the global consumption of cobalt. The results of simulation presented in Fig. 4A show a marked increase in the global energy consumption for the primary production of cobalt from 8.98 million GJ in 2000 to 79.42 million GJ in 2050, which corresponds approximately to a 9-fold growth within the 50-year interval. The secondary production of cobalt experiences a more rapid increase compared to primary cobalt refining. In particular, it was estimated to grow 15-fold from 0.96 million GJ in 2000 to 15.01 million GJ in 2050. In general, global cobalt recycling is projected to consume on average 74.2 percentage points energy less during 2000–2050 than the global primary production. The annual mean of the global consumption of energy is estimated to be around 43.71 million GJ for the primary and 7.11 million GJ for the secondary supply chains of cobalt. In addition, the specific energy demand per 1 kg of produced cobalt was assessed. The analysis shows that the specific energy demand for the primary production of cobalt accounts for about 27.32 GJ/kg of cobalt, while for the secondary production of cobalt it is assumed to have a specific energy demand of approximately 14.66 GJ/kg of cobalt. In the case when the entire supply chain is considered, this result implies that recycling of cobalt requires approximately 46.35 % less energy than its' primary production.

The projected development of the annual water consumption for primary and secondary production of cobalt is depicted in Fig. 4B. Values presented in the figure illustrate the direct water demand, which considers the water use for production of cobalt but does not include the energy-related water consumption. The direct water demand for the primary cobalt production is projected to increase from 0.46 million m^3 in 2000 to about 4.09 million m^3 in 2050. In case of the secondary production of cobalt, this quantity grows from 0.06 million m^3 to 0.93 million m^3 in the same time interval. It was estimated that the global recycling of cobalt requires on average 70 percentage points of direct water less than the global primary production. The assessment of the specific water demand to produce 1 kg of cobalt should include the assessment of the energy-related water use. The detailed analysis is presented in the section 3.3 of this study titled 'Effects of changes in energy system on water demand for cobalt'.

Fig. 4C and 4D represent the projected development of GHG and SO_x emissions from the global supply chain of cobalt between 2000 and

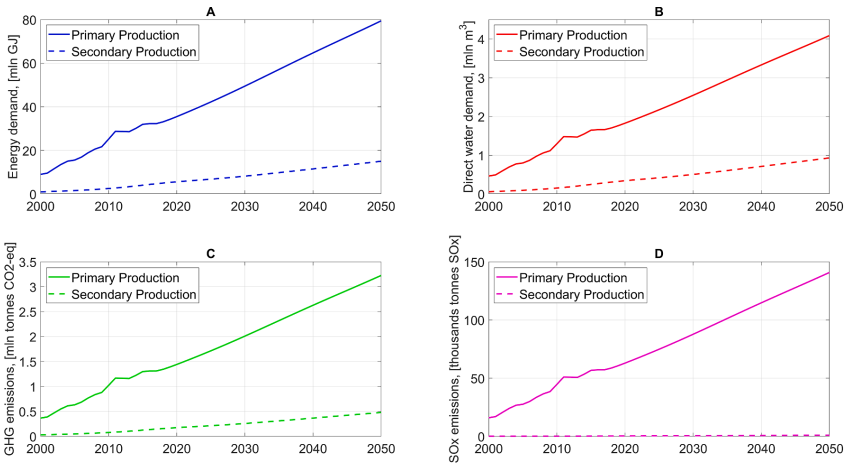

Fig. 4. Environmental performance of primary and secondary production of cobalt between 2000 and 2050. **A)** Annual global energy consumption, in million GJ. **B)** Annual global direct water consumption, in million cubic meters. **C)** Annual global GHG emissions, in million tonnes CO_2-equivalent. **D)** Annual global SO_x emissions, in thousand tonnes SO_x. The presented values refer to the processes of primary and secondary production of cobalt, thus excluding energy-related water demand and emissions.

2050. The global annual mean of GHG emissions from the primary and secondary stages amount to about 1.78 million tonnes CO_2-eq and to 0.22 million tonnes CO_2-eq respectively. GHG emissions from the primary production of cobalt will reach a maximum of approximately 3.23 million tonnes CO_2-eq while the maximum of GHG emitted through secondary production reaches around 0.48 million tonnes CO_2-eq in 2050. In case of cobalt recycling, the specific CO_2-eq emissions are 58.7 % lower than in its' primary production (4.58 kg CO_2-eq/kg of cobalt and 11.09 kg CO_2-eq/kg of cobalt, respectively).

The strong negative influence of the production of cathode containing cobalt on the environment by generating SO_x emissions, especially during the smelting step, has been reported by Dunn et al. (2015). The outcomes of the calculation show that recycling of cobalt may contribute to a considerable reduction of SO_x emissions. The specific SO_x emissions per 1 kg of produced cobalt amount to 0.48 kg SO_x/kg of cobalt in the case of primary production and to about 0.01 kg SO_x/kg of cobalt during the recycling stage. Therefore, the production of 1 kg of cobalt through recycling emits on average 98 % less SO_x than the primary production of cobalt. In 2050, annual global SO_x emissions are projected to reach 141.75 thousand tonnes SO_x, of which only 0.66 % is estimated to originate from the recycling of cobalt.

This finding highlights that the contribution of cobalt recycling to energy saving and water consumption as well as to avoiding or reducing GHG and SO_x emissions is the key driver to develop technologies and improve policies related to the secondary production of cobalt.

3.3. Effects of changes in energy system on water demand for cobalt

In this section, a detailed analysis of the water demand related to cobalt production is presented. As depicted in Fig. 5A, the total water demand (including the direct and indirect water consumption) accounts for 37.47 million m^3 in 2020. Subsequently, it grows to 37.09 m^3 in 2030, 39.23 m^3 in 2040 and 41.07 m^3 in 2050. Thus, the projected increase in the annual total water demand appears to be 9.61 % by the end of 2050, compared to the 2020 level. In general, the indirect (energy-related) water consumption accounts for 90.94 % of the total amount of water used globally by the cobalt supply chain during 2020–2050, while the direct water demand represents only 9.06 %. It was established that the share of indirect water demand in the total water consumption might change over time: from 94.22 % in 2020 to 87.86 % in 2050. The underlying reason for this development is the gradual fossilization of the global energy system during 2020–2050, which is projected by the LUT Energy System transition model (Bogdanov et al., 2019) and discussed by Lohrmann et al. (Lohrmann et al., 2019). The average annual water consumption in the period 2000–2050 is projected at the level of 32.37 million m^3 for the primary and 6.35 million m^3 for the secondary production of cobalt.

In contrast to the above-mentioned increase of the total water demand, the specific total water demand (STWD) for the production of 1 kg of cobalt is estimated to decrease considerably in the future (as shown in Fig. 5B). An assessment of the STWD values was performed for the primary and secondary production. In addition, the 'global average' metric was introduced, which represents a weighted average value of the global demand. The results of the study reveal that the STWD for primary processing of cobalt is considerably higher than for cobalt recycling. For instance, in 2020, the STWD for the primary production accounts for 0.25 m^3/kg of cobalt and for recycling for 0.13 m^3/kg of cobalt. Such a difference could be explained by the fact that water demand values correlate strongly with the assumed location of cobalt processing capacities. As discussed in the next section of the paper, the primary production of cobalt is mainly located in regions with water-intensive energy systems, whereas recycling capacities are assumed to be distributed more evenly worldwide. As shown in Fig. 5B, compared to the STWD for cobalt recycling, the STWD for primary cobalt processing is projected to experience a rapid decrease during 2020–2030. As noted by Lohrmann et al. (Lohrmann et al., 2019), this might be caused by the extensive decommissioning of old water-demanding thermal power plants and their replacement by renewable energy technologies. By the end of 2050, the STWD for the primary and secondary production of cobalt will reach 0.12 m^3/kg of cobalt and 0.07 m^3/kg of cobalt, respectively. In the same year, the global average STWD is estimated at the level of 0.11 m^3/kg of cobalt. The analysis revealed that recycling of cobalt consumes on average 39.77 % less water than the primary production. The finding suggests benefits resulting from a systemic approach to the recycling stage. This, in turn, sheds light on the marked contribution of the recycling stage to the reduction of energy and water demand in the cobalt life cycle.

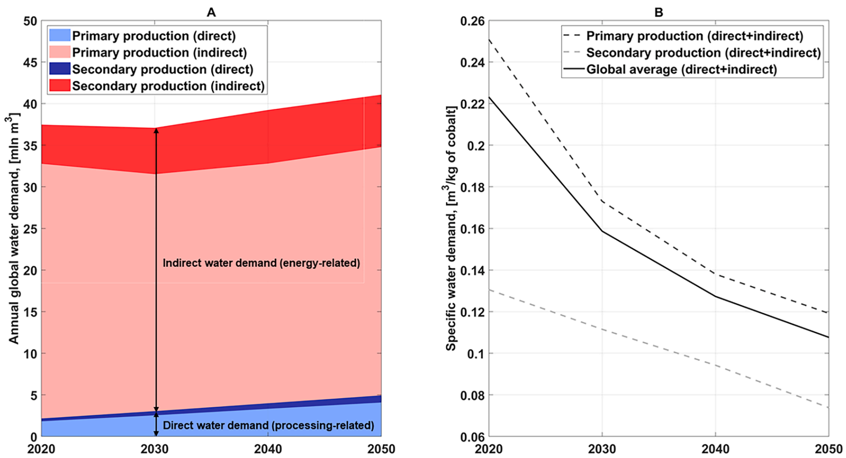

Fig. 5. Direct and indirect water demand for cobalt production. **A)** Annual global demand of water in primary and secondary cobalt production, in million m^3. **B)** Specific demand of water in primary and secondary cobalt production, in m^3/kg of cobalt.

3.4. Projected cobalt-related energy and water use

Fig. 6 presents geographical distribution of energy demand for the cobalt production. As can be seen in the figure, in 2020 energy demand associated with cobalt refining from primary sources (Fig. 6A) emerges mostly in the territories highlighted by Sun et al. (Sun et al., 2019). The top countries with the highest energy demand for primary cobalt production are: China, Japan, South Korea, the USA, and UK. In the same year, China accounts for 48 % of the global energy demand for primary refining of cobalt, which corresponds to about 15.01 million GJ. This situation is projected to change slightly by 2050 (Fig. 6C), increasing the energy demand for primary processing of cobalt by developing countries. China, Japan, the USA, UK, and Germany are expected to have the highest energy demand in 2050, while the largest relative change in the energy demand of up to 158 % is projected for a group of African states: Djibouti, Somalia, Kenya, Uganda, and the Democratic Republic of Congo. Considering secondary production, in this case, cobalt recycling is assumed to be completely separated from primary refining of cobalt and, thus, it is tied to the demand rather than to the supply of materials. Therefore, the energy demand for cobalt recycling, which is assumed to be performed locally, is more evenly distributed than for the primary processing of cobalt. Since the geographical cobalt demand is associated to GDP per capita and population, both associated with their respective country, in 2020 (Fig. 6B) most of the energy demand for cobalt recycling (about 25 % or 1.35 million GJ) is located in China due to the high population density and global average GDP per capita level. Europe and North America also have regions with considerable recycling, such as Germany, UK, France, and the USA. As the projections shift towards 2050 (Fig. 6D), regions in Asia and Africa become the demand leaders as their GDP per capita and population are expected to increase considerably from their current levels. By the end of 2050, India is expected to represent the highest energy demand with projected 2.66 million GJ for recycling of cobalt.

The contrast of the geographical distribution between primary and secondary processing of cobalt highlights the importance of recycling and shifting the energy load from current carbon-intensive energy systems (China, Russia, USA, etc.) to countries with energy systems of lower carbon emissions per unit of energy (Nordic countries, Germany, France, UK, etc.).

Finally, Fig. 7 highlights that the total (cobalt-processing- and energy-related) water use has strong variations in its geographical distribution between primary (Fig. 7A,C) and secondary production of cobalt (Fig. 7B,D). The main reasons of these differences are the projected variations in energy intensity of cobalt processing in specific areas and the composition of the energy system in those regions. On one hand, regions with energy systems which have large shares of thermal capacities such as coal, gas-fired and nuclear power plants as well as reservoir-based hydropower plants, experience a much higher water consumption per unit of energy compared to wind power and solar photovoltaics (Lohrmann et al., 2021). On the other hand, it was demonstrated previously that cobalt recycling reduces the associated water consumption considerably in absolute numbers both globally and locally. Therefore, cobalt recycling can relocate some of the water consumption away from the regions of primary processing of cobalt and distribute it more evenly across the world.

In 2020, China was estimated to consume 18.45 million m^3 of water, which represents 56.92 % of the total amount of water used by the primary production of cobalt worldwide. Unsurprisingly, other countries with high water consumption are Japan, the USA, Russia, South Korea, and France, since the energy systems of these countries are characterized by a high share of water-intensive power plants (International Energy Agency (IEA), 2018).

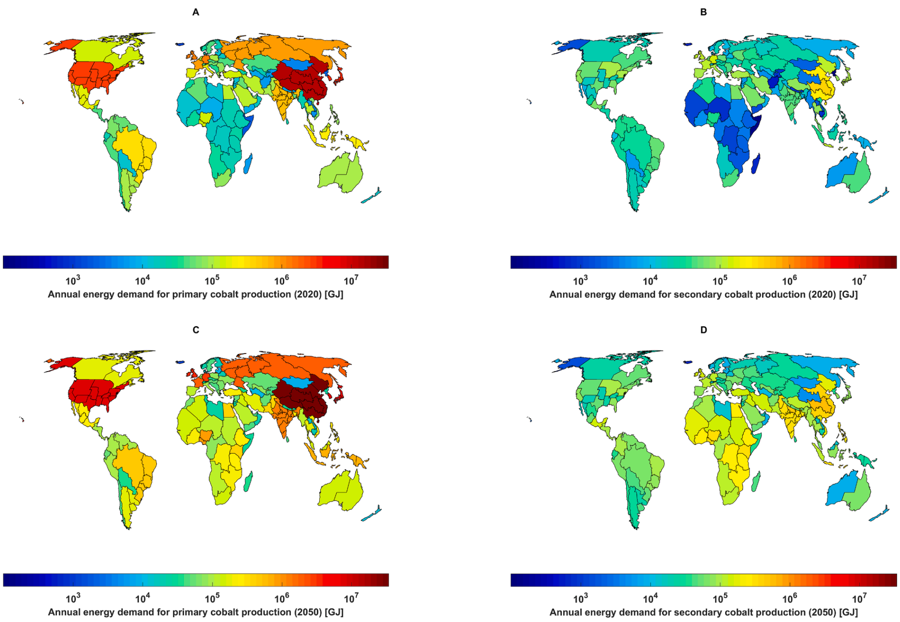

Fig. 6. Geographical distribution of energy demand for cobalt production. **A,C)** energy demand for primary production of cobalt in 2020 and 2050. The total global energy demand for production of cobalt increases from 35.48 million GJ in 2020 to 79.43 million GJ in 2050. **B,D)** energy demand for secondary production of cobalt in 2020 and 2050. The total global energy demand for secondary production of cobalt increases from 5.58 million GJ in 2020 to 15.01 million GJ in 2050.

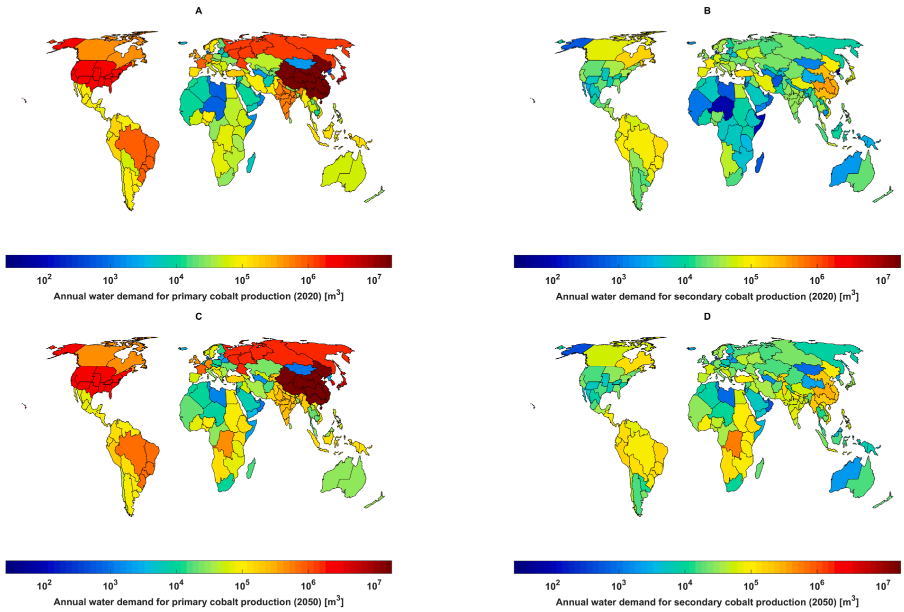

Fig. 7. Geographical distribution of total (cobalt-processing- and energy-related) water consumption of cobalt production. **A,C)** water demand for primary production of cobalt in 2020 and 2050. The total global water consumption for primary production of cobalt increases from 32.42 million m^3 in 2020 to 33.91 million m^3 in 2050. **B,D)** water demand for secondary production of cobalt in 2020 and 2050. The total global water consumption for secondary production of cobalt increases from 5.05 million m^3 in 2020 to 7.16 million m^3 in 2050.

In the same year, China has also the largest water demand for cobalt recycling with 1.43 million m^3 (28 % of the global estimates). Similarly to energy consumption, the water use associated with secondary production of cobalt increases particularly in Asia and Africa, as the projections shift to 2050. This could be explained by the expected growth of GDP and population in these developing countries. When a division of the world into 145 regions (as shown in Figure 7B,D) is considered, the Democratic Republic of Congo, with the largest water demand by secondary production of cobalt, extracts 0.61 million m^3 in 2050. As highlighted in Figure 7D, a large water consumption for cobalt recycling is projected in several provinces of China, Myanmar, Tajikistan, and Kyrgyzstan. According to the WRI Aqueduct Atlas (Water Resources Institute (WRI), 2020), many of the above-mentioned regions are reported to have a medium–high and high baseline water stress. Thus, the projected implementation of cobalt processing capacities might put an additional stress on the local water resources and stimulate a higher competition for water with agriculture and food production sector. Therefore, a more comprehensive approach is required to evaluate the effects of the commissioning of these capacities for each specific region.

It should be noted that geographical distribution of primary processing of cobalt is likely to change in the future.

4. Discussion

Previous research studies on cobalt were limited to particular stages of the supply chain such as mining or recycling, as well as restricted to case studies, e.g. lithium-ion batteries (Ciez and Whitacre, 2019; Nkulu et al., 2018; Tran et al., 2019). Moreover, none of those studies offered a comprehensive environmental analysis across all stages of cobalt supply chain globally. The detailed analysis discussed in this article has provided new and useful insights that have the potential to benefit policy and decision making in practice aimed at reaching a more sustainable future circular utilization of cobalt in the world economy. Some important environmental issues such as high energy consumption, water use, greenhouse gases (CO_2, N_2O, CH_4 emissions), and sulfur oxides emissions need to be addressed to ensure environmentally sustainable cobalt supply chain. This article gives a comprehensive overview of various flows in cobalt supply chain from the perspective of environmental sustainability.

Changes in cobalt supply and demand resulting from various factors have been studied extensively (e.g., batteries production together with demand for alloys, and the effect of increasing world population on cobalt consumption) (León and Dewulf, 2020). One of the main challenges in cobalt supply chain management results from increased production of electric vehicles in near future. The problem consists in limited resources of cobalt. Therefore, cobalt recovery is very important as a solution that may help manage its shortages in the future. On the other hand, an increase in the production of cobalt requires more energy and water as well as generates more waste, GHG emissions and SO_x emissions in production stages of its supply chain. Therefore, we examined the above-mentioned issues through all stages of the supply chain: mining, processing, production, and recycling.

The principles of circular economy are based on the conservation of the value of materials within the economic system as long as possible (El Wali et al., 2021). There are various definitions for circular economy, however, recycling is always a prominent feature of the concept (Golroudbary et al., 2020). This concept serves the mitigation of cobalt criticality, as it aims to extend the useful life of raw materials extracted from the environment, reduce reliance on finite resources, and mitigate permanent waste disposal. As shown in our results, cobalt recycling operations could have a significant contribution on reducing energy consumption, water use and mitigating GHG and SO_x emissions comparing primary production. The obtained results show that around 10 % of GHG emissions and 0.50 % of SO_x emissions in cobalt life cycle originate from secondary production, which consumes around 13 % of total energy and 16 % of total water used in cobalt production stages. This finding highlights the need for an appropriate strategy of secondary sources management that would ensure a better use of cobalt recycling in line with its circularity. New planning policies should overcome the barriers hindering recycling to benefit efficient using of resources and reducing energy and water consumption as well as avoiding GHG and SO_x emissions through the recovery of cobalt from end of life products.

It is worth noting that increased cobalt recycling positively contributes to the environmental goal agreed in the Paris Agreement (Waisman et al., 2019) and the 2030 Agenda for Sustainable Development goals (SDGs) such as SDGs 7, 12, and 13 among others (Church, 2019). As cobalt is critical in developing and deploying green energy technologies, securing its sustainable and affordable supply — through recycling activities — could contribute to the SDG 7. Also, primary production of cobalt can be associated with higher levels of waste production when compared to recycling processes. Therefore, secondary production of cobalt contributes directly to achieving the targets of SDG 12 — ensure sustainable consumption and production patterns as well as to mitigation of climate change set out by SDG 13.

Another finding of this analysis shows that the improvement of the efficiency of waste separation technologies increases cobalt recovery significantly. Therefore, it could also result in a significant reduction in water and energy consumption if the respective additional consumption of energy and water for the secondary treatment of cobalt is lower than that of primary sources. Moreover, the generated projections show that an increase in global consumption of cobalt may occur in a significantly different manner for primary and secondary cobalt as its demand grows. Cobalt recycling will play an incredibly significant role in the cobalt industry benefiting not only material conservation. Secondary cobalt production can significantly reduce the carbon emissions. It can also alleviate the energy and water demand associated with cobalt processing from the regions where currently primary processing of cobalt is concentrated. In addition, cobalt recycling can be done locally, thus, it may reduce the domestic dependence on primary cobalt in regions where cobalt is not naturally available. This may also reduce the need for long-distance transport and, consequently, mitigate transport-related emissions and energy consumption.

5. Conclusion

This article presents a comprehensive overview of the global–local cobalt supply chain considering mass, waste, energy, water, and air emissions. The paper aims to answer three key questions, beginning with addressing how the consumption of cobalt is projected to develop and the impact of its supply from primary and secondary sources on the environment globally by 2050. The second key question is about the role of recycling of cobalt in saving energy and water through its supply chain. Finally, the third key issue is whether recycling of cobalt contributes to reduction of emissions such as GHG and SO_x.

The obtained results show that cobalt recycling might lead to reduction of energy consumption by 46 % and diminishing the use of water by 40 % when compared to primary production. Also, recycling contributes to mitigation of GHG and SO_x emissions of cobalt flow by 59 % and 98 %, respectively. The detailed analysis has shown around 25 % of total required cobalt could be supplied from secondary sources by 2050.

The projections presented in this article show that an increase in global consumption of cobalt may occur in a significantly different manner for its primary and secondary production as demand for this material grows. Every 1 % of improvement in efficiency of waste separation represents roughly a 4 % increase of material recovery by 2050. Our findings highlight that cobalt recycling performed at the country of consumption mitigates the import reliance of cobalt from a few global producers. Cobalt recycling performed at the country of consumption also promotes decentralized energy and water demand, which is currently constrained to the small number of cobalt producers.

This finding emphasizes the need for developing new strategies for management of cobalt recycling. The extent of cobalt recovery from secondary sources should steadily increase. Moreover, technology development for cobalt recovery should be taken into account due to its significant contribution to mitigation of energy consumption as well as water and environmental footprints.

CRediT authorship contribution statement

Saeed Rahimpour Golroudbary: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Javier Farfan:** Conceptualization, Formal analysis, Investigation, Methodology, Software Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alena Lohrmann:** Formal analysis, Investigation, Methodology, Software Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Andrzej Kraslawski:** Conceptualization, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102568.

Reference

Ahmed, S., Nelson, P.A., Gallagher, K.G., Susarla, N., Dees, D.W., 2017. Cost and energy demand of producing nickel manganese cobalt cathode material for lithium ion batteries. J. Power Sources 342, 733–740.
Alves Dias, P., Blagoeva, D., Pavel, C., Arvanitidis, N., 2018. Cobalt: demand-supply balances in the transition to electric mobility. Eur. Comm. Jt. Res. Centre, EUR-Scientific Tech. Res. Reports. Publ. Off. Eur. Union. DOI 10, 97710.
Nkulu, C.B.L., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.-M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. 1 (9), 495–504.
Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A.S., Barbosa, L. de S.N.S., Breyer, C., 2019. Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat. Commun. 10, 1–16.
Campbell, G.A., 2019. The cobalt market revisited. Miner. Econ. 33 (1-2), 21–28.
Chagnes, A., Swiatowska, J., 2015. Lithium Process Chemistry: Resources, Extraction, Batteries, and Recycling. Elsevier.
Chen, Z., Zhang, L., Xu, Z., 2019. Tracking and quantifying the cobalt flows in mainland China during 1994–2016: insights into use, trade and prospective demand. Sci. Total Environ. 672, 752–762.
Church, C., 2019. Sustainability and Second Life: The Case for Cobalt and Lithium Recycling. International Institute for Sustainable Development.
Ciez, R.E., Whitacre, J.F., 2019. Examining different recycling processes for lithium-ion batteries. Nat. Sustain. 2 (2), 148–156.
EU Commission, 2014. Report on Critical Raw materials for the EU. Retrieved April 30, 2015.

EU Commission, 2015. Closing the loop-An EU action plan for the Circular Economy. Commun. from Comm. to Eur. Parliam. Counc. Eur. Econ. Soc. Comm. Comm. Reg. COM 614, 2015.
EU Commission, 2017. Study on the review of the list of critical raw materials. Eur. Comm. Brussels, Available from http//hytechcycling.eu/wp-content/uploads/Study-on-the-review-of-the-list-of-Critical-Raw-Materials.pdf.
Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life Cycle analysis of lithium-ion batteries for automotive applications. Batteries 5, 48.
Dunn, J.B., Gaines, L., Kelly, J.C., James, C., Gallagher, K.G., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy Environ. Sci. 8 (1), 158–168.
El Wali, M., Golroudbary, S.R., Kraslawski, A., 2021. Circular economy for phosphorus supply chain and its impact on social sustainable development goals. Sci. Total Environ. 777, 146060.
Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751.
Ferron, C.J., 2013. The Recycling of Cobalt from Alloy Scrap, Spent Batteries or Catalysts and Metallurgical Residues—an Overview, in: Ni-Co 2013. Springer, pp. 53–71.
Forrester, J.W., 1997. Industrial dynamics. J. Oper. Res. Soc. 48, 1037–1041.
Glöser-Chahoud, S., Schultmann, F., 2019. Potential contribution of secondary materials to overall supply-the example of the European cobalt cycle. Mater. Sci. Forum. 11–21.
León, M.F.G., Dewulf, J., 2020. Data quality assessment framework for critical raw materials. The case of cobalt. Resour. Conserv. Recycl. 157, 104564.
Golroudbary, S.R., El Wali, M., Kraslawski, A., 2019b. Environmental sustainability of phosphorus recycling from wastewater, manure and solid wastes. Sci. Total Environ. 672, 515–524.
Golroudbary, S.R., El Wali, M., Kraslawski, A., 2020. Rationality of using phosphorus primary and secondary sources in circular economy: game-theory-based analysis. Environ. Sci. Policy 106, 166–176.
Golroudbary, S.R., Calisaya-Azpilcueta, D., Kraslawski, A., Al., E., 2019a. The Life Cycle of Energy Consumption and Greenhouse Gas Emissions from Critical Minerals Recycling: Case of Lithium-ion Batteries. Procedia CIRP 80, 316–321.
Golroudbary, S.R., Makarava, I., Kraslawski, A., Repo, E., 2022. Global environmental cost of using rare earth elements in green energy technologies. Sci. Total Environ. 832, 155022 https://doi.org/10.1016/j.scitotenv.2022.155022.
Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S. F., Sonnemann, G., 2011. What do we know about metal recycling rates? J. Ind. Ecol. 15, 355–366.
Hagelüken, C., 2014. Recycling of (critical) metals. Crit. Met. Handb. 41–69.
Huang, L., Liu, Y., Yu, L., Quan, X., Chen, G., 2015. A new clean approach for production of cobalt dihydroxide from aqueous Co (II) using oxygen-reducing biocathode microbial fuel cells. J. Clean. Prod. 86, 441–446.
Huisman, J., Leroy, P., Tertre, F., Söderman, M.L., Chancerel, P., Cassard, D., Løvik, A.N., Wäger, P., Kushnir, D., Rotter, S., others, 2017. Prospecting secondary raw materials in the urban mine and mining wastes.
International Energy Agency (IEA) Statistics. Global energy data at your fingertips 2018 Paris. [Available].
Kovacheva-Ninova, V., Savov, G., Vassileva, V., Vutova, K., Petrov, E., Petrov, D., 2018. Trends in the development of cobalt production. Electrotech. Electron. 53, 84–94.
Lebedeva, N., Di Persio, F., Boon-Brett, L., 2017. Lithium ion battery value chain and related opportunities for Europe. https://doi.org/10.2760/6060.
Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C., Breyer, C., 2019. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. Nat. Energy 4 (12), 1040–1048.
Lohrmann, A., Child, M., Breyer, C., 2021. Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system. Energy 233, 121098.
Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ. Res. Lett. 7 (4), 045802.
Monge, M., Gil-Alana, L.A., 2019. Automobile components: Lithium and cobalt. Evidence of persistence. Energy 169, 489–495.
Mudd, G.M., Weng, Z., Jowitt, S.M., Turnbull, I.D., Graedel, T.E., 2013. Quantifying the recoverable resources of by-product metals: the case of cobalt. Ore Geol. Rev. 55, 87–98.
Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., Oshita, Y., 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. Environ. Sci. Technol. 48 (3), 1391–1400.
Ober, J.A., 2018. Mineral commodity summaries 2018. US Geol. Surv.
Ordoñez, J., Gago, E.J., Girard, A., 2016. Processes and technologies for the recycling and recovery of spent lithium-ion batteries. Renew. Sustain. Energy Rev. 60, 195–205.
Pagnanelli, F., Moscardini, E., Altimari, P., Atia, T.A., Toro, L., 2016. Cobalt products from real waste fractions of end of life lithium ion batteries. Waste Manag. 51, 214–221.
Palanivel, S., Natarajan, S., 2012. Cobalt Recovery from Waste Catalysts (Petroleum Refining Industry from Gujarat). Open J. Met. 2012.
Rahimpour Golroudbary, S., Krekhovetckii, N., El Wali, M., Kraslawski, A., 2019. Environmental sustainability of niobium recycling: the case of the automotive industry. Recycling 4, 5. https://doi.org/10.3390/recycling4010005.
Romare, M., Dahllöf, L., 2017. The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries. Stock. Zugriff am 23, 2017.
Shedd, K., 2016. Cobalt Statistics and Information. US Geol. Surv. (USGS). Available https//www.usgs.gov/centers/nmic/cobalt-statistics-and-information.
Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., others, 2013. Climate change 2013: The physical science basis. Contrib. Work. Gr. I to fifth Assess. Rep. Intergov. panel Clim. Chang. 1535.
Sun, X., Hao, H., Liu, Z., Zhao, F., Song, J., 2019. Tracing global cobalt flow: 1995–2015. Resour. Conserv. Recycl. 149, 45–55.
Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2017. Integrated modelling of the global cobalt extraction, supply, price and depletion of extractable resources using the world6 model. Biophys. Econ. Resour. Qual. 2, 4.
Swain, B., 2017. Recovery and recycling of lithium: a review. Sep. Purif. Technol. 172, 388–403.
Tisserant, A., Pauliuk, S., 2016. Matching global cobalt demand under different scenarios for co-production and mining attractiveness. J. Econ. Struct. 5, 4.
Tkaczyk, A.H., Bartl, A., Amato, A., Lapkovskis, V., Petranikova, M., 2018. Sustainability evaluation of essential critical raw materials: cobalt, niobium, tungsten and rare earth elements. J. Phys. D. Appl. Phys. 51 (20), 203001.
Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D., Breyer, C., 2019. Long term load projection in high resolution for all countries globally. Int. J. Electr. Power Energy Syst. 111, 160–181.
Tran, M.K., Rodrigues, M.-T., Kato, K., Babu, G., Ajayan, P.M., 2019. Deep eutectic solvents for cathode recycling of Li-ion batteries. Nat. Energy 4 (4), 339–345.
United Nations Department of Economic and Social Affairs, 2019. 2019 Revision of World Population Prospects. United Nations New York, Retrieved from https://population.un.org/wpp/.
Waisman, H., De Coninck, H., Rogelj, J., 2019. Key technological enablers for ambitious climate goals: insights from the IPCC special report on global warming of 1.5 °C. Environ. Res. Lett. 14 (11), 111001.
Wang, S., 2006. Cobalt—its recovery, recycling, and application. JOM 58 (10), 47–50.
Wang, M., Elgowainy, A., Benavides, P.T., Burnham, A., Cai, H., Dai, Q., Hawkins, T.R., Kelly, J.C., Kwon, H., Lee, D.-Y., others, 2018. Summary of Expansions and Updates in GREET®2018.
Water Resources Institute (WRI), 2020. "Aqueduct Atlas - Baseline Water Stress Country Rankings." [Available]. https://www.wri.org/applications/aqueduct/country-rankings/.
Zeng, X., Li, J., Singh, N., 2014. Recycling of spent lithium-ion battery: a critical review. Crit. Rev. Environ. Sci. Technol. 44 (10), 1129–1165.

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