WATER FOOTPRINT OF THE EUROPEAN ENERGY SECTOR IN THE PLANETARY BOUNDARIES CONTEXT

From fossil-based production to the era of renewables

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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The ongoing energy transition means transforming from fossil-fuel based energy production into renewable and low-carbon energy production. Societies are seeing ever increasing signals of global warming in the form of extreme weather, such as droughts and floods. Water scarcity has already been seen as a root cause for conflicts and expected to be so in the future as well.

The concept of planetary boundaries was introduced in the beginning of 21st century and defines the Earth processes and their limits, within which operations remain on a sustainable level. So far, majority of focus has been directed to climate change, but questions around water have become increasingly self-evident. The energy sector consumes water for different process stages. Especially coal-fired- and nuclear power plants consume water for cooling purposes. Despite evidences about water scarcity and the role of water in the energy sector, there has been only limited amount of studies on the matter.

This study takes an empirical focus to investigate whether the European energy sector operates within planetary boundaries when it comes to water use. Energy transition is taken into account by analysing water withdrawal data from 2015 to 2050. Planetary boundaries have been defined in multiple methods to give comparison on the methodology and concept's suitability for water-related questions.

Some of the results indicated that the water withdrawal of the European energy sector is currently not on a sustainable level. By 2050 the situation is expected to change, as less water-intensive renewable energy production will scale. The analysis also showed the need for common principles to define water footprint calculations. This is needed to integrate water-related questions closer to decision-making.

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Meneillään oleva energiatransitio tarkoittaa siirtymistä fossiilipohjaisesta energian tuotannosta kohti uusiutuvaa- ja vähähiilistä energiantuotantoa. Yhteiskunnat näkevät yhä enemmän merkkejä ilmaston lämpenemisestä sään ääriolosuhteiden kautta (esim. kuivuus ja tulvat). Jo tähän päivään mennessä kuivuuden ja vesiniukkuuden on havaittu olevan konfliktien taustalla, ja kehityksen odotetaan vain kiihtyvän tulevaisuudessa.

Planetaaristen rajojen konsepti esiteltiin 2000-luvun alussa ja sen tarkoituksena on määritellä Maan luonnollisia prosesseja ja niiden rajoja, joita noudattamalla voidaan varmistaa toiminta kestävällä tasolla. Toistaiseksi suurin fokus on ollut ilmastonmuutoksessa, mutta vesiaiheiset kysymykset ovat myös alkaneet nousta esille. Energiasektori käyttää vettä erilaisiin prosessin vaiheisiin. Erityisesti hiili- ja ydinvoimalaitokset tarvitsevat paljon vettä jäähdytystarkoituksiin. Huolimatta selvistä merkeistä veden niukkuuden suhteen, veden roolia energiasektorilla on toistaiseksi tutkittu vain vähän.

Tämä lopputyö tarkastelee empiirisesti Euroopan energiasektorin veden käyttöä ja suhdetta planetaarisiin rajoihin. Energiatransitio on otettu huomioon analysoimalla veden käyttöä vuodesta 2015 vuoteen 2050. Planetaaristen rajojen määrittelyyn on käytetty vaihtoehtoisia menetelmiä, jotta on mahdollista vertailla eri metodologioiden vaikutusta lopputulokseen ja niiden sopivuutta veteen liittyviin kysymyksiin.

Osa tuloksista osoitti, ettei Euroopan energiasektori ole tällä hetkellä kestävyyden rajoissa veden käytön suhteen. Vuoteen 2050 mennessä tilanteen voi odottaa muuttuvan, kun vesi-intensiivisistä tuotantoa poistuu ja korvautuu uusiutuvalla energialla. Analyysi myös korosti tarvetta yhteisille laskentamenetelmille, jotta vesijalanjälkeä voidaan käyttää entistä tehokkaammin työkaluna päätöksenteon ja regulaation kehittämisen tukena.

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Introduction

1.1 About the topic

The ongoing energy transition from fossil fuels to renewables can be viewed as one of the greatest shifts since the Industrial Revolution in the 18th century. The amounts of energy needed for electrification and new industrial production processes, for instance, electrolysis usage for hydrogen production, are significant. The public debate and governmental targets are now based largely on the novel energy infrastructure and capacity needed, driven by renewables (Statkraft, 2022). With different kinds of scenario analyses and roadmaps, the societies have modelled their pathways to net zero; achievable in terms of capacity and materials. Even though societies are putting lots of effort to identify the tools to mitigate climate change, there is increasing focus on seeking to understand what are the supply requirements to do so. Decarbonisation and energy transition will require material recourses derived from the Earth's cycles. A lot of attention has recently been put into the availability of rare Earth metals for energy transition (IRENA, 2021). The energy crisis which started in early 2022 and further escalated due to the Ukraine war has made people question the availability of energy. As these scarcities have become more known, more attention has been put on the requirements of energy production (Kuzemko et al. 2022). One of these resources is water, which plays a key role in energy production today and will continue to do so in the future (Tovar-Facio et al. 2021).

Baggio et al (2021) estimate that out of 180 countries, 87 will face water scarcity by 2050. Already today there are signs of water use not being at sustainable levels, considering the water availability (Mekonnen et al. 2015). The competition for water will likely increase in the future, for citizens, agriculture and industrial processes. Since the 1950s there has been a remarkable increase in blue water demand due to the agricultural and industrial sectors (Unfried et al. 2022). Agriculture is so far the biggest water consumer globally, followed by other industrial activities (Biswas & Tortajada, 2022). Even though water scarcity can be viewed as a global issue, the impacts should be addressed on a local level. Based on European Environmental Agency (2022) the annual renewable freshwater amount in Europe is 4560 m^3 per person. Water availability is better in the Northern European countries whereas in In Southern Europe a large share of the population is facing some water scarcity issues throughout the year. In 2017, the annual freshwater resources were 120 m^3 per person in Malta and respectively 70,000 m^3 per person in Norway. The agency points out the key trend of decreasing freshwater resources across Europe. When talking about freshwater, it is important to divide between blue and green water. Blue water includes water in rivers, lakes and aquifers. Green water refers to soil water in the unsaturated zone, being available for plants (Vanham et al. 2019).

A lot of attention in water research has focused on analysing the water supply, whereas data limitations and complexity have limited the research on all the various use cases of water as well as its treatment and recycling (Curmi et al. 2014). This has also led to limited guidance on decision-making related to water management. The research community has already pointed out that if the European energy sector doesn’t focus on improving the power plant’s water use, the water demand might increase uncontrollably in the decades to come (Lohrmann et al. 2021).

Simultaneously, the world sees an increasing number of extreme weather-related events impacting water availability. World Economic Forum has listed the water crisis as one of the top 10 global risks (World Economic Forum, 2019). At the moment over 140 million Europeans are living in areas experiencing high baseline water stress. Water scarcity can lead to severe consequences in the future, especially in regions already experiencing heavy droughts like the Middle East. It is estimated that water scarcity can increasingly be the background reason for conflicts. (World Economic Forum, 2019.) Even though water scarcity might be seen as an occasional issue in Europe during the summers, it has already impacted energy production. In 2018, French utility EDF had to cut down nuclear electricity production in four reactors due to a heatwave in France (Reuters, 2018). A similar situation occurred again in the summer of 2022 when rising river temperatures limited French nuclear production (Reuters, 2022). Nuclear reactors depend on cooling water from nearby water areas. Hydropower plants might experience uncertainties in energy output if dry summers become more common (IEA, 2017). In the future, new routes to secure water supply might be needed to guarantee operations. For example, desalination of seawater and water reuse might become required options (Simoes et al. 2021). On the other hand, many of these purification technologies require a lot of electricity, which might cause even more problems for the energy system. IEA (2020) estimates that in the Middle East, desalination electricity consumption will increase from 5% to 15% of the total energy mix by 2040.

According to Terranon-Pfaff et al. (2020), the global energy sector totals around 10-15% of the global freshwater withdrawal. International Energy Agency, IEA, calculates that in 2016 the majority of water consumption in energy production was within fossil fuels, especially coal use and biofuels. Taking predictions further to 2030, the estimate sees significant growth in water consumption with biofuels production whereas the portion for fossil fuels as a primary energy source will decrease. (IEA, 2020.) Energy sector amounts to 42% of total water abstraction within the EU (European Commission, 2019). Literature covers the linkage between energy production and water, but the focus has previously been mainly on water quantity, water quality and wider climate change-related context (Vanham et al. 2019). In addition, the focus has been very regional and not taken into account from an energy transition perspective (Tovar-Facio, 2021). Vanham et al. (2019) point out that even though water scarcity is acknowledged in Europe as an issue, the EU has not taken any actions to include water resource use in its energy policy. Yang et al. (2013) emphasise that in order to successfully perform water resource management, high-quality data is needed on the global and local levels.

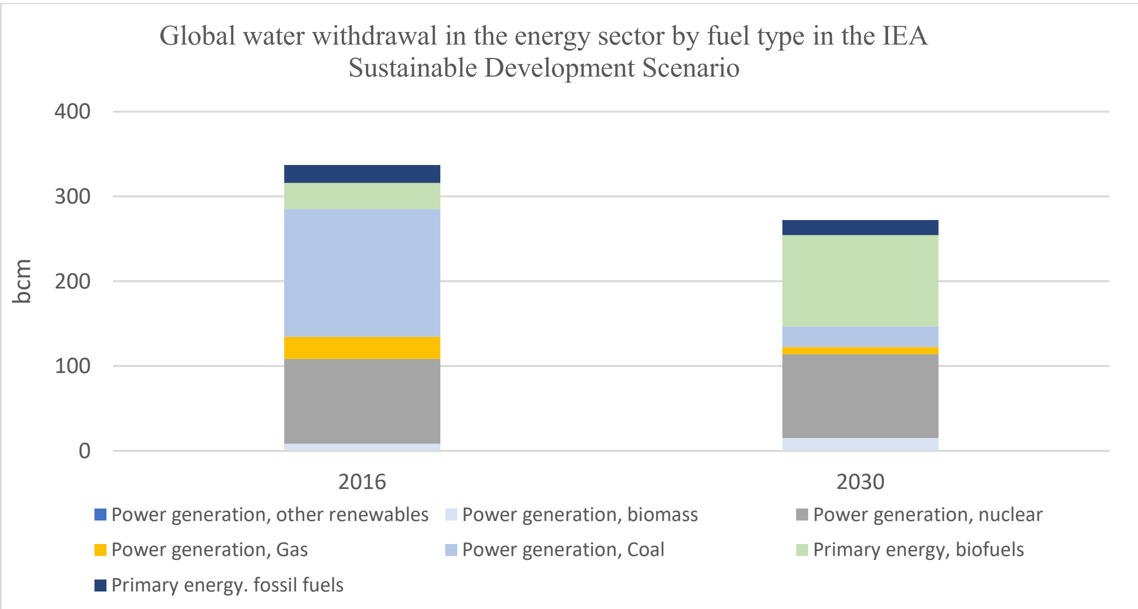

Figure 1 Water withdrawal and consumption estimates by IEA Sustainable Development Scenario (IEA, 2020)

1.2 Motivation of the study and research question

The ambitions to tackle climate change are increasing with countries and companies making record amounts of pledges for reaching net zero. The main focus is put on reducing emissions by switching the form of energy used from fossil-based sources like oil and coal into renewables and carbon-free sources like wind, solar and nuclear. Simultaneously, fuels used in processes are changing: for instance, in the heavy transportation, the shift from heavy fuel oils to hydrogen-based derivatives is already addressed by major transportation companies. With this fundamental shift in energy sources comes also a new kind of pressure on the Earth systems, which are increasingly debated in addition to the GHG emissions. It is recognized that water use in the energy sector today might be at unsustainable levels, especially seen by the normalization of extreme weather conditions.

Based on these underlying assumptions of the role of water in energy production, there is a clear need to understand better the current and expected future state of water use in the energy sector. The aim is to identify the systemic change and how solving one sustainability dilemma with renewable energy production might impact the sustainable use of other resources, here meaning freshwater. If and when water is to become a scarce resource in the future, it might also experience tighter competition among sectors and therefore require new actions and solutions to secure the needed water supply. The geographical focus of this work is in Europe, as the continent has high ambition climate targets and a major energy transition is happening not only because of climate targets but also due to the security of supply needs. Compared to the magnitude of economic activity in Europe, the available land area is limited. This poses an interesting angle for the food-water-energy nexus and raises a question of land use. Europe was chosen as the focus region also since there is high-quality data available. Considering only the Nordic countries would not be as interesting as taking Europe as a whole since in the Nordics the water availability is much better than in central Europe. The focus is on the energy industry’s water demand, including energy production and sourcing. The key share of this energy production is traditional and existing generation technologies but the study will also note the emergence of novel decarbonization technologies such as carbon capture and hydrogen. To grasp the full-scale changes in the energy sector and expected water demand, the timeframe of the study is set to 2050. This is mainly because many countries have set their net zero targets until 2050. The timeframe also allows a clear comparison between fossil-based energy production and the transition to renewables.

The study aims to provide an understanding of whether the European energy sector is operating within the planetary boundaries when it comes to freshwater use. First, it’s needed to set and define those boundaries for the energy sector. This definition will be done with the support of a literature review, where the concept of planetary boundaries will be introduced. The literature review will also provide the reader understanding of how water is currently measured and considered in decision-making. The current energy production mix and the water use of different energy technologies are also analysed in the literature review. The reader is provided with an understanding of how different energy sources vary in terms of water use and where water is exactly utilized.

With this framing, the research question could be as follows:

Is the European energy sector operating within the planetary boundaries when it comes to freshwater use?

2 Planetary boundaries and freshwater use

2.1 Planetary boundaries

Over the years it has become increasingly evident that human behaviour is impacting the capabilities of the Earth. After industrial activities were initiated back in the 18th century, the world started to face an increasing amounts of signals of phenomena such as climate change, air pollution, water degradation and biodiversity loss. The majority of Earth's major ecosystems are under some level of stress. Industrial production has taken up a lot of land area and resources, influencing different nature cycles such as nutrient circulation. Simultaneously the global population is growing rapidly mainly focusing on developing economies in the global South. Economies are urged to rethink their approach to growth, which is based on limited and scarce resources.

More focus has been put on developing an understanding of the frames where humans can continue their operations in order to maintain a liveable planet (Bogardi et al. 2013). The concept of **planetary boundaries** was introduced at the beginning of the 21st century in order to map the environmental limits for human societies to operate on the planet. It can also be understood as a limit to growth as the concept was initially defined. Later, the planetary boundaries have been utilized both in the corporate world as well as in international policy making. (Steffen et al. 2015.) Rockström et al. (2015) identified nine planetary boundaries but usually, only seven boundaries are utilized for scientific quantification. Going beyond the boundaries increases the threat of permanently damaging the underlying processes and worsening the condition of the Earth System. Planetary boundaries have been studied in various research institutions in order to create suitable concepts for decision-making (Bunsen et al. 2020).

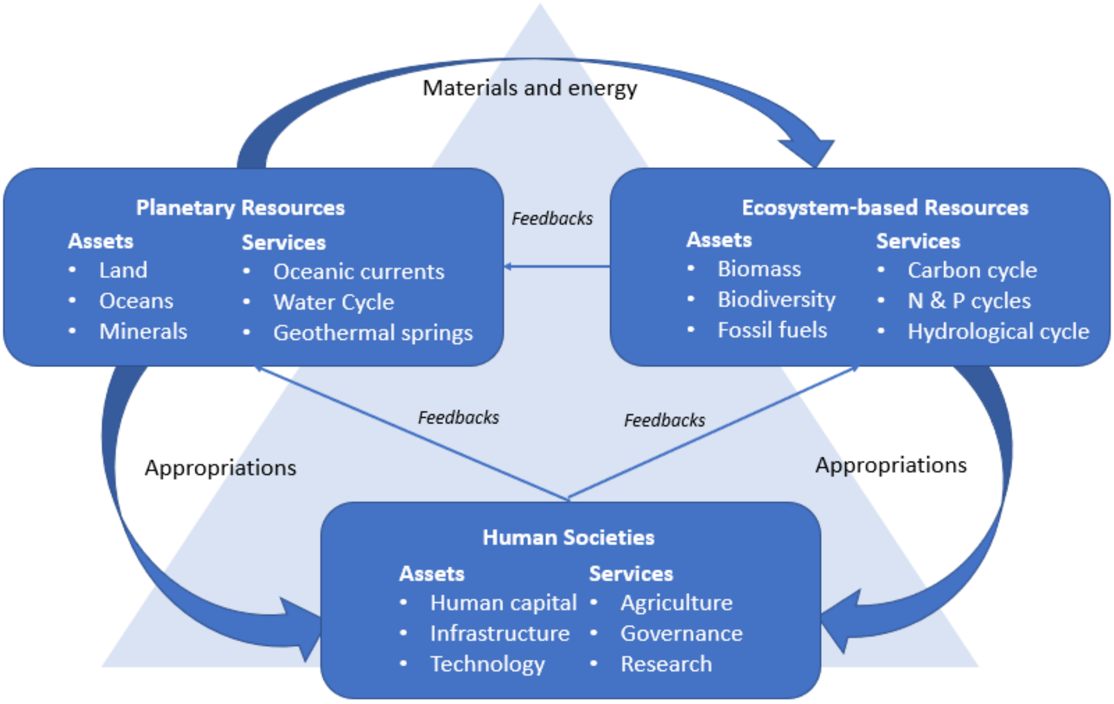

Figure 2 Balanced Triangle for planetary boundaries, following Bogardi et al. (2013)

Bogardi et al. (2013) illustrate the framework for planetary boundaries as represented in Figure 2. Three dimensions of Planetary Resources, Ecosystem-based Resources and Human Societies describe the limits of the Earth. All these dimensions have assets and services, of which assets are existing features and services are dynamic flows. As shown in Figure 2, Planetary Resources are linked to major planetary cycles like climate and oceans. Ecosystem-based Resources use the materials and energy from Planetary Resources to modify into new assets and services. One example is that while oceans and oceanic currents are Planetary Resources, they also create a basis for vital Ecosystem-Based Resources like biodiversity and the hydrological cycle. Humans can link to Planetary- and Ecosystem-Based Services in multiple ways. The main question is what human societies are looking for from the other resource dimensions and in what quantities. For example, freshwater availability could be seen as a Human Societies service, but it is dependent on the other resource dimensions. Essentially, the triangle aims to highlight the balance needs between the resource dimensions. It can also bring up the question of compensation between the resource dimensions if some boundary would be exceeded elsewhere.

Since the introduction of the concept of planetary boundaries, the approach has included nine planetary boundaries. All these nine processes are somehow being modified by human activities. (Steffen et al. 2015.) The nine boundaries and their measurements are:

- Climate change
- Ocean acidification
- Stratospheric ozone depletion
- Biochemical nitrogen cycle and phosphorus cycle
- Global freshwater use
- Land-use change
- Biological diversity loss rate
- Novel entities
- Air pollution and aerosol loading

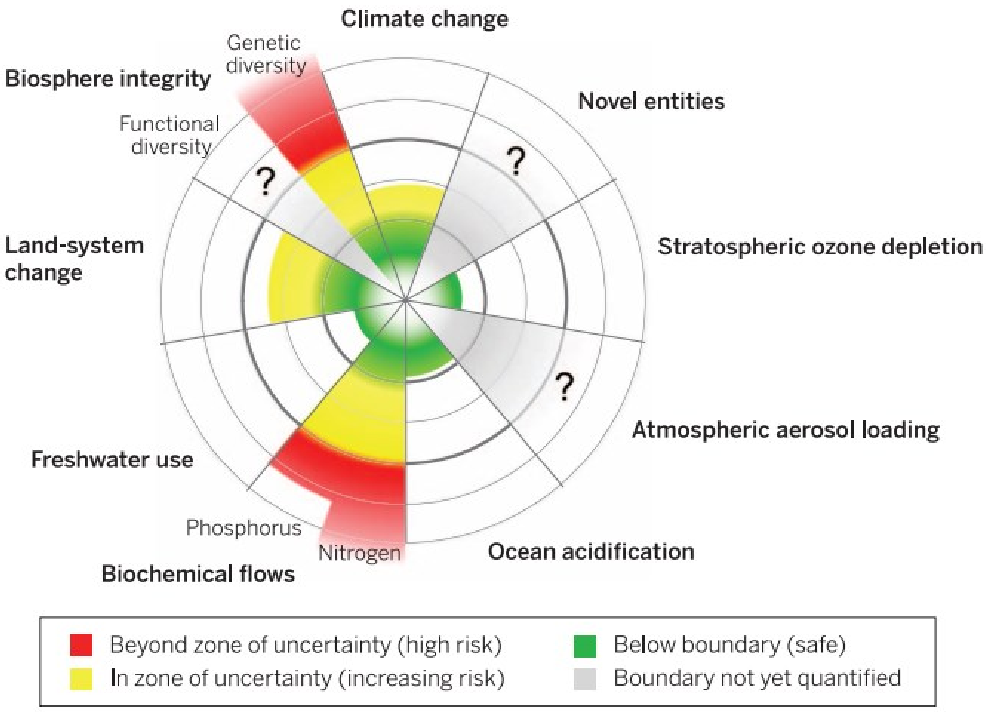

Figure 3 Planetary boundaries and their current status (Steffen et al. 2015)

Steffen et al. (2015) note that planetary boundaries can be viewed in a hierarchical order. Climate change and biosphere integrity are interlinked and system-level phenomena. Other planetary boundaries are somehow linked to these two main boundaries. For example, freshwater availability is strongly linked to weather conditions. Extreme droughts can lead to water scarcity, which should be taken into account in water use and planning. Notable changes in weather conditions can be seen as one of the key impacts of climate change. Hence, IEA (2020) has pointed out that water is a key indicator for climate change impacts. Remarkable changes in climate change and biosphere integrity could push the Earth system further out from sustainable boundary levels. If there happens to cross a boundary in any of the other planetary boundaries, it can have a significant impact on human well-being, especially on regional scales but does not lead to a new position on the Earth system level.

Rockström et al. (2015) chose the nine boundaries also based on how much data there was to define precise boundary levels. In order to analyse these boundaries, certain variables have been set to understand their development. All of the planetary boundaries have control variables that can be paired with response variables. Control variables should be quantifiable and influenceable by humans. Response variables should follow the Earth's natural conditions and be influenced by the control variable. Each planetary boundary is defined with control variable range values. (Gleeson et al. 2020.) Control and response variables can change over time due to changes in other planetary boundaries (Zipper et al. 2020). For example, climate change has two control variables; atmospheric concentration of CO2 and radiative forcing. The boundary level for atmospheric CO2 concentration is currently set to 350 ppm because data predicts that over that limit large polar ice sheets start to melt. For global freshwater use the boundary is set to no more than 4000 km^3 per year of consumptive water use. Going beyond that level, for example river exploitation, could cause a remarkable decrease in the condition of aquatic ecosystems. As seen in Figure 3, the biodiversity planetary boundary is currently most at risk of exceeding the sustainable operating space. Freshwater use is still identified to be within the planetary boundary, but Rockström et al. (2015) point out that sustainable levels could be a risk in the long term. Planetary boundaries should be seen as dynamic targets with connections to one another. As addressed already above, climate change can have impacts on freshwater availability and water use within the planetary boundary. Planetary boundaries can't be managed one at a time and this is important to acknowledge when implementing them into policymaking. Planetary boundaries should be seen as a holistic package of different biosphere elements. (Rockström et al. 2015.)

2.1.1 Water planetary boundary

Freshwater has its dedicated planetary boundary to understand the global limits for water use and anthropogenic water cycle changes (Zipper et al. 2020). Water planetary boundary is mainly based on ecological metrics and can therefore be viewed as an ecological indicator. However, since water has wide linkages to societies and economic activities, it can also be seen as a socio-economic indicator. (Bunsen et al. 2020.) Currently, the planetary boundary dedicated to freshwater use is based on allowed blue water consumption. The allowable freshwater use is defined to be 4000 km^3/year globally. Going beyond this amount would cause significant risks for the blue and green water reservoirs. (Gleeson et al. 2020.) Gerten et al. (2013) have suggested that the freshwater planetary boundary should be linked to the streamflow needed to maintain the natural requirements in all of Earth's rivers. Streamflow can be defined by analysing the stream stage and the stream discharge. With this method, they suggested that the functional planetary boundary would be 2,800 km^3 per year (Gleeson et al. 2020).

When talking about planetary boundaries the focus is usually global. Different kinds of emissions and ozone layer impacts are of interest to all regions. For water, the focus is more local since the local water systems have crucial impacts on local ecologies and people. Even though water cycle impacts are local, the drivers are global. Extreme weather conditions have a wider influence, but impact water cycles and -reservoirs locally. For water planetary boundary the measured variable used has typically been freshwater use. It takes a look at the amount of freshwater that can be taken out while environmental flow remains the same. (Gleeson et al. 2020). Many researchers have then suggested detailing the water planetary boundary into sub-boundaries, depending on the exact water source. Gleeson et al (2020) define sub-boundaries based on water stores and the most vital processes within water sources. Sub-boundaries are needed to specify the differences in water locations and their impacts on other Earth components.

Sub-boundaries for fresh water are:

- Surface water
- Frozen water
- Soil moisture
- Atmospheric water
- Ground water

There have been attempts to define the control and response variables for water planetary boundary, but a remarkable amount of work is still to be done. Freshwater use can provide some answers but is problematic due to a lack of proper water withdrawal data and how to calculate water use. (Gleeson et al. 2020.) There are no global water management and governance institutions that would have taken the lead in unifying the parameters used (Biermann et al. 2012). In addition, the water boundaries are global but impacts are local. This causes difficulty to set up unified variable ranges. Steffen et al. (2015) point out that freshwater use is one of the example boundaries where the differences between sub-global and global control variables might have different development paths. This poses a challenge in defining global variables when changes in the local context need to be taken into account carefully. Steffen et al. (2015) suggested creating a two-level set of control variables and boundaries to be able to map the changes on both micro- and macro levels.

There are a couple of methods on how freshwater planetary boundaries should be defined in practice. **The fair shares approach** represents a top-down method of defining the boundaries and variables. The fair shares approach begins with defining the global planetary boundary values and then allocating a safe operating space locally. The last step involves the analysis of each control variable based on current and safe space performance levels. While setting the global planetary boundaries might be supported by reference values, the local allocation requires a deeper understanding of the regional context. For commercial organisations, the allocation could be done based on their market share or revenue. For nations, the allocation could be done based on per capita. The problem with such allocations is that the pressure on planetary boundaries might not be directly in correlation to the respective fair share. For example, a nation might have a large population but only little impact on freshwater withdrawal. Choosing the proper fair share allocation method is always a matter of subjective evaluation. Previous research has included allocations into per capita boundary levels, composed for example by Nykvist et al. (2013).

In the fair shares approach the control variable defines the maximum amount of consumptive blue water use in cubic kilometres annually. The estimate for an acceptable planetary boundary for global freshwater use is 4000 cubic kilometres annually. Estimations also allow variation between 4000 to 6000 cubic kilometres, which can be called the zone of uncertainty. The estimated current value of the control variable is 2600 cubic kilometres annually. (Zipper et al. 2020; Steffen et al. 2015.)

A second method to evaluate freshwater boundaries is the **local safe operating space approach**. This is a bottom-up method supported by global planetary boundaries. The process begins from a local level and defines the vital control and response variables. These variables might also be different from general planetary boundaries. After defining the variables, they are enriched with value ranges and safe local operating space. Currently, the control variable for the local safe space approach can be derived as blue water withdrawal as % of mean monthly river flow. The planetary boundary is linked to acceptable withdrawal from monthly river flow. For low-flow months the acceptable share is 25%, for intermediate flow 30%, and for high-flow months 55%. The zone of uncertainty is 20% more for each boundary. There is no available information on the current state of the control variable, potentially because this variable needs to be defined on a local level, and therefore global boundary conclusions might not be accurate. (Zipper et al. 2020; Steffen et al. 2015.)

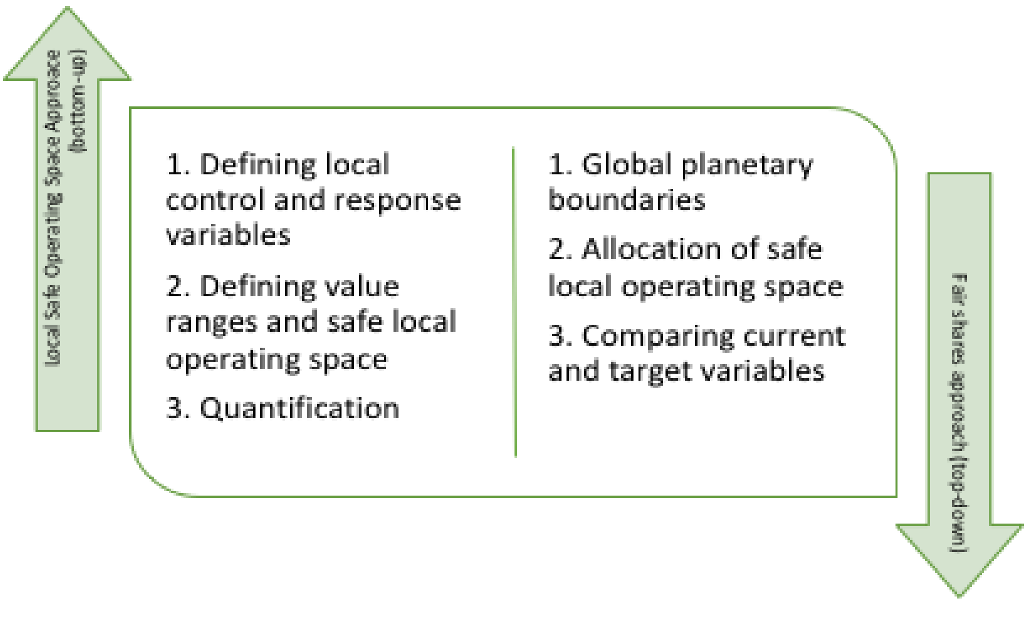

Figure 4 Freshwater planetary boundary definition methods (Zipper et al. 2020)

Even though the freshwater planetary boundary is acknowledged by organizations like the United Nations and in corporate sustainability initiatives, it is still limitedly used in water management. The link between concrete local policies and their outcomes is unclear, even though there are many signals that boundaries are being taken into account on some level. Without holistic coverage of the water management field, there is a risk that the freshwater planetary boundary is oversimplified. This creates further questions of whether the freshwater boundary is well equipped for real-life use cases or whether organizations should develop better methods of including water in decision-making. (Gleeson et al. 2020.) The academic community has been discussing the concept of freshwater planetary boundaries and their applicability. Gleeson et al. (2020) argued that without a thorough definition, the freshwater planetary boundary might be unable to address the complex nature of water cycles.

2.2 Global water system

Water forms a crucial role in the basis of life, affecting the well-being of societies and nature. In total 71% of Earth's surface is water (NGWA, 2022). All living species contain some proportion of water. Bogardi et al. (2013) define water as a planetary service, as all terrestrial biomes are dependent on freshwater availability. On Earth, water can be found in three different conditions based on temperature: solid, liquid, and gas. Only a small portion of total water is available for humans to use, as a majority of water is in oceans, soils, icecaps, and the atmosphere. Hence, majority of the human water use comes from rivers. According to Nace (1967), almost 98% of the water on Earth is in the oceans, whereas approximately 2% is in glaciers and other solid formats of water. Other water sources count only minority shares of the total water amount.

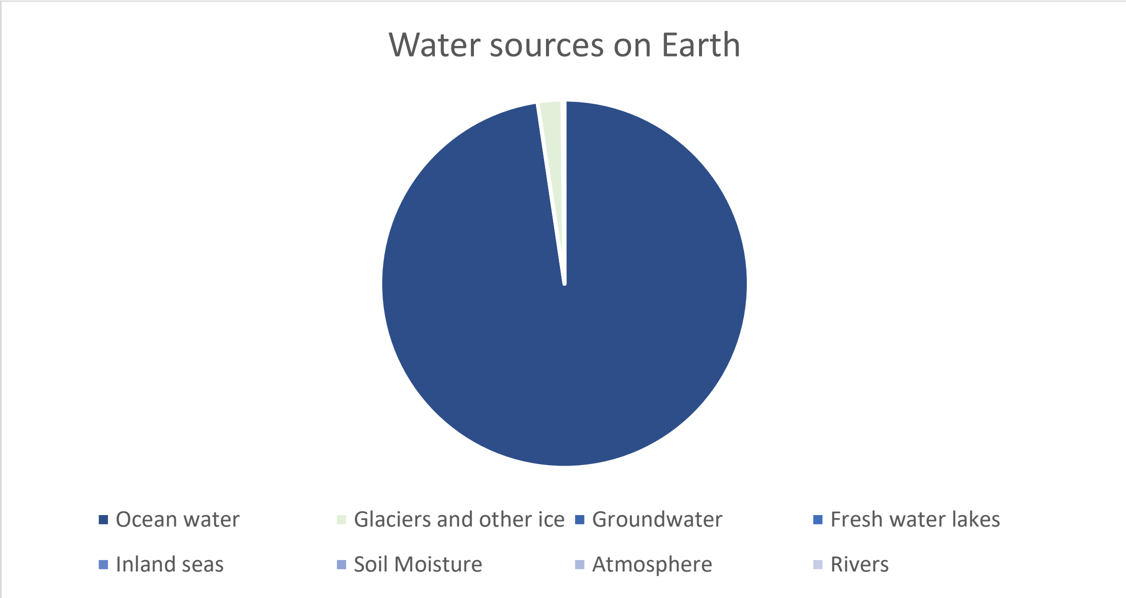

Figure 5 Water source distribution on Earth (Nace, 1967)

Surface water includes oceans, rivers, streams, and lakes. In other words, surface water is an easily reachable water source and therefore much used for human purposes. Even though oceans make up a large portion of total water reservoirs, the seawater salinity limits the use cases. Desalination technologies already exist but can be costly and require large quantities of electricity. Due to temperature changes caused by climate change, the water phase changes will occur on more untypical occasions (e.g. in areas where water has always been in a certain condition such as ice). Extreme weather conditions can decrease the reliability of water resources. Greenhouse gas emissions can accelerate the hydrological cycle as well as reduce snow and ice formation during the winter. Impacts on the sea can also be dramatic, with impacts on ocean circulation and seawater level (NGWA, 2022.)

Even though the major focus on future water availability is driven by climate change impacts, there are multiple other root causes for the increasing interest in water availability. The impact of human behaviour and activities on the local ecosystems should be viewed holistically. For example changes in land use, industrialization, and urbanization are changing the ways water is consumed. The growing population worldwide is increasing water consumption and demand. This is not only linked to drinking water needs, but population growth will also result in growing economic activity demanding water. With a growing population, people are moving from the countryside to the urban environment, impacting the way water is consumed and distributed. The growing population will also require food, resulting in increased irrigation water needs for agriculture. All these changes can cause alterations in land use, that impact the water cycles locally. Water withdrawals can rather easily rise above the accepted river flow and water might be reused for many rounds. With increasing pressure from extreme weather conditions and human pressure, water resources management becomes more unpredictable. (Baggio et al, 2021.)

Water cycle means redistribution of water from oceans to lands through atmospheric circulation, and bringing the water back to the oceans via surface and sub-surface water flows. Of all precipitation globally, 113 000 km^3 per year, approximately 73,000 km^3 per year returns to the atmosphere and is not part of the further water cycle, e.g. groundwater flow (Trenberth et al. 2011). Consumptive freshwater use refers to human behaviour where certain amounts of water are being used and not returned to runoff (Gleeson et al. 2020). Sometimes grey water is mentioned while discussing freshwater. However, the concept of grey water tends to divide opinions among scientists. Grey water is mainly meant to show the impact of water quality degradation. Currently, the consumptive blue water use is estimated to be between 1000 – 1800 km^3 per year. The majority of this withdrawn water is used for agriculture and irrigation and therefore a large share of it is returned to surface and groundwater. It is estimated that even though the freshwater withdrawal still seems to be at acceptable levels, it will increasingly happen in regions where the freshwater resources are more limited than the global average. (Bogardi et al. 2013.)

2.3 Measuring water

Water footprint is one of the most typical ways to measure water usage. It was first introduced in the early 2000s with an increased focus on global water scarcity. (Yang et al. 2013.) It measures the volume of freshwater consumed to produce goods or services during their lifecycle. Water footprint can refer to green or blue water footprint. Despite being a widely accepted measurement tool, water footprint has been mainly defined only in certain regions of the world. Water footprint and freshwater planetary boundaries are globally recognized and are measurable with different models, but there are many uncertainties related to what is included in the values. (Gleeson et al. 2020.) For example, key questions to address are what is the balance between blue-, green, and grey water, and what timeframe to include in the calculation. Sometimes water footprint calculations can be weighted with regional water scarcity and pollution factors to give more relevant information on the local level (Yang et al. 2013).

Bogardi et al. (2013) define water footprint as the degree of freshwater delivery to human use cases in liquid form. Both blue and green water footprints are usually described as consumptive water footprints, of which the main use case is agriculture. Mekonnen and Hoekstra (2011) define water footprint as the result of the human consumption of freshwater. Blue water footprint considers the consumption of surface and ground waters whereas green water footprint takes into account rainwater as well. The green water footprint is especially topical for agriculture and forest industry use cases. In the energy sector context, the blue water footprint can be considered more relevant, but the green water footprint should not be completely forgotten especially when it comes to biomass-based energy production (Mekonnen et al. 2015).

A second potential measure for water is **virtual water**, which is usually considered an alternative to water footprint. Both of these are widely studied. The concept of virtual water was initiated in the early 1990s, hence being a slightly older framework than water footprint. Virtual water refers to water used to produce commodities (Yang et al. 2013). Similarly to water footprint, virtual water can be divided into blue-, green- and grey water. The key difference between the two methods is that virtual water is mostly used in international trade, whereas water footprint is more relevant to production.

Only recently these two methods have been further elaborated with emerging methods like life cycle analysis. Previously the focus has been on studying water footprints and virtual water in the production chain and as per unit of product. There has been a strong link between measuring people’s daily consumption choices and therefore increasing the general level of knowledge on water issues. Lately, the focus of water accounting and -measuring has been shifting towards impacting relevant policymaking. Therefore the quantification of water usage is more important on the economic level and in different geographical and demographic areas. (Yang et al. 2013.) There have been attempts to quantify water use in certain regions and economic sectors. Usually, the economic growth potential and water intensity have been used as a framework to define the sustainability limits for water use. These methods, even though still partially incomplete, have managed to point out several regional and sector-specific water scarcity issues.

In addition to water footprint and virtual water, one measuring tool is to directly discuss water scarcity. The water scarcity index measures the total water use in comparison to scarce water use within a region. (Yang et al. 2013.) Water scarcity and water use impacts in general are very dependent on the region, as the type of water, the exact location of usage, and the amount of polluted water impact the overall water use. Hence regional uncertainties should be taken into account while calculating water measures, for example by adding water-intensive economic activities to the models.

Even though there has been remarkable development in water measurement and -accounting over the years, some limitations remain. The increasing popularity of the life cycle analysis (LCA) approach has had impacts on water-related measuring. The core idea of LCA is to analyze the environmental impacts of a product or service throughout its life stages. Water has been identified as an important aspect to consider in LCA analysis, especially when it comes to water-intensive products like biofuels or food. There has been debate over how water footprint should be considered in LCA calculations. Despite the disagreements, both water footprint and LCA aim for the same goal, which is to ensure sustainable water use during the product lifetime. Even though not fully integrated, water footprint-related analysis can be used as part of LCA analysis – as well as LCA results can support water footprint evaluations. LCA analysis can also provide insights about water pollution, which is useful in water-related calculations (Gerbens-Leenes et al. 2021).

Yang et al. (2013) point out that measurement tools like water footprint and virtual water focus mainly on blue water. Green water and soil moisture are typically excluded. The majority of sectors use blue water, and adding green water into the calculations would give an unrealistic high proportion for agricultural water use. Green water is still a valuable resource in biomass production and could also be considered in the analysis. However, the distinction between green and blue water is crucial in water management and policies, to establish impactful sector-specific guidance. Analyzing grey water as part of the water footprint is particularly interesting through the LCA approach, as water pollution can be viewed from an emphasized perspective.

2.4 Water security and regulation

The impacts of water are not only ecological but also socio-economic. In the last decades, starting from 1998, over 1.5 billion people have somehow suffered from droughts. The economic cost of droughts is estimated to be over $124 billion. In the future, lives are increasingly threatened by floods, droughts, and other water security-related weather hazards. (Biswas &Tortajada, 2022.) Limitations on water use can also impact businesses and therefore make previously self-evident components a new critical factor. This is a case for example in agriculture, which is largely dependent on irrigation water. Water is also a provider of crucial ecosystem services that result in indirect benefits for humans as recreational values (Curmi et al. 2014).

Water security can be defined as safe and abundant access to good quality water, without limitations (Biswal and Tortajada, 2022). Water scarcity varies a lot between regions based on the geographical freshwater resources. Baggio et al. (2021) estimate that freshwater availability per capita will start to decrease in the future. The change will be most dramatic in developing countries but also developed and water-rich countries will face water scarcity more often. Bates et al. (2008) note that the International Panel on Climate Change, IPCC, urged about water stress-related risks already many years ago. Sustainable water management was introduced as a topic to United Nations' Agenda 2030, including a specific target for freshwater. The clause aims to increase sector-wide efficient use of water and ensure sustainability in water withdrawal activities. Freshwater is also linked to other goals on the agenda 2030 (Bunsen et al. 2020). Freshwater access and protection of water ecosystems is one of the UN Sustainable Development Goals (UNEP, 2022). The European Water Framework Directive is a tool to consider water planetary boundaries in ongoing water management. The purpose of the Directive is to maintain good ecological and chemical balance. Therefore it seems inevitable that international organizations have tried to consider water scarcity for some time already.

Biswas & Tortajada (2022) note that the global community has mismanaged water security for many decades. Providing a safe and sustainable quantity of water for the entire population was not used to be a notable problem before, whereas now clear difficulties are occurring to complete this. Poor governance and insufficient water-related institutions are claimed to be one of the root causes of problems. Countries have also been reacting to water stress-related policy-making. However, countries might not have prioritized water-related issues, especially in countries where water scarcity hasn’t typically been a problem. Biswas & Tortajada (2022) point out that holistic water security can be achieved only when policy-makers truly engage in solving the issues and predicting the future. This should include activities like building sufficient water-related infrastructure. Modeling uncertainties related to climate change also occur in water management.

In recent decades, the world has seen an increasing amount of conflicts related to water (World Economic Forum, 2019). Droughts and water limitations have already been identified as potential conflict root causes. Unfried et al. (2022) point out that there is a correlation in grid-cell data for Africa and Central America during 2002-2017 showing an increasing connection between water mass declines and local conflicts. For example in India, there have been many conflicts over rivers crossing multiple countries during the past decades. Construction of the Grand Ethiopian Renaissance Dam resulted in conflicts between Ethiopia, Sudan, and Egypt in 2020. While there might be new conflicts arising due to weather events and water resource management questions, changes in water access might also result in old conflicts to re-escalate. Water assets can also be used as conflict weapons as examples shown from the Syrian civil war and the latest Ukraine ware (Unfried et al. 2022).

While it is almost evident that water security-related issues will remain or increase in the future, the question around decision-making is highlighted. When it comes to climate change-related implications, many of the most visible damage and economic losses occur in low-income countries. This leads to a situation where the losses are substantially greater in low-income countries, whereas the majority of the pollution takes place elsewhere. This issue has lately been debated at COP27 climate meeting where low-income countries were urging high-income countries to compensate for climate change-related losses (Biswas & Tortajada, 2021). A similar debate might be ahead with water scarcity-related topics. The set-up creates a question about who should define and take action about global water policies.

3 Energy transition and water use

The global community is increasingly awakened by the concern over CO2 emissions and climate change. Since 1960 the annual CO2 emissions were around 9.39 billion metric tons of CO2 whereas they were now already 36.4 billion metric tons of CO2 in 2021 (Statista, 2022). The growth in emissions has come during years when governments and international organizations have pledged to cut their emissions. Indeed, many countries and organizations have introduced targets and strategies to cut CO2 with different measures. The biggest effect comes from switching fossil-fuel energy sources (e.g. coal, gas) to renewable sources such as solar- and wind power. Electrification of final energy use is emerging as a key trend in the transition, applying to all sectors from industries to transportation (Tovar-Facio et al. 2021).

The global electricity demand is expected to grow up to four times by 2050, driven by high electrification and a global increase in living conditions (McKinsey, 2022). DNV states in its Energy Transition Outlook (2022) that electrification will be the key engine of the entire global energy transition. Today the largest portion of electricity generated to the grid comes from coal- and gas-fired power plants but this share will decrease significantly by 2050. Decarbonization initiatives and financial drivers will result in a more rapid phase-out of coal plants, whereas gas will remain longer as a portion of the energy mix, despite the supply shock caused by the Ukraine war. Fossil-based power plants will remain as backup power when the rapidly increasing share of renewables will generate more flexibility needs to the grid.

This chapter will walk through the current and future outlook of European energy production and the expected impacts on water withdrawal. Sub-chapter 3.2. will introduce estimates for water withdrawal levels, collected by various institutes. The sub-chapter 3.3. will specify the water usage of different energy production methods, giving the reader tools to compare energy production methods and understand the different phases of production processes, where the water footprint is the largest.

3.1 Energy transition in Europe

The European Union has done remarkable pledges for net zero in the past years. The concrete actions have included the creation of an internal electricity and gas market, energy efficiency promotion, and renewable energy deployment (Vanham et al. 2019). The European Green Deal was introduced in 2019, setting the actions to prepare a journey to climate neutrality in 2050. EU's greenhouse gas emissions decreased by 17% between 2005 and 2018 (IEA, 2020). One of the key drivers for emission reduction has been shifts in the energy production mix. Wind- and solar power are becoming major production sources of electricity. IEA (2022) announced that 2021 marked a new record for renewables deployment globally. The main growth comes from new solar PV and wind power additions, but other forms of renewable energy such as bioenergy, concentrated solar power (CSP), and geothermal also increased between 2020 and 2021. After China, the European Union is the second largest market for renewables when it comes to new capacity additions. Lately, the main capacity increases have come from solar PV expansion in big member states like Spain, France, Poland, and Germany. The EU has supported investments in renewable energy by creating new policies and incentives (e.g. long-term power purchase contracts). For example, solar PV installations have been supported by various incentives. Renewable energy capacity in Europe is expected to continue increasing, especially after energy security has become more topical. The ongoing energy transition from fossil fuels to renewables and low-carbon energy production will have impacts on the required water usage. Simultaneously, new emerging net zero solutions, such as hydrogen and carbon capture emerge to decarbonize industries and transportation. Location, availability of water, and competing use cases will be key questions for companies to consider, simultaneously as climate change is pressing more regions on the threat of water scarcity.

Figure 6 illustrates the recent split for energy production in primary energy. Around a third of primary energy comes from nuclear power and 40% from renewable sources. The remaining production comes from various fossil-based sources. Hydropower and biobased energy production are included in renewable production, where biomass still accounts for a large share of production (Eurostat, 2022). The Ukraine war and energy crisis have showed that Europe is not fully energy independent region. Dependence on fossil fuels is not expected to disappear in the near future. The majority of oil and gas to Europe is imported from other regions, even though Norway and the UK have their own production. With coal, there is more own extraction taking place in Europe, as the continent can cover almost 80% of its coal needs. The EU is expected to heavily drive away from fossil-fuel dependency, which might lead to sourcing from other countries such as American LNG and in the longer term focusing on establishing a stronger renewable footprint (DNV, 2022).

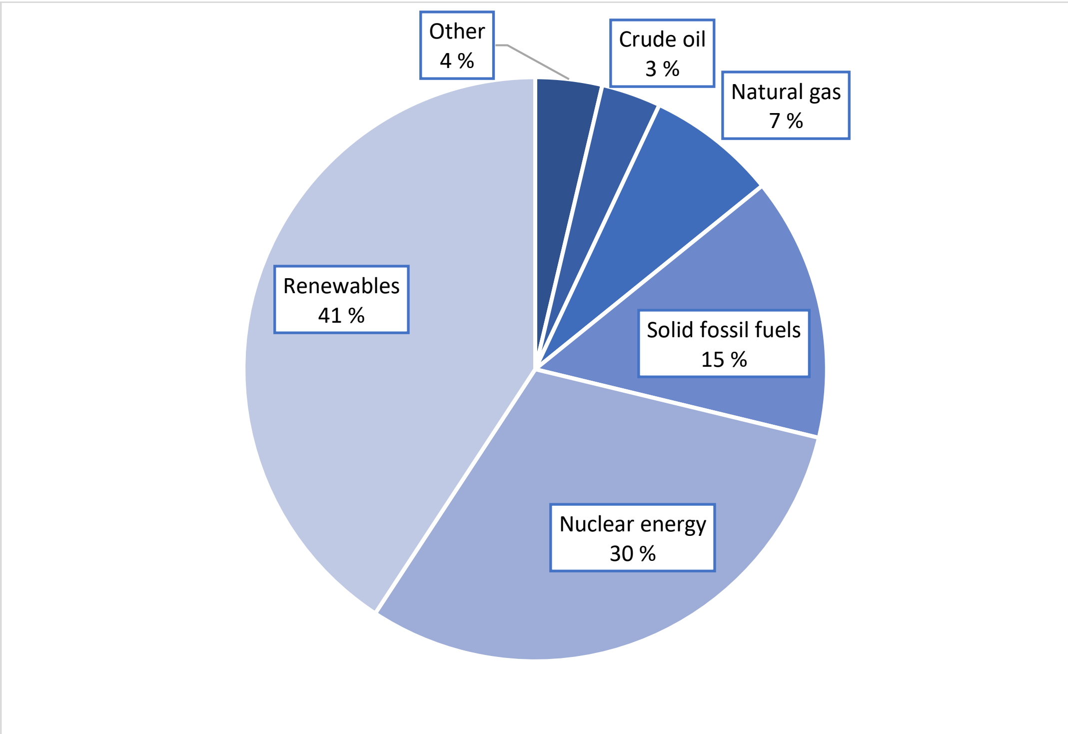

Figure 6   Production of primary energy, EU, 2020 (Eurostat, 2022)

Even though the EU has ambitious targets to see its member states phasing out coal, fossil fuel usage has continued in many countries. Vanham et al. warned in 2019 that the EU is still remarkably dependent on various fossil fuels, nuclear and energy imports. Fossil fuel dependency, however, can be viewed as a global phenomenon, McKinsey (2022) estimates that oil demand will peak in the next five years and gas remains the most competitive fossil alternative. 43% of global energy demand is estimated to be covered with fossil fuels in 2050. Before 2022 the energy markets saw notably low fossil-fuel prices, which led to further reliance on such sources instead of active phase-out or fuel replacement activities.

There is a massive shift from fossil-based energy sources to renewables but some core elements of the energy mix will remain relatively stable. Hydropower will continue to provide around 13% of the global electricity supply, experiencing only a modest decrease until 2050. Compared to other renewables, the growth in hydropower is limited as the majority of the suitable river locations are taken. The role of hydropower will, however, change from purely renewable energy generation into complementing and balancing wind and solar and providing flexibility to the grid. The future hydropower sector will include both traditional and new pumped hydro projects. Even though often debated from an emissions point of view, bioenergy is still a crucial part of the energy system, providing renewable alternatives, especially for hard-to-abate sectors. Bioenergy can use multiple different biomasses as feedstock, including organic waste-based sources. Especially biomethane is gaining a lot of attention as a potential complementary fuel to natural gas. DNV estimates that the use of bioenergy will continue for at least until 2030.

3.2 Water use in the European energy sector

Currently, European power generation is heavily dependent on water usage, such as in hydropower generation and thermal power plants. Understanding the current and future expected water usage for the European energy sector can provide policymakers with tools to design environmental policies considering the food-energy-water nexus (JRC, 2018). The European electricity sector accounts for approximately 55% of the total water withdrawal (Lohrmann et al. 2021) Researchers have already urged the European power sector to consider the potential water scarcity risks for energy generation. An increase in water demand within the energy sector would most likely put increasing risks, particularly to regions that already suffer from water scarcity. Water-energy studies have been addressed in many regions in the world but so far little focus has been put on Europe, even though the continent is a leading region for the energy transition. It is clear that the role of fossil fuel is decreasing in Europe, as the share in primary energy consumption decreased from 92% to 70% during the past thirty years (DNV, 2022). The majority of primary energy consumption will be directed to renewables, as wind and solar take an increasingly larger share in the mix.

The majority of water is used to generate electricity, especially in thermal power plants that still today account for 70% of installed power plant capacity (Terranon-Pfaff, 2020). In addition, the extraction of fuels and their water footprint should be taken into account

(JRC, 2018). The water use in the energy sector is illustrated as a flow chart in Figure 7. In the picture, light blue arrows stand for water flow, and dark blue ones for the fuel chain. This picture shows that water is involved as an input in many energy sector supply chain stages. According to DOE (2005), cooling makes up 80-95% of the water used in power plants. The power plant design, used fuels, and thermal efficiency impact the exact amount of water needed (JRC, 2018). Mekonnen et al. (2015) highlight that blue water resources are facing major pressure from electricity and heat generation and cooling needs. On the other hand, Terranon-Pfaff (2020) argue that even though the electricity demand will grow in the future, the growth in water demand for electricity production might not be as certain.

There are significant differences in the water use of different energy generation technologies as well as the cooling processes applied. The local, national and global energy mix choices paired with general economic and political development will determine what kind of energy sources will be in use during the next decades to come, as well as how water-intensive the energy mix will formulate to be. Currently, many power plants in operation that will retire or face asset lifetime extensions in the upcoming decades. The majority of these plants are fossil-fuel-based plants but include also some nuclear power plants. All of these have high water intensity and therefore their future will impact the water usage of the European energy sector (Terranon-Pfaff et al. 2020).

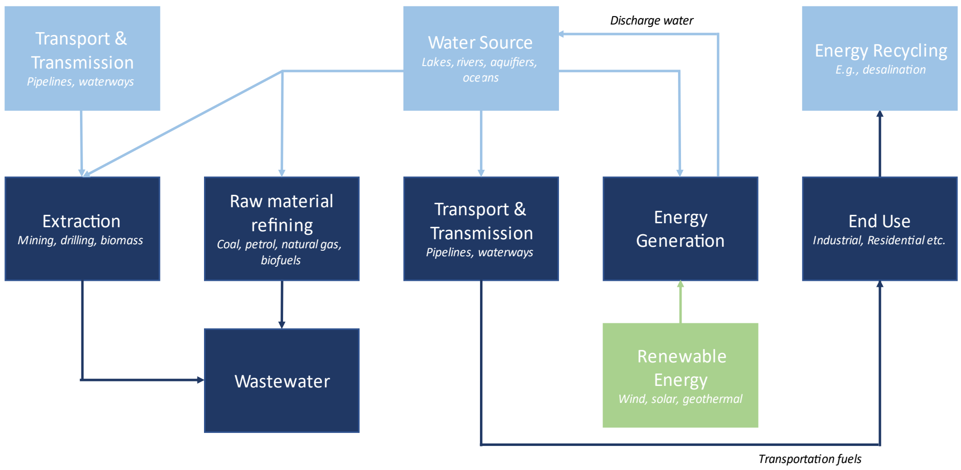

Figure 7 Different estimates for energy production water withdrawal in the EU region (JRC, 2018)

The European Joint Research Centre has completed a comprehensive estimation of the European water footprint in 2018. The report was part of The Water Energy Food and Ecosystem Nexus project, where the aim has been to design European water-related policies by providing a better understanding of dependencies. The water data was built from multiple sources and climate models, to get a view of current and future water withdrawal levels. In addition to projected water use, the report also provides insights on the regional level. When talking about water withdrawal, the meaning covers all the water that is taken from the ground or any natural water source for use in the energy sector. This can also be understood as gross water abstraction. From the gross water abstraction, one can also specify net water abstraction, or in other words, water consumption. This refers to the part of withdrawn water that is not returned to the natural source (JRC, 2018). In order to get a wider analysis, the focus of this work will be on water withdrawal levels.

Based on the JRC report (2018), the total water withdrawal of the European energy sector was 73,6000 million m^3 per year in 2015. This is estimated to decrease to 65,000 million m^3 per year in 2030, and further to 45,900 million m^3 in 2050. The decrease is mainly expected to happen due to the decarbonization of energy production, mainly through moving to renewable energy sources (JRC, 2018). To get some comparison, the World Energy Council (2010) reported 60.6 billion m^3 of water withdrawal for primary energy production in 2015, 57.3 billion m^3 in 2035 and 53.1 billion m^3 in 2050. These are presented in Table 1. Different estimates include various degrees of the whole supply chain, explaining the wide variety between estimates. Some calculations might include only cooling water for power plants whereas some figures include water needed for hydropower generation. It should also be noted that the data from World Energy Council can be somewhat outdated due to its release in 2010.

Source	Water withdrawal 2015	Water withdrawal, 2030	Water withdrawal, 2050
Joint European Research Centre	74 km^3	65 km^3	46 km^3
World Energy Council	61 km^3	57 km^3	53 km^3

Table 1 Different estimates for energy production water withdrawal in the EU region (JRC, 2018; World Energy Council, 2010)

Figure 8 below provides an overview of the water withdrawal split between energy production methods. From the graph, it becomes clear that the share of solid fuel energy production and nuclear power generation require the largest water withdrawals throughout the decades, even though the absolute amount is decreasing. The role of solid fuel energy production is decreasing due to the phase-out of fossil-fuel-based power plants. Nuclear power plants amounted to over half (58%) of the energy sector water withdrawals. The nuclear fleet operating in the EU region is the largest in the world. There are many countries whose approach to nuclear is increasingly positive and have announced further investigating new nuclear plants. Simultaneously, the development of small modular reactors is materializing and some nations, like the UK, have already included SMRs on their official future nuclear roadmaps. Many nuclear plants in Europe are facing their end-of-life and hence critical decisions have to be taken in many countries; whether to make lifetime extensions or rely on other energy sources. This share will most likely increase in the future due to a stronger push toward nuclear energy. Based on this dataset, the role of gas-fired power plants is expected to increase from 10% in 2015 to 30% in 2050. The role of oil-fired power plants is already marginally small and is expected to decrease close to zero-percent share by 2050.

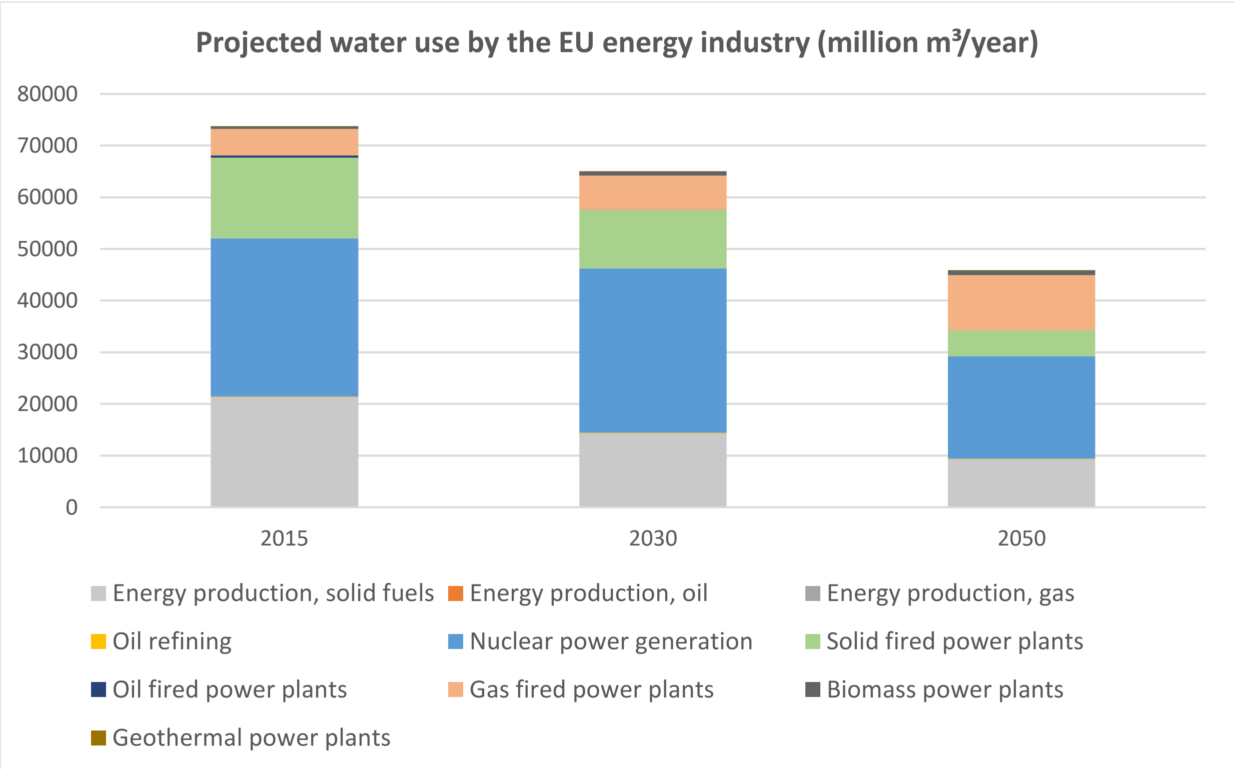

Figure 8 Projected water use by the EU energy industry for the next decades (JRC, 2018)

The next chapter will look more in detail at the water consumption of different energy generation methods. The study will use the European Joint Research Centre Data (2018) as a basis to compare different energy sources.

3.3 Water consumption of different energy production methods

Vanham et al. (2019) present a comparison of the water footprints of different energy sources. As visible in Figure 9 below, the reservoir hydropower and bioenergy have the highest water footprints. In bioenergy, the high water footprint results mainly from crop cultivation. The second highest water footprints come from nuclear- and coal-fired generation, which can be explained by the cooling needs of the plants. Kelly & Tatari (2019) point out that conventional power plants include cooling, steam production, and air pollutant removal, which all have high water withdrawal. For wind and solar power, the water footprint is small, which illustrates the fact that renewables require less water than other energy production methods.

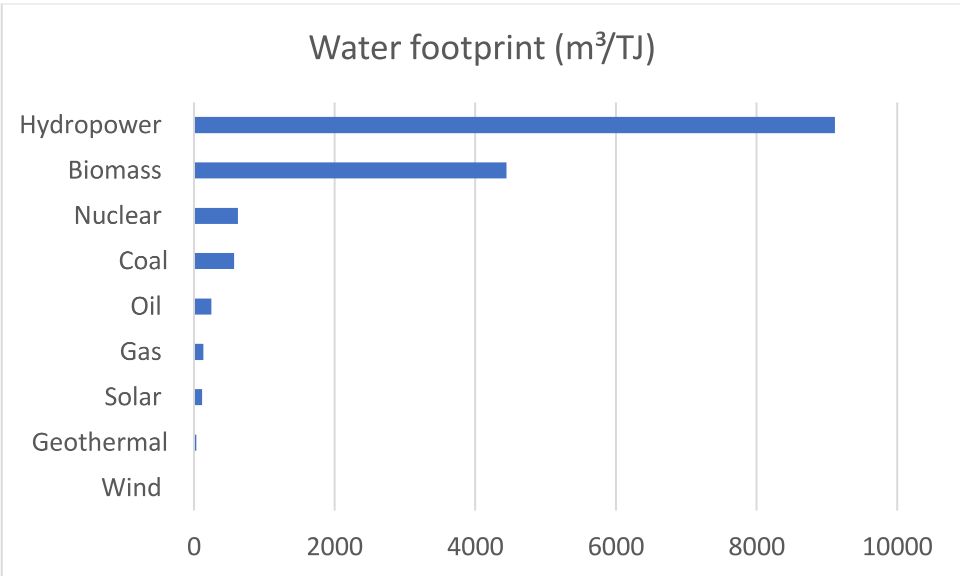

Figure 9 Water footprints of different energy production methods (Vanham et al. 2019)

To discuss the changes in water use within the energy sector, it is important to understand how the different energy production methods differ in their water use and what exact parts of the production process are the most water-intensive. The following sub-chapters will elaborate on the origins of each energy production method of water withdrawal.

3.3.1 Renewables and biomass

As presented previously in the chapter, renewable energy sources require significantly less water than any other energy source. During operation and maintenance, the water needs are mainly related to small tasks like cleaning. This is especially the case for solar PVs that use water for cleaning purposes (Kelly & Tatari, 2019). Even though the water amounts needed are not significant, it should be noted that solar PV production is often placed in regions where water might already be scarce. However, the solar industry is already working to find less water-consuming methods to clean solar panels. Concentrated solar power (CSP) consumes relatively more water. CSP plants use mirrors to convert solar power into energy to heat water and then convert it to steam. This steam is then used to run turbines and to produce electricity. After the steam has been used, it needs to be cooled down to use the water again in a closed cycle. The cooling process is the source of high water withdrawal amounts of CSP (European Commission, 2019). Some CSP technologies can withdraw almost 3,500 liters of water per Megawatt hour, which is over 1000 MWh more than coal-fired power plants (World Bank, 2013). In addition to cooling purposes, CSP plants use water to wash the mirrors. For the wind industry, the water use requirements are even less than for solar panels.

Biomass has been used as an energy source for a long time with the key variation being in the feedstock over the years. Biomass is of organic origin and can include products like agricultural crops, forestry products, and multiple forms of organic wastes and by-products. In addition to energy production, biomass can be applied as food and materials. Typically biomass can be converted into biofuels, making it easier to transform into different forms. (Gerbens-Leenes et al. 2008.) There are many different technology routes to produce energy from biobased feedstock, for example, anaerobic digestion and gasification. Suffice to say, the water consumption of biobased power generation depends heavily on the chosen technology. In 2015 the water withdrawal for biomass and waste-to-energy plants in Europe was 475 million m^3. Water use is expected to increase rather significantly to almost 800 million m^3 in 2030. The decarbonization targets are a key driver behind the increase in biomass and waste use as an energy source. Biobased power plants are expected to support the energy mix while fossil-fuel-based power plants will be phased out. The biggest biomass-based power users are in the Nordics. (JRC, 2018.)

3.3.2 Hydropower

Hydropower is a remarkable electricity source globally, offering wide opportunities for energy flexibility. It also forms a core basis for many countries' decarbonization strategies (Statkraft, 2022). DNV (2022) estimates that hydropower will cover approximately 13% of the total global electricity supply in 2050, staying relatively stable throughout the decades. The role will change from pure electricity production into complementing weather-dependent renewables production and providing daily- and seasonal flexibility. Pumped hydro storage projects will increase, but traditional hydropower is still expected to cover the main share. The biggest additions in hydropower will take place in Greater China, whereas in Europe the situation will stay relatively stable.

Changes in the hydrological cycle will have key impacts on hydropower production. Climate change has already caused the melting of mountain glaciers as well as increased rainfalls in regions. On the other end, extremely dry periods have become more common (DNV, 2022.). These changes will make hydropower production more unpredictable and unstable, compared to its previous role as a stable flexibility provider. In many cases, hydropower plants are also used for water management, flood control and irrigation. Hence, especially large damns have a significant regional role in addition to sole electricity production.

When it comes to water footprint definitions, the role of hydropower seems to have always been slightly unclear. Hydroelectric generation can be viewed as an in-stream water user or an actual water consumer. Mekonnen and Hoekstra (2011) note that even though there are differences in the single hydropower plant water footprints, it is without question that hydropower is a major water consumer. In hydropower production, the water is first collected to dams and reservoirs and is then run into hydro turbines in order to produce electricity. Water is used only in activating the turbines and afterward returned in the format of free flow in the river.

3.3.3 Fossil fuels

Fossil fuels like coal, oil shale, and natural gas are used in solid-fuel-fired power plants. Oil is typically used in the forms of crude oil or petroleum. In order to get access to crude oil, drilling, and pumping processes are taken first. Coal, for instance, is a rock that can be found in various geological locations on Earth, typically extracted through open-pit mining. (Gerbens-Leenes et al. 2008.) Water has a role in plant cooling as well as to fill in losses in other parts of the process (Retamal et al. 2008). While the water use in this energy production is expected to decrease in the future, the security of supply concerns could postpone the phase-out for some years. Poland, Germany, and Estonia have the biggest water withdrawals when it comes to solid fossil fuels. Coal is especially dependent on water. Lorenzo et al. estimated in 2020 that 43% of the current coal-fired power plants globally are located in regions where water scarcity is an issue at least one month per year.

Oil is used to produce power on a standalone plant and water is similarly used for cooling and filling in process losses. In Europe, oil has a smaller share in power production and hence the water withdrawal amount is relatively smaller than for other fossil fuels. In 2015 the water withdrawal for oil power plants was 388 million m³ and is expected to decrease to 42 million m³ by 2030 and 4 million m³ in 2050. Countries' decarbonization targets are taking a strict approaches to oil-based power production which also explains the drastic drop in water amounts. (JRC, 2018.)

Solid-fuel-fired power plants are expected to withdraw 4.9 billion m³ in 2050 from 15.5 billion in 2015 (JRC,2018). The amount of solid-fuel-fired power plants is expected to decrease from 177 GW in 2015 to 52 GW in 2050. This trend could be challenged by two factors. First, the rapid scaling and commercialization of carbon capture technologies could allow extending the solid-fuel-fired powerplants' use time. (JRC,2018.) Another potential disruption for the trend is the rapid cut-off from Russian natural gas, pushing many countries to consider coal-fired power plants as alternative sources of energy. The coverage of solid-fuel-fired power plants is wide, as there are 110 regions with such power plants in the EU. Out of these, 82 plants use freshwater in their operations but only four regions exceed the withdrawal level of one billion cubic meters. (JRC, 2018.)

Natural gas is a common fuel in power plants. The technology used is either gas- or steam turbines. In gas extraction processes, water is mainly used in the drilling phases or the fracking phases. Off-shore wells utilize seawater for their operations and onshore drilling requires freshwater supplies. Gas turbines don’t require any water usage and steam turbines use water mainly for cooling purposes. The usage of gas turbines is expected to decline in the EU due to the high deployment of renewables. On the other hand, gas power plants have been seen to have an important role in supporting coal- and oil phase-outs and providing baseload power to the system, especially in countries where nuclear power plants are few.

Peat can be also considered as a solid fuel. It is organic material on the top layer of soil. In the energy sector peat is used in electricity and heat generation. It is extracted from the ground as sods or fine granules. It has a water content of over 90%, which is decreased in the extraction process. The extraction and drying process does not require large amounts of water withdrawal or consumption and therefore is one of the least water-intensive solid-fuel sources.

3.3.4 Nuclear technologies

Nuclear energy has long been discussed as an emission-free energy source. Historical environmental footprint is significant as nuclear power has managed to avoid about 70 gigatonnes of CO2 over the past five decades (IAEA, 2022). With an increasing share of weather-dependent renewable power generation, nuclear power can support the electricity system by providing steady base load. The use of nuclear power is increasing especially in emerging countries, but also developed countries have expressed renewed interest in nuclear power driven by net-zero targets and security of supply. In 2020, there were 32 IAEA member states operating nuclear power of which 19 countries also had projects in planning to expand nuclear generation. Conventional nuclear power plants are large and are usually time-consuming and capital-heavy projects. The focus has increasingly shifted to small modular reactors (SMR), which are small and easily transportable generators of up to 300 megawatts. The novel SMR designs include multiple safety features. SMRs are commonly discussed under one title but include multiple alternatives, from water-cooled reactors to molten salt reactors. (IAEA, 2020.)

The expected water withdrawal of nuclear power production in the EU is expected to be around 32 billion m^3 by 2030 and 20 billion m^3 by 2050. In 2015 the withdrawal amounted to 31 billion m^3. (JRC, 2018.) These figures are highly dependent on phase-out and new investment decisions within nuclear energy. Many countries like France and the Netherlands have pledged for new nuclear power plants, whereas the UK has announced high targets for new-build SMRs. On the other hand, countries like Germany and Belgium have been phasing out their nuclear power fleet. In 2015 there were 49 EU regions with nuclear power production and 29 of these were using freshwater sources in production. This share is expected to decrease in the future, partially due to changes in the European nuclear power plant fleet. Around 29 of these regions use freshwater resources. Back in 2015 eight of these regions withdrew over one billion cubic meters per year. The largest freshwater withdrawal took place in the Rhône-Alpes region with 9.8 billion m^3. Nuclear power plant phase-outs are expected especially in Belgium and Germany, which would decrease the water withdrawals in those regions. (JRC, 2018.)

The cooling system has a remarkable impact on the overall water withdrawal and this is especially the case for nuclear power generation. Geographical location plays a key role in defining the cooling system needed, as it defines the water source and purity levels available. Geographical location impacts the seasonal characteristics of water, such as the intake temperature. There is regulation in place for certain plants and their water intake requirements. This can impact for example the water discharge levels. Cooling systems can be divided into open-loop- and closed-loop systems. Open-loop systems require large water withdrawal levels and usually take the water from seas or large lakes in order to access the needed quantities. The water is usually pumped from the water source to the turbine condenser, and after that returned. Closed-loop systems pump water from the condenser to the cooling source. In these cooling sources, like cooling towers, the water interacts with the air. After that, the water is returned to the condenser. The usage of cooling sources like cooling towers can reduce the amount of water needed on the plants. In Europe, closed-loop solutions are more common, with over 75% share including cooling towers. Thermal efficiency determines the water withdrawal and cooling needs of a power plant. Water requirements can also vary based on the fuel source used. Supercritical power plants have high energy efficiency and low freshwater intensity compared to other power plants. Coal-fired power plants use quite a lot of water in general, whereas gas-fired power plants have less cooling requirements and therefore less water use. Nuclear power plants have higher cooling needs due to steam-cycle conversion. (JRC, 2018.)

3.3.5 Emerging technologies

Hydrogen is one of the leading solutions to tackle the decarbonization challenge. Hydrogen can be produced from many feedstocks such as fossil fuels or biomass, but the most potential feedstock for hydrogen production is water. Water electrolysis offers a solution to generate green hydrogen, where electricity is intended to come from renewable power sources. This implies that in the future, the hydrogen economy will be dependent on water resources. (Simoes et al. 2021.) Hydrogen demand is expected to only increase in the future, being modest in the 2030s due to supply constraints. In 2050 the hydrogen demand could be 150 – 500 million metric tonnes per year, depending on different climate ambition scenarios (PwC, World Energy Council, 2022). With ambitious hydrogen targets for the decades to come, producers and the value chain need to figure out securing the needed water sources. Simoes et al (2021) suggest that seawater purification could be a lucrative solution due to large quantities and good availability. Groundwater and surface water are also potential sources but their availability varies largely between regions. Usage of these water sources might also be publicly unacceptable and water sources could be prioritized for other use cases.

Another emerging solution to tackle climate change is capturing carbon dioxide from industrial processes. Carbon capture technologies have emerged during the past couple of decades boosted by the increased awareness to reduce CO2 emissions. Even though there has been a lot of interest in carbon capture, the technology hasn’t yet scaled to its full maturity. Carbon capture technologies can be implemented in power plants and industrial sites. Hence, the technology could offer decarbonization opportunities, especially for those sectors where emission cuts would otherwise be difficult. Once the CO2 is captured it’s compressed and transported to storage in geological formations or for direct utilization for example in the construction industry. Current designs of carbon capture facilities are focusing on a capture rate of 85% - 90%. (IEA, 2020.)

Despite carbon capture often being discussed as one single term, it includes multiple different technology routes that are necessary to understand in order to debate their environmental footprints. Carbon capture and storage (CCS) means capturing CO_2 and storing it in geological locations. Carbon capture and utilization (CCU) takes the captured CO_2 into usage. Carbon capture can offer a route for negative emissions, especially if the captured carbon is biogenic (BECCS). All of these solutions are integrated into the respective production process with post-combustion capture technologies. CCS technologies are expected to gain space especially in gas-fired power generation and in those industries where emissions reductions would otherwise be difficult. (IEAGHG, 2020.) A completely alternative capture technology is Direct Air Capture (DAC) which captures CO_2 as a stand-alone unit. This is in comparison to point source capturing, where the majority of existing post-combustion carbon capture takes currently place. Even though there has been high interest in DAC, it is still less mature than other carbon capture technologies. (Concave, 2019.)

The estimates for CCUS deployment are remarkable. The Global CCS Institute (2022) estimates that the CO_2 capture capacity is around 244 million tonnes per year, due to existing and developed CCS projects. Approximately 230 Mt of CO_2 is used per year, mainly in fuels and oil recovery. In the future new CO_2 application areas are expected to emerge, led by construction materials and synthetic fuels. CCS will remain the more mature solution for carbon end-use. (IEA, 2022.) Despite CCUS gaining a lot of interest and promising demonstration, its impacts on water resources have not been studied in depth. If carbon capture is added to the system, it would add the need for a cooling process, which increases the water use of the system. Retrofitting a coal-fired power plant with post-combustion carbon capture technology would increase the plant's water intensity by 55% while simultaneously decreasing the plant's efficiency. If composed for bioenergy, the water requirements for biomass cultivation need to be taken into account in addition to the water footprint of the actual combustion phase. (Lorenzo et al. 2020.)

Of all carbon capture technologies BECCS is considered to consume the largest amount of water due to the water requirements of biomass cultivation. It is estimated that BECCS has a water footprint of around 575 m^3/tonne per CO_2 captured. The biomass feedstock in question results in a variation of BECCS water footprints. DAC is so far the most water-efficient way to remove CO_2 from the atmosphere. The technological readiness of DAC is behind other carbon capture technologies and hence still rather costly technology. DAC has a blue water footprint of 4.01 m^3/tonne of CO_2. Blue water consumption might compete with municipal and industrial water use as well as irrigation water for agriculture. (Lorenzo et al. 2020.)

4 Empirical part

4.1 Data collection and methods

The empirical analysis is carried out with quantitative methods. The literature review included the main theoretical framework of the study, presenting the concept of planetary boundaries. It also clarified the relation between the planetary boundaries and global water cycles, aiming to provide reader understanding of what kind of resource water is currently viewed and how it should be perceived in the future. The third chapter, being the second chapter for theoretical discussion, covered outlook for the energy transition and energy technologies' water usage. It provided the reader understanding of the systematic change within the energy sector as well as how different energy production technologies consume water in processes.

Based on the water withdrawal estimates identified from the literature and presented in chapter 3.3, they are benchmarked against the respective planetary boundary levels to see whether water use is sustainable now and in the future. In order to identify the sustainable water withdrawal levels, the planetary boundary needs to be defined. This is done in two different methods following the guidance from the literature. The analysis includes three parts. The first part includes defining the planetary boundaries in two different methods; fair shares approach and local safe operating space. After defining the boundaries, the current and expected future water use is benchmarked against these boundaries to see whether the European energy sector water use is within sustainable limits. The results will then be analysed in the very end of this chapter, as well as potential sensibilities and limitations for the analysis.

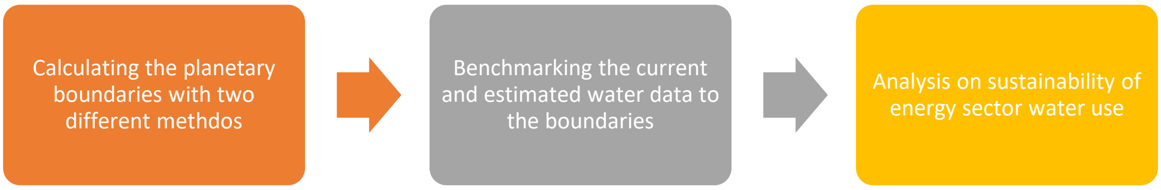

Figure 10 The process for empirical analysis

The analysis of energy sector water withdrawal was conducted from European Joint Research Centre (JRC) analysis from 2018, presented in Chapter 3.2. The study included projected freshwater use from the European energy sector from 2015 until 2050. The focus is especially on energy production and transformation, which according to European Joint Research Centre (2018) includes:

- Mining and quarrying of solid energy carriers (e.g. coal, lignite, peat, uranium and thorium)
- Extraction of oil and gas
- Refining of crude oil
- Production of electricity in all kinds of power plants except hydropower plants

Regarding the data, it is worth noticing that as hydropower is excluded from the figures, the water footprint varies. Data from JRC (2018) considers only freshwater use, and hence for example seawater has been excluded.

4.2 Calculating water planetary boundary for European energy sector

As described in the second chapter, Zipper et al. (2020) find two alternative ways to build planetary boundaries and analyse sustainable water consumption. The fair shares approach is a top-down approach that starts from the global level. The respective planetary boundaries are then calculated by different allocation methods to get regional- or sector-specific information. The other approach described by Zipper et al. (2020) is the local safe operating space approach, which the contrary can be described as a bottom-up method. Here the local level planetary boundaries are defined first after being combined into a region- or sector-wide context. The local safe operating space approach is more time-consuming, as regional characteristics like hydrological cycles impact the boundary levels. Therefore in this analysis, the local safe operating space approach is calculated as an example, and further study suggestions include a plan for how to conduct a European-wide local safe operating space approach for the energy sector. So far, there are some analyses done on the European energy sector water use based on local safe operating space approach, which has typically been linked to power plants or certain economic regions.

4.2.1 Fair shares approach

The global water planetary boundary is estimated to be 4000 km^3/year (Gleeson et al. 2020). There are no clear principles on how to allocate the global water planetary boundaries on lower levels, such as organizations, with a clear top-down approach. Some suggestions have included using economic figures, per capita figures or other attributes to ensure fair allocation of water burden (Zipper et al. 2020).

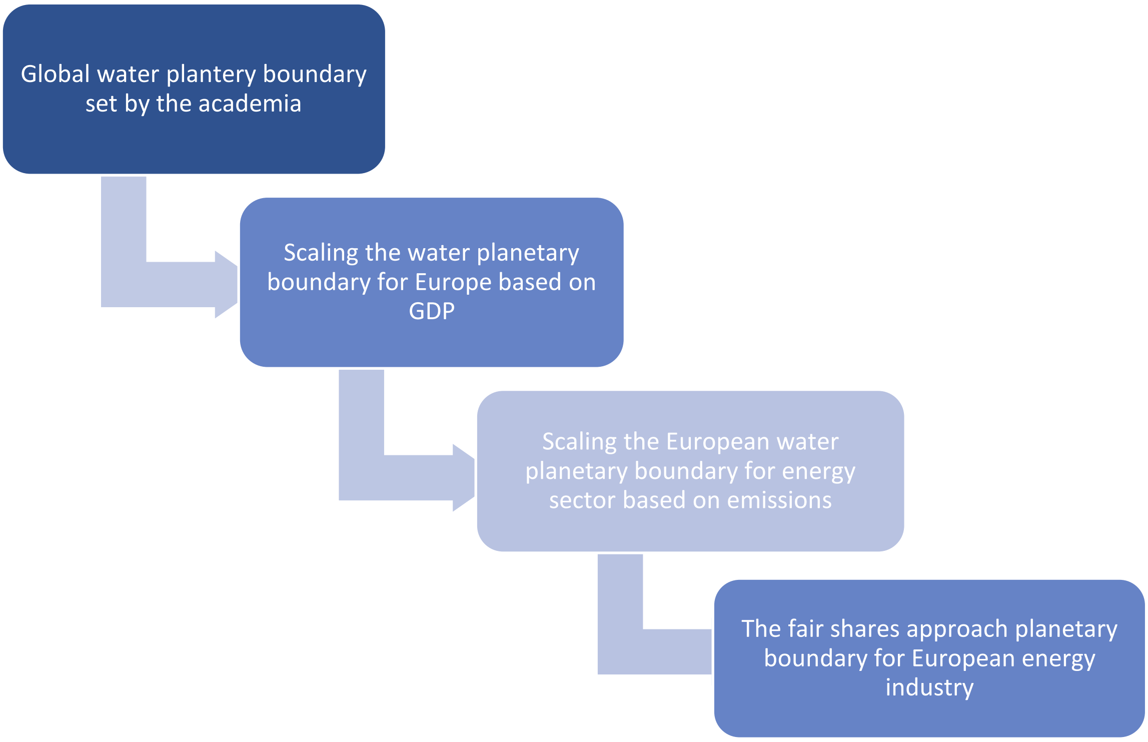

Figure 11 Description of the process for the fair shares approach

In this study, the water planetary boundary is calculated for the European energy sector in order to know whether current and future production are in line with planetary boundaries when it comes to water withdrawal. First, there is a need to calculate the European share of the global water planetary boundary, and then scale it down to the energy sector. As Zipper et al. (2020) mentioned, economic attributes are example allocation method for planetary boundaries. Based on World Bank (2022) the global GDP amounted to USD 96.53 trillion in 2021 whereas the European Union GDP, when converted to US dollars, was USD 15.77 trillion in 2021 (Statista, 2022). From here, it is possible to calculate the European share of global GDP:

European GDP share: USD 15.77 trillion / USD 96.53 trillion = 0,16337 = 16.3 %

From there, the calculation goes further to the overall European water planetary boundary:

*European water planetary boundary: 4000 km³/year * 16,3 % = 652 km³/year*

This figure sets healthy and sustainable water intake amounts for Europe in general, including all industries. Now, this needs to be scaled down to the energy industry. When it comes to energy production, emissions share is used to allocate the planetary boundary for energy production.

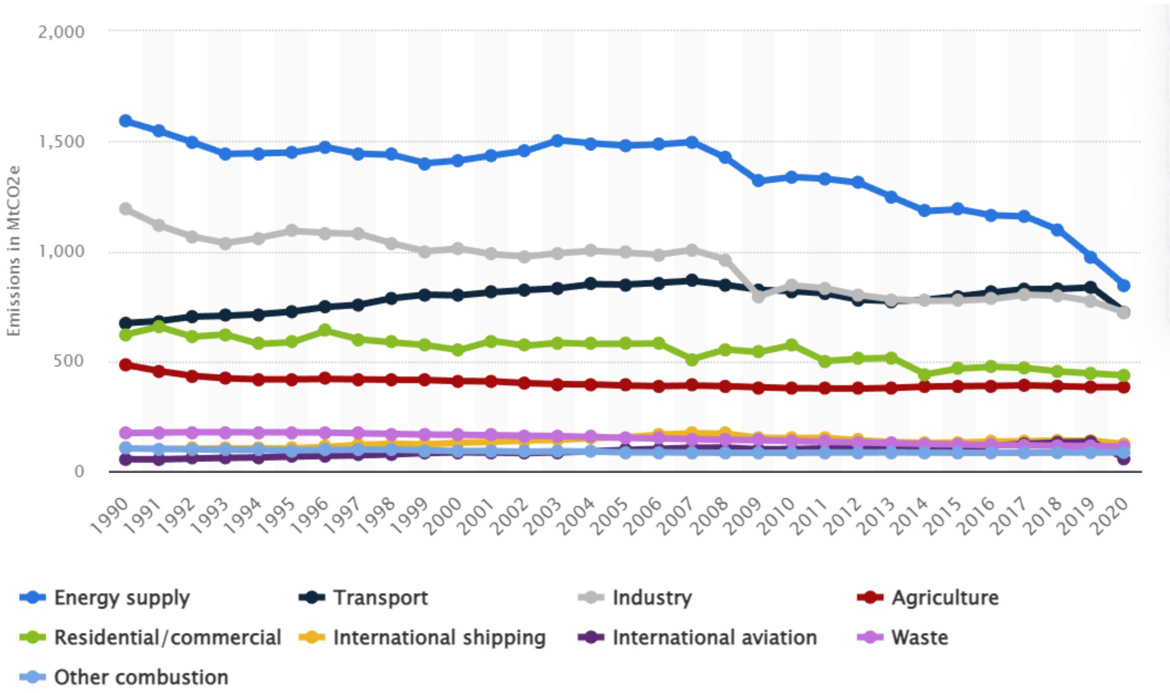

Figure 12 Annual greenhouse gas emissions in the European Union (EU-27) from 1990 to 2020, by sector (Statista, 2022)

Based on the data above, the energy supply amounted to 843 million metric tons of CO2-equivalent emissions in 2020. This is around 24% of the total emissions in 2020. Hence, this factor is used to allocate the share of energy production of the overall water footprint in Europe:

*The planetary boundary for the European energy sector water use, by GDP: 652 km³/year * 24 % = <u>156,5 km³/year</u>*

The acceptable planetary boundary can be built with the same logic but emphasizing different attributes. However, one should note that Europe's GDP is relatively high on a global scale. When the water planetary boundary is allocated through GDP, it might give a misleadingly large allowance for water withdrawal based on the high GDP. In this situation, the planetary boundary would link to economic performance. In order to get closer to the real environmental impact, some other allocation methods should be tested. One possible method suggested by Zipper et al (2020) is to allocate through per capita. Europe's population is decreasing and compared to many emerging regions, the amount of people is few. The population of the European Union was a bit over 447 million in 2021 (World Bank, 2022.). The global population was 7.89 billion in 2021 (World Bank, 2022). From here we can calculate:

The EU population share of the global population: 447 199 800 / 7 890 000 000 = 0,0567 = 5.67%

*European water planetary boundary per year: 4000 km³/year * 5,67 % = 226,8 km³/year*

Based on this allocation, the sustainable limit for water use in the total European water withdrawal is approximately 227 km³ per year. Compared to the same limit allocated by GDP (652 km³/year) one can notice that the water planetary boundary for European water use is significantly lower when calculated based on population. This is a logical outcome since the GDP per capita figure is globally one of the highest. On the other hand, the result already points out the difference between allocation methods. The water planetary boundary for the European energy sector can be calculated similarly as above, using the allocation of energy sector emissions (24%):

*The planetary boundary for European energy sector water use, by population: 227 km³/year * 24% = <u>54,48 km³/year</u>*

Based on these two allocation methods, it is possible to argue that the safe operating space for European energy sector water withdrawals is around 54.5 – 156.5 km³/year, based on the different calculation methods. Within these limits should be the sustainable amount of freshwater withdrawal for energy production in Europe. However, before analysing the current and future situation further, it is important to point out that the figures include some sensitivities that should be taken into account and will be discussed later in this chapter. Based on these results, we can compare the water withdrawal amounts in the European energy sector to the given planetary boundaries.

Source	Water withdrawal 2015	Water withdrawal, 2030	Water withdrawal, 2050
Joint European Research Centre	74 km^3	65 km^3	46 km^3
Planetary boundaries			
Water planetary boundary, by GDP	156,5 km^3	156,5 km^3	156,5 km^3
Water planetary boundary, by population	54,48 km^3	54,48 km^3	54,48 km^3

Table 2 Comparison between water withdrawal and planetary boundary limits

From Table 2 one can already see that if calculating with the GDP-based fair shares approach, the water withdrawal is below the water planetary boundary limits throughout the study period. The water withdrawal estimates by JRC (2018) are far from the planetary boundary limit of 156.5 km^3. When looking at the population-based fair shares approach, the water withdrawal amount exceeds the planetary boundary until the end of this decade (74 km^3 in 2015 and 65 km^3 in 2030). From this, it could be interpreted that the current and near-term energy sector water withdrawal wouldn't be within sustainable limits. Only in 2050 the water withdrawal, 46 km^3, would be less than the planetary boundary.

4.2.2 Local safe operating space approach

In opposition to the previously demonstrated fair shares approach, the local safe operating space approach starts from the microlevel and builds from there to the macro level. It aims to define local stable conditions for water use. In this approach, the local water system's hydrological stability can impact the overall boundary values. In comparison to the fair shares approach, the local safe operating space approach adds more emphasis on local decision-making than considering the Earth-level system perspective. Therefore the data requirements for the local safe operating space approach are wider, which makes the method more time-consuming (Steffen et al. 2020).

Defining the local safe operating space approach includes three steps:

1. Defining locally meaningful control and response variables
2. Setting boundary values that define the local safe operating space
3. Quantify the state of each control variable

In order to test the local safe operating space approach, the analysis needs to be conducted on a local level (Gleeson et al. 2020). As an example, this study has chosen a test region in the EU that is doing water withdrawals for energy industry purposes and uses rivers as freshwater sources. The study has accessed data from Rhine discharge at Lobith measuring point. Lobith belongs regionally to the NL-22 region (Gelderland), which is one of the NUTS-2 regions in the Netherlands. NUTS classification stands for Nomenclature of territorial units for statistics. It is a European-level system to distinguish the economic territory to collect regional statistics and socio-economic analyses. (Eurostat, 2022.) The river Rhine is a vital part of European infrastructure and industrial activity. In 2022, the water level at the Lobith measuring point dropped to record-low levels. This happened during the summer, even though usually the lowest results are recorded in the fall as there is no water melting from the Alps. (New York Times, 2022.) The water withdrawal for the NL-22 region based on JRC (2018) data was 300 million m^3 (0.3 km^3) in 2015 and is expected to decrease to 5 million m^3 by 2030. In 2015, the NL-22 region was the second largest water withdrawal region but is expected to have one of the most significant decreases in water withdrawal. This is due to the phasing out of old solid fuel-fired power plants.

The discharge in the Rhine river at Lobith is visualized in the graph below, based on the European Copernicus dataset. Discharge is measured in cubic meters per second. The graph includes historical data already since 2021, but for this analysis data from 2018 is topical in order to link it to JRC (2018) water withdrawal data. The seasonal change in river discharge is visible from the graph. In the spring months, the discharge level is high, which can be related to ice- and snow melts as well as heavier rains. Towards the summer months the discharge amounts start to decrease.

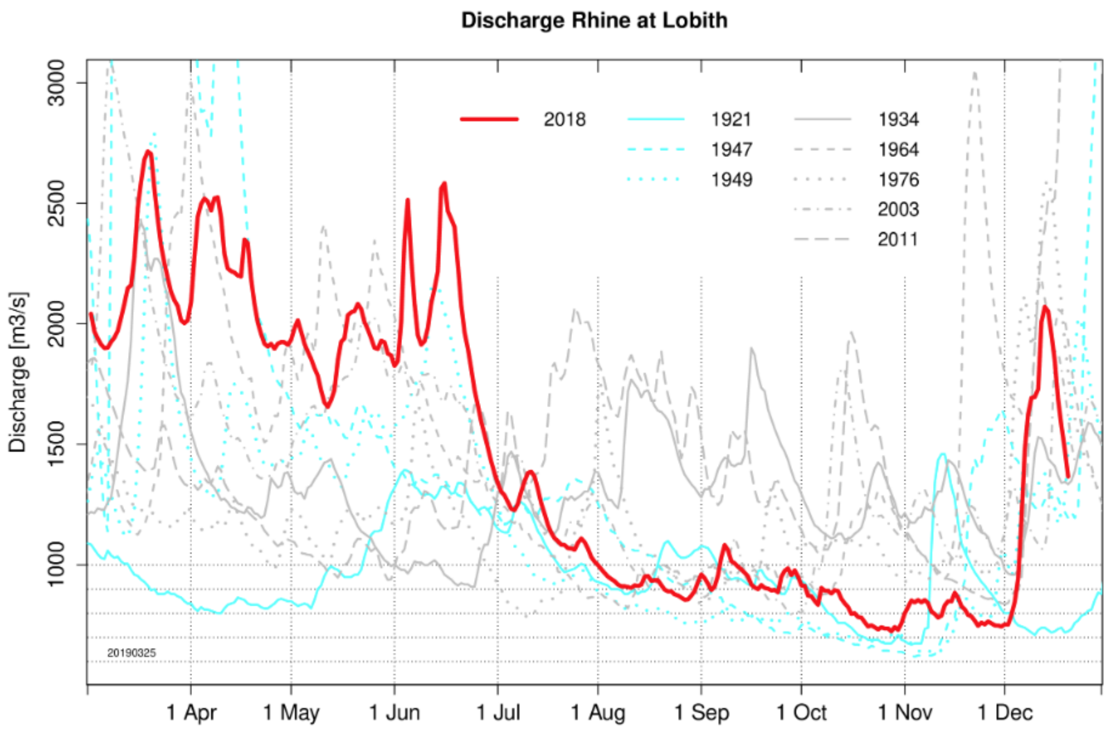

Figure 13 Rhine river discharge amounts at Lobith measuring point, NL-22 region (Copernicus, 2022; Original data source Rijkswaterstaat, Netherlands Ministry of Infrastructure and the Environment)

In order to get an overview of the annual water discharge cycle, three data points are chosen, based on the graph:

Month	**Discharge level**
April, 2018	2500 m^3/s
August, 2018	1000 m^3/s
November, 2018	600 m^3/s

Table 3 Discharge levels at Rhine river during different time points

As present, these figures are average discharge amounts per second. In order to get the average monthly discharge level, the seconds need to be transformed into month. There are 2,592,000 seconds in a month (60 x 60 x 24 x 30).

Month	Discharge level (per second)	Discharge level (per month)
April, 2018	2500 m^3/s	6.48 km^3/month
August, 2018	1000 m^3/s	2.59 km^3/month
November, 2018	600 m^3/s	1.55 km^3/month

Table 4 Monthly discharge levels

According to Steffen et al. (2015), the acceptable planetary boundary level for blue water withdrawal depend on the monthly flow state. For low-flow months the acceptable withdrawal is 25%, for medium-flow months 30% and for high-flow months 55%. The zone of uncertainty is an additional 20% for all of the boundaries, but in this calculation, the official boundary levels will be used. From Figure 13 it appears that in Rhine river at Lobith measuring point we can see that summer and early autumn periods are low-flow months when the discharge levels drop below 1000 m^3/s starting from June. This is typical for summer and autumn as warmer weather and less rainwater will impact the flow amount decreasingly, as well as lack of melting water from the mountains. Based on these recommendations, the planetary boundaries will be calculated respectively for different months:

- April 2018, high-flow month, acceptable withdrawal 55%
- August 2018, medium-flow month, acceptable withdrawal 30%
- November 2018, low-flow month, acceptable withdrawal 25%

Multiplying the monthly water discharge levels with acceptable withdrawal share gives estimate for the boundary level.

Month	Acceptable withdrawal (%)	Discharge level (per month)	Boundary level (km³/month)
April, 2018	55%	6.48 km³/month	3.56
August, 2018	30%	2.59 km³/month	0,78
November, 2018	25%	1.55 km³/month	0,39

Table 5 Comparison of discharge levels to planetary boundaries

The boundary levels calculated in the last column represent the acceptable withdrawal amounts based on the respective annual discharge cycles. Now that the acceptable local safe operating space is defined, it's time to compare the current state of water withdrawal for energy use. In 2015 the annual water withdrawal for energy use was 300 million cubic meters per year and this is expected to decrease to 5 million cubic meters by 2030 due to phase-outs in solid fuel power plants. The monthly water withdrawal for energy use can be calculated:

- 300 million m^3 = 0.3 km^3 / 12 = 0,025 km^3
- 5 million m^3 = 0.005 km^3 / 12 = 0,0004 km^3

Both these figures are then to be compared with the calculated boundary levels for water withdrawal. From this, it becomes clear that the current and expected future water withdrawal levels for the energy industry are below the acceptable water withdrawal levels. Hence, this would indicate that the water withdrawal is also currently on a sustainable level. In order to make a better analysis on the local level, the water use on NL-22 should be specified in order to get the respective share of the energy industry's water use and acceptable boundary.

The local safe operating space approach was an example analysis of how the so-called "bottom-up" analysis would work while defining planetary boundaries. In order to gain a full view on the European level, all NUTS-2 economic regions and their water boundaries should be analysed based on river discharge amounts. By comparing these regional boundaries versus actual water withdrawal amounts, it would be possible to form a view on European-level water sustainability with local safe operating space approach.

5 Discussion

5.1 Interpretation of results

There are many uncertainties and variables when it comes to defining water planetary boundaries and control variables related to it. Subjective analysis plays a role in boundary definitions, for example when it comes to choosing allocation methods and criteria. While using the fair shares approach, i.e. so-called "top-down" approach, the analysis started from a global safe operating space for freshwater use (4000 km^3 / year). This was then allocated first to Europe-level based on either GDP or population. These two allocation methods were chosen as they are both descriptive demographic attributes and also have different development expectations; the GDP in the EU is one of the highest in the world whereas the population is decreasing. Energy sector-specific allocation was then performed by allocating through emissions share. It would have been possible to use other allocation methods but the share of emissions is descriptive of the characteristics and societal role of the energy sector. Another allocation option would have been to split by the energy sector's share of the European GDP, but there were no trustworthy estimates available.

Through these allocations, it was possible to reach the water boundary for the European energy sector. This is the acceptable amount of water withdrawal within a year to ensure sustainable operations. Allocation through GDP resulted in higher planetary boundary limits, and neither the past nor future energy sector water withdrawal was close to limits of exceeding the boundary. Based on this result solely it would seem that the European energy sector is using water in a sustainable way. However, it is important to note that allocation through GDP gives a particularly large planetary boundary level, since the European GDP is high, if considered globally. Therefore it was important to test another allocation method where the population was used as the allocation attribute. From these results, it was clear that the energy sector water withdrawal exceeded the acceptable boundary levels both back in 2015 and expected 2030. Only in 2050, the water withdrawal would return to sustainable levels, due to the phase-out of solid-fuel-fired power plants. These two allocation methods of the fair shares approach show that there can already be wide variations of results even with small alterations. Interpreting the correctness of these two allocation methods would require more detailed analysis, but given the literature review and clear signals of water scarcity impacting the European energy sector already today, the population-based allocation method is most likely closer to reality. Population changes and urbanization have been identified as one of key impacts to water scarcity (Baggio et al, 2021).

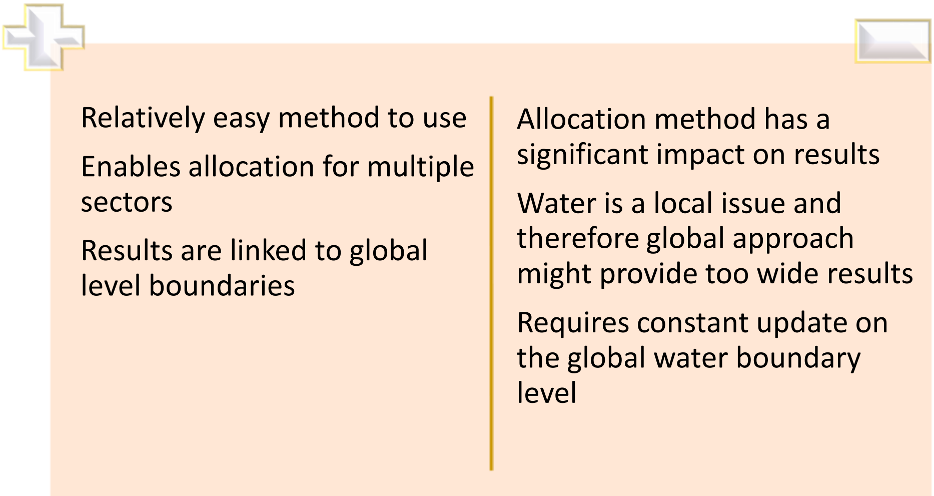

Figure 14 Evaluation of the fair shares approach analysis

The local safe operating space approach is a more precise tool to be used on a local level. It can offer precise impacts on the local hydrological systems and their changes. Local insight can support local decision-making in water management. The key challenge with the local safe operating space approach is the extensive requirement for data, in case a global or wider regional view is to be applied. First, the method requires the user to divide the desired region into smaller parts to calculate the local impacts. In this work, the NUTS-2 region was used as an example of a smaller economic region. If data would have been available and the scope of this work wider, the local safe operating space approach would have combined all NUTS-2 regions, their average river discharge and water consumption. One technical difficulty is related to the sea. There is more detailed measuring data available on inland waters like rivers, whereas local impacts on seawater are more complicated to define. Hence, the local safe operating space approach gives fewer opportunities for subjective choices.

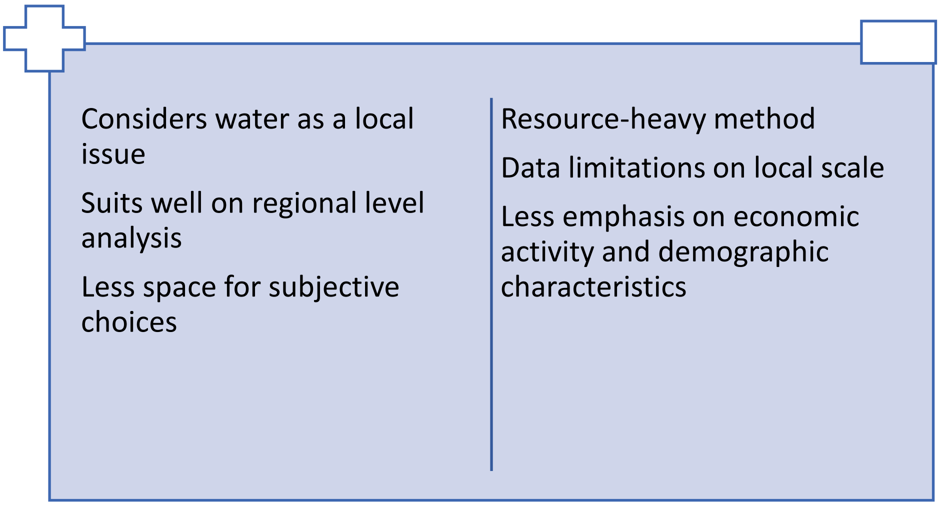

Figure 15 Evaluation of the local safe operating space approach

5.1.1 Sensitivities

The analysis can be elaborated further with some sensitivities. For example, this analysis did not include hydropower. This was mainly done due to the available data, but also because the water footprint of hydropower is not a self-explanatory figure. The presented water withdrawal amounts from Joint Research Centre were from 2018. The gap between 2023 and 2018 is already five years, including years when Europe has seen severe droughts during summers as well as come across a major energy crisis. Hence, the water withdrawal amounts could have been updated already from the basic level. The latest changes in the European energy security landscape have dramatically shifted the role of some energy production methods. The usage of natural gas is questioned as countries aim to decrease their dependency on Russian gas and oil. The diminishing use of fossil fuels was indeed taken into account in the original data, but the transition could now happen faster by 2030 rather than 2050, driven by security reasons. Another big uncertainty is nuclear energy. The Joint Research Centre estimates had a rather careful view of the future of European nuclear power. According to the report, the role of nuclear energy would decrease by 2050. Even though some member countries like Germany still seem to go for nuclear phase-out, there is a growing list of countries with new plans for nuclear. The coverage of nuclear energy in the water withdrawal data didn't pinpoint the expectations for small modular reactors. There is increasing interest towards next-generation nuclear technologies enabling modular size and purpose-located use. Given these developments in the nuclear energy sector, it could be assumed that the share of nuclear energy is not decreasing as much as anticipated a couple of years ago. The development of the nuclear sector is important for water consumption, as the cooling purposes at nuclear power plants are one of the largest water users in the energy sector.

Based on Steffen et al. (2015) the current global freshwater planetary boundary is 4000 km^3/year and the current control variable is around 2600 km^3/year. In this work, the global planetary boundary was taken as a given figure, However, it could be questioned whether this planetary boundary should be modified in the years to come, given that the study timeframe is until 2050. Currently, the water planetary boundary is still identified to be in a safe and sustainable zone, compared to other planetary boundaries like biodiversity where the sustainable operating levels have already been exceeded, as shown in Figure 3. It is still likely that the changes in weather conditions as well as other climate change impacts (e.g. melting of glaciers) can have an impact on the available freshwater. Even though the planetary boundary for freshwater use would not be changed, the control variable within it should most likely be modified.

A few words could be mentioned around the validity and generalization of the study. Validity can be defined as whether the research has been framed correctly to understand the phenomenon in question. Reliability, on the other, hand links to the correctness of the data and whether data can provide answers to the exact research question. (McKinnon, 1988.) In this thesis, the phenomenon of scope was to understand the freshwater planetary boundaries and whether the European energy sector is operating within those boundaries now and in the future through the expected net-zero transition. The research was conducted by forming planetary boundaries for European energy sector water withdrawal with two different methods presented in academia. There is a limited amount of examples of freshwater planetary boundary calculations for energy use and therefore this study should be viewed as an attempt to frame the sustainability of the energy sector's water use. As discussed previously in this chapter, the applied methods of forming planetary boundaries can include some biases. The fair shares approach uses subjective allocation methods, where the allocation attributes were chosen with the best available knowledge. In the local safe operating space approach the example was calculated only for an example region, as the European-wide data set was not available and would have been extensive to the scope of work. Even though the data from the European Copernicus Centre can be considered trustworthy, it could have been analyzed in the full European context to get the full picture of the freshwater planetary boundaries on local levels. Extending the local safe operating space approach to the European wide dataset would improve the validity and reliability of the research. However, McKinnon (1988) notes that utilizing multiple methods to analyze the research topic can improve validity and reliability. The thesis attempts to address this point, as it includes both bottom-up and top-down approaches to constructing the water planetary boundary levels. Expert interviews could have been utilized to validate the results, which would have made the thesis both quantitative and qualitative.

5.2 Reflection on water planetary boundaries

It is clear that the EU is boosting its renewable energy targets in order to decrease the dependency on Russian gas and reach its net-zero targets. In practice, this materializes as increasing deployment of renewable energy production. While societies try to tackle climate change through the energy transition, the focus has been shifting to other planetary boundaries such as biodiversity and water. Extreme weather events like droughts, forest fires and heavy floodings have shaken Europe and North America. Based on both theoretical and empirical analysis of water use in the European energy sector, the ambitious decarbonization targets are decreasing the need for water. This is visible in the JRC (2018) data, where the estimated energy sector water use is estimated to be 46 km^3 in 2050, compared to 76 km^3 back in 2015. This shift is mainly driven by the phase-out of fossil-fuel-based power generation and some countries phasing out nuclear power plants.

A wider impact to be considered in the future is the role of fossil fuels and nuclear. For many years, it seemed that the EU was experiencing intentions to phase out nuclear power plants, where some countries like Germany announced plans to focus their energy production otherwise. On the other hand, many countries have been increasing their nuclear advocacy by either welcoming new power plants online or boosting the development of modular reactors. Due to the Ukraine war and the increased need for energy self-sufficiency, many countries have considered altering their nuclear agendas. If nuclear power gets more attraction in Europe, it might not come without questioning its water withdrawal needs. Heat waves have impacted nuclear power generation, especially in France, where a lack of cooling water caused major disruptions in certain nuclear power plants during the summer of 2018 and 2022. If planning new nuclear power plants in Europe, location will likely be considered more critically linked to water (e.g. on the seashore).

Measuring and quantifying water scarcity is still a very immature field. According to Yang et al. (2013), water footprint is a generally accepted method to talk about water use, but it’s so far been calculated mainly for only certain regions instead of holistic use. The lack of unified quantification measures can cause limitations in adopting water scarcity as part of decision-making and monitoring processes. As mentioned by Yang et al. (2013), the data quality and lack of accurate data are one of the key barriers in today’s water measurement. More efforts would be needed to create comprehensive models to cover hydrological, agronomic and economic models to map topics such as water availability and pollution. Current measurement models leave rather limited space for uncertainty assessment, which would be a crucial addition given the already-seen impacts of climate change on water availability. The virtual water and water footprint measuring could be supported by unified policies and frameworks, making the approaches comparable and transparent throughout the regions and sectors. This would also include a better definition of the roles of blue, green and grey water in the calculations.

If there would be sufficient water quantification as well as acceptable operating limits for water withdrawals, business- and political decision-making could integrate these into existing processes. Water scarcity should be increasingly considered while planning the new energy infrastructure. Lohrmann et al. (2021) have already urged the European energy sector to focus on water efficiency improvements in order to prepare for potentially more unstable water availability in the future. The question is not only about what kind of energy production future societies should rely on but also about the locations where energy production should be placed. Currently, energy production is placed close to consumption like big industrial clusters and urban areas. While this might still be the case in the future, water availability might be one additional criterion for a location. This would require an in-depth analysis of the expected future changes in the regional water cycles. By measuring water scarcity, e.g. with water footprint measures, the energy sector can make better-informed decisions. Since renewables have the lowest water footprint of all future energy sources, the production mixes should be optimized in a way where renewable power generation can minimize the overall water footprint of electricity production. Societies must also understand the connection between greenhouse gas emission reductions and water scarcity. The regulatory understanding of water planetary footprint is still limited, hence impacting the applicability to different sectors. Vanham et al. (2019) urge the European Union to include water scarcity in its energy policies. Planetary boundaries could develop into a useful tool for decision-makers by giving methods to analyse global sustainability beyond GHG emissions. It should be remembered that the planetary boundaries model from Rockström et al. (2015) include total of nine planetary boundaries, of which it is certainly known that some boundaries have already been exceeded. Hence, it would be recommended to increase the general awareness of planetary boundaries and develop methods to ensure operations within the boundaries.

As discussed in the empirical analysis, defining water planetary boundaries is a somewhat subjective exercise. This is especially the case in the fair shares approach, where the boundary allocation can be performed with multiple denominators. As recommended by Zipper et al (2020) GDP and population were used as example allocation methods, giving very different results for acceptable water use. This was also in order to demonstrate the differences and impact of chosen allocation factors. Considering that the European population density and economic activity are high, it would make sense to argue that European water usage is high. If calculating the fair shares approach with GDP allocation, the resulting planetary boundary level is high. This would indicate that there is a lot of room for additional water use from current operations, as high GDP will result in a high planetary boundary level through allocation. This is the opposite for population, as the European population is small, hence the allowance for water use results in smaller. The fundamental question is, which allocation method to use in order to secure a rightful planetary boundary for a certain region. The planetary boundary should reflect the realistic situation of sustainability in order to guide policy-making and business decisions.

Finding a common ground for measuring principles and responsibility allocations has been problematic in global climate politics. The COP27 meeting in late 2022 didn’t result in any major conclusions or agreements between countries, nor mutual understanding on countries compensating for the climate change impacts to more impacted countries. This raises a question of how water planetary boundary measurements can be performed in the future if there are no common principles to do so. Without international, scientific coordination there most likely is a risk that countries might define planetary boundary levels with favourable allocations. Water is a local topic compared to many other planetary boundaries, like climate change. Even though the impacts and actions are local, the water resources might belong to multiple different nations. There have already been several water conflicts, especially in the regions most impacted by water scarcity. World Economic Forum (2019) listed the water crisis as one of the most significant global crises. As water scarcity is expected to increase in the future due to climate change, water related conflicts will increase as well.

Even though the empirical analysis showed early signals of potential overconsumption of water in the energy industry, the cross-industry reality should be considered in order to get a full understanding of water scarcity. There is a need for new innovative solutions and technologies as well as consumption changes from individuals and societies. With increasing instability of the weather, including extreme droughts, a larger portion of the world's population might face difficulties in accessing water. Biswas & Tortajada (2022) note that societies have the needed capabilities to innovate for sustainable water use and reduce water footprints. Closing industrial water cycles and collecting wastewater from urban water systems can reduce the amount of freshwater outtake from water assets. In a long run, this would ease the blue water footprint consumption and reservoirs.

5.3 Further research ideas

This research was a brief overview of water planetary boundaries, and how they should be understood and taken into account in the energy sector in the European context. The concept of planetary boundaries is increasingly addressed in the public- and economic decision-making, but many of the boundaries are still unclear and complicated to measure and tell the borderline between sustainable and non-sustainable levels. The study could be developed further to define the concept of water planetary boundary for the energy sector and energy production methods. This would be particularly useful for energy sources such as coal-fired power plants, nuclear generation and bioenergy. These energy sources consume the highest amount of water and therefore water management is a crucial part of planning and operating the plants.

Many novel energy technologies are crucial for societal decarbonization but not calculated here as part of the water withdrawal. The best example case is hydrogen, which requires both clean electricity and large amounts of water in production. Carbon capture technologies are novel decarbonization tools that are slowly being implemented to use in hard-to-abate industries. Carbon capture technologies also require electricity and water to perform. These novel and increasing electricity users alter the European energy demand outlook and therefore water withdrawal amount.

Defining different environmental footprints is an overarching phenomenon when it comes to organizations' sustainability agendas. More emphasis has been put on understanding the impacts throughout the whole value chain in order to see the holistic footprint of a certain product or service. This is especially topical when it comes to carbon footprint and emissions, where supply chain stages like transportation can impact the overall GHG emissions significantly. A similar approach could be implemented in water footprint, where water withdrawal could be measured throughout the value chain. In this work, the energy sector water withdrawal data included some figures from oil and gas extraction, which are part of the energy production supply chain. However, in Europe the extraction activities are limited and the raw materials are usually sourced from elsewhere. So in order to define the full water footprint of European energy production, the impacts on the sourcing locations and transportation should be understood. By doing this, one could state the water demand for the entire energy value chain.

An interesting area of study continuation would be to analyse the various methods and routes to decrease water usage and ensure the position within the global freshwater planetary boundary. The water purity requirements in the energy sector are high, which poses challenges to recycling and reusing water in processes. Despite this, many industrial processes have already introduced various water recycling methods in order to not only reduce freshwater intake but also to secure access to water during the time of extreme weather conditions. For example, the hydrogen industry must actively consider various routes to ensure water supply, and water recycling opportunities or rainwater usage are potential alternatives to reduce the freshwater intake. Previous research has debated the integration of water planetary boundaries into life cycle analyses (LCA). LCA is a widely used tool in organizations to analyse their environmental impacts. However, for example, Gerbens-Leenes (2021) suggest that integration might not be simple. One key issue could be the potential overlaps with the approach to water as well as data gathering. This indeed could be the case especially before there are common and holistic principles for applying water planetary footprint.

6. Summary

The European energy sector is on its way towards decarbonization and phasing out fossil-based production. The most remarkable shift is towards the massive deployment of renewable energy, mainly wind and solar power. Many countries are also reconsidering their nuclear agendas, as small modular reactors have shown promising signals. There is also a strong political and economic appetite to decarbonize the continent and secure energy self-sufficiency (IEA,2020). While the energy transition itself has been ongoing for some time, it has been further boosted by the energy crisis and Ukraine war in 2022. The shift towards renewable energy is expected to happen in the next decades when wind and solar power take over from oil, coal and natural gas (DNV, 2022). Simultaneously as societies are longing for more renewable capacity, some focus has been drawn to question the availability of materials and resources to fulfil the transition. Some questions have been raised about whether energy transition targets are achievable in a sustainable way when it comes to, for example, raw material supply chains. So far, only a little attention has been put to water availability for energy production, though it plays a major role, especially in coal- and gas-fired generation and nuclear power. The water concern has been acknowledged during the several drought periods seen in Europe during the past years.

The planetary boundaries concept was introduced in early 2000 by Johan Rockström. Planetary boundaries set the limits for sustainable operations on the Earth. The definition includes in total nine boundaries, of which one is freshwater availability. (Rockström et al. 2015.) According to the current estimates, there is no immediate threat for global freshwater availability to be exceeding the boundaries, compared to how the situation is for biodiversity. However, the focus towards water availability is increasing. Despite the increasing attention, water footprint analyses have mainly been conducted in some regions but not for industry-specific use cases. Hence, there seemed to be limited understanding of whether the European energy industry, while ongoing its biggest transition since the industrial revolution, can maintain its water use within the planetary boundaries. Gaining an understanding of this question was the aim of this thesis work.

The empirical part of the thesis aimed to answer the question of whether the European energy sector is operating within freshwater planetary boundaries. In other words, whether the current energy mix and the expected energy transition are done with sustainable water use. Joint European Research Centre has completed a thorough analysis of European energy sector water use in 2018, including forecasts until 2030 and 2050, hence taking into account the implications of the energy transition. The European energy sector water consumption was 74 km³ per year in 2015 and is expected to decrease to 46 km³ by 2050. The majority of current water use is related to power generation and cooling processes. Hence, conventional gas- and coal-fired generation as well as nuclear power use large quantities of water. On the contrary, renewable power sources like wind- and solar power require only marginal amounts of water. Therefore it seems clear that the energy transition is expected to decrease the amount of water use in energy generation. Reservoir hydropower was excluded from the JRC (2018) data.

Even though there seems to be a declining trend of water use in the energy sector, the question of sustainable water use remains. There is still little or no certainty whether this water use is within acceptable and sustainable levels. There are multiple ways to define planetary boundaries for freshwater use and these methods were tested in the empirical part. Starting point for the allocation was the data point of safe operating space for freshwater use (4000 km³ / year) based on Gleeson et al. (2020). The fair shares approach takes a top-down method in defining sustainable water use based on different allocations. In the fair shares approach, the global safe operating space for freshwater use is allocated to the desired sector based on different criteria (Zipper et al. 2020). In this case, the allocation was done for the European energy sector. In this study, the fair shares approach was allocated both through economic figures, here GDP, and population, as these were suggestions found from the research (Zipper et al, 2020). The second method presented was the local safe operating space method, which could be described as a bottom-up approach. In this approach, the water usage and boundaries are first analyzed locally and then built up to a desired macro level state. For example, this could mean calculating regional implications first and then combining the result in order to get a national freshwater boundary (Zipper et al. 2020).

The final part of the empirical analysis compared the calculated planetary boundaries towards the estimated water use of the European energy sector. As a result, it occurred that in 2015 the European energy sector water use of 74 km³ was exceeding the allowed planetary boundary of 54,48 km³ if allocating per capita. If allocated with GDP, the water use was within the set planetary boundary. This difference highlights the difference between allocation methods but also points out the fact that at least with one method the water use is not at sustainable levels. In 2030 and 2050 the overall water use was set to be within planetary boundaries, regardless of allocation method. This is because water use itself is expected to decrease due to the shift to renewables.

Curmi et al. (2014) pointed out that the majority of water-related research has so far focused on water supply, whereas different water use cases haven't been thoroughly analyzed. Lohrmann et al (2021) urged the energy sector to analyze its water use better in order to use water more efficiently in investments and operations. Hence, it is clear that academia had welcomed more research on the topic of energy sector sustainable water use. Even though the analysis performed in this thesis was to visualize the different methods to define planetary boundaries, it should not be left unnoticed that with some planetary boundary methods, the energy sector water use is exceeding the sustainability boundaries today. Even though the water use of the energy sector is expected to decrease due to decarbonization, sustainable water use should still be implemented as part of decision-making. In history there has been rather a little amount of discussion about water availability, but warm and dry summers have started to change the dialogue. Hence, more water-related analysis and unified understanding on water planetary boundaries are needed.

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