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Faculty of Technology
Degree Programme in Environmental Technology
Bachelor's Thesis

An overview of Water Footprint Assessment of Electricity Generation

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Clarisse Jay

ABSTRACT

Lappeenranta University of Technology
School of Energy
Degree Programme in Environmental Technology

Clarisse Jay 0385980

An overview of Water Footprint Assessment of Electricity Generation

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Examiner: Professori Lassi Linnanen
Instructor: M. Sc. Maija Leino

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Abstract:

In this bachelor's thesis we take a look at the international standard EN ISO 14046:2016 ”Environmental management. Water footprint. Principles, requirements and guidelines (ISO 14046:2014)” and conducted a literature review on the water footprints and water-related environmental impacts caused in the life cycles of electricity production. The water use and water-related impacts of three life cycles phases, fuel procurement, construction and operational phase, were inspected. For each fuel, building material and electricity production process information was gathered on how water is used, how much is used and consumed, as well as what possible water-related environmental impacts may be caused. The water footprints and environmental impacts of the fuels and electricity generation technologies were assessed together in order to compare the technologies and outline their overall water-related impacts. Based on the overview comparative assessment done, wind and PV solar power turned out to be the least water-intense electricity production methods, whilst biomass combustion and hydropower consumed the most water and shale gas production caused the most water-related environmental impacts.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
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An overview of Water Footprint Assessment of Electricity Generation

Kandidaatintyö

2017

42 sivua, 7 taulukkoa ja 0 liitettä

Tarkastaja: Professori Lassi Linnanen
Ohjaaja: DI Maija Leino

Hakusanat: kandidaatintyö, vesijalanjälki, veden käyttö, veden kulutus, vesilaatu, sähköntuotanto, elinkaari, ympäristövaikutus, polttoaine, lauhdevoima, ISO 14046, aurinkovoima, CSP, tuulivoima, vesivoima, ydinvoima, biomassa, hiili, maakaasu, liuskekaasu, uraani, polttoaineen hankinta, avoin läpivirtausjärjestelmä, suljettu märkä jäähdytysjärjestelmä

Tiivistelmä:
Työssä tarkasteltiin kansainvälisen standardointiorganisaation vesijalanjäljen standardia EN ISO 14046:2016 ”Environmental management. Water footprint. Principles, requirements and guidelines (ISO 14046:2014)” ja laadittiin kirjallisuuskatsaus sähköntuotannon elinkaaren vesijalanjäljestä. Standardi käsittää veden käytön, kulutuksen ja vesiympäristön ulkoisvaikutukset polttoaineiden hankinnassa, voimalaitosten ja teknologioiden rakennusmateriaalien valmistuksessa, sekä sähköntuotannossa. Näitä veteen liittyviä vaikutuksia kartoitettiin selvittämällä hankinnan ja tuotannon toteutusta, veden käyttötapoja prosessissa, käyttötapojen vaikutusta veden laatuun ja veden käytön määrää. Löydettyjen tietojen pohjalta laadittiin koostearviointi, jossa vertailtiin polttoaineiden ja uusiutuvien sähköntuotantomuotojen vesijalanjälkiä sekä vesiympäristövaikutuksia. Tavoitteena oli hahmottaa kunkin sähköntuotantomuodon kokonaisvaikutukset vesitaloudessa. Arvioinnin perusteella tuuli- ja aurinkovoiman veden kulutus ja vesiympäristövaikutukset ovat vähäisimmät, kun taas biomassan polton ja vesivoiman vesijalanjäljet ja liuskekaasun vesiympäristövaikutukset suurimmat.

TABLE OF CONTENTS

1 INTRODUCTION

Water is becoming an ever more scarce resource on our planet due to massive global population growth and the resulting higher demand for food, water and energy. Fresh water is required in agriculture, industry and as drinking water for the human and animal populations. As the human population on earth continues to increase at an exponential rate so does the need for fresh water, and so it has become imperative to manage fresh water resources and strive towards more sustainable uses of water. Most conventional energy production methods are dependent on water for process cooling. Water-efficient cooling systems need to be identified for improved sustainable water management. The water use in the life cycle of energy production includes taking into account the water use and water-related environmental effects of fuels and construction materials. Global pressure to cut down on CO_2 emissions is pushing the energy sector towards renewable energy options: bioenergy, wind and solar. The ever-increasing use of biomass for energy also increases water consumption of the energy sector.

In order to improve water resource management a proper understanding of the water-energy nexus is needed. In essence, a proper charting of the balance between water uses in energy production versus the energy use in clean water production will provide a useful tool in the assessment of sustainable water use. The main task in this work is to identify the major water-related environmental impacts of various electricity generation methods. The inspected electricity generation methods will be coal-fired power plants, hydroelectric power plants, solar electricity production, both PVC and solar-thermal, wind electricity production, nuclear power plants and biomass for energy. This water related impacts will be evaluated with the European Standard EN ISO 14046:2016 “Environmental Management – Water footprint – Principles, requirements and guidelines (ISO 14046:2014)”. The aforementioned standard shall be assessed as to how it affects the determining of the water footprint of electricity generation.

2 WATER FOOTPRINT ASSESSMENT

In this section, we will discuss what needs to be taken into consideration when determining a water footprint for electricity generation. The standard ISO 14046:2014 Environmental Management. Water footprint. Principles, requirements and guidelines will be used as a guideline tool in our water footprint evaluation of electricity generation. According to ISO14046.2, a water footprint assessment needs to include four phases of an LCA; goal and scope definition, waterfootprint inventory analysis, water footprint impact assessment and the interpretation of the results, as shown in Figure 1. According to the standard, without the water footprint impact assessment phase, the study is a water footprint inventory analysis.(EN ISO 14046, 2016, p. 10).

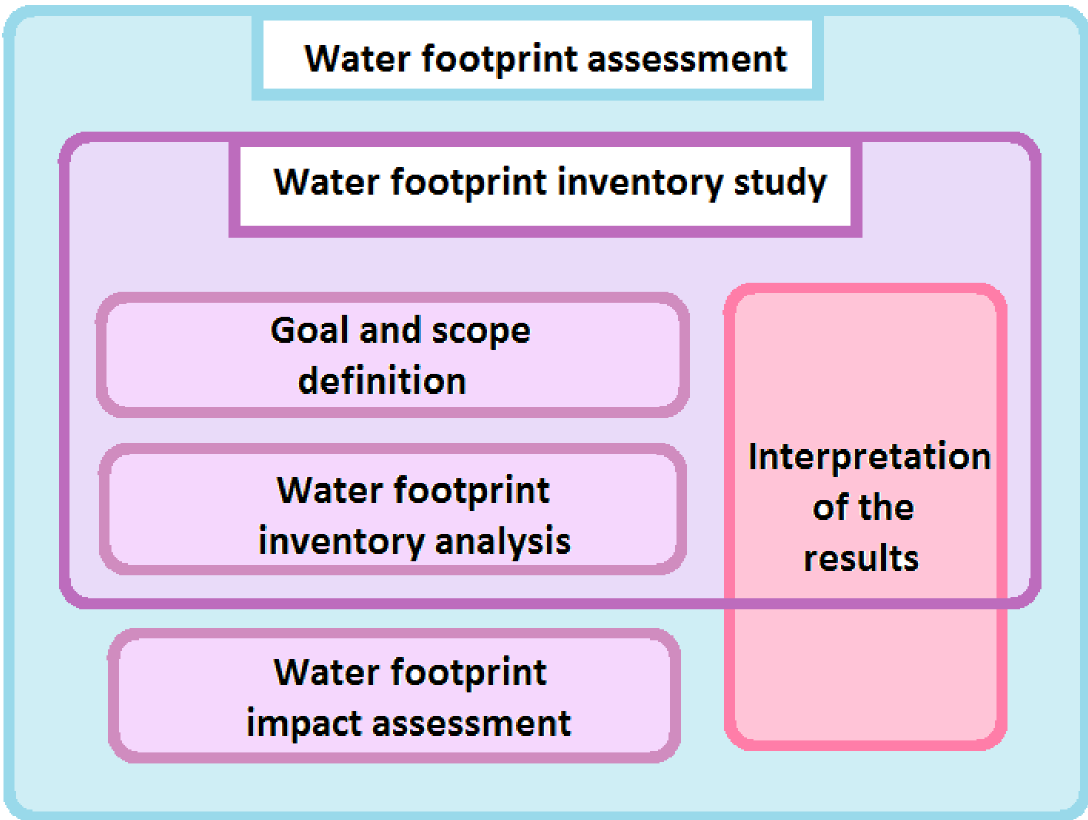

Figure 1 Phases of water footprint assessment (EN ISO 14046, 2016, p. 12)

As a water footprint assessment is akin to an LCA, one needs to outline the life cycle phases of the product or service under evaluation. A correct assessment would evaluate the water-related uses and impacts of the construction of the power plants or renewable energy technologies, acquisition and preparation of fuels, transport of fuels, electricity generation, maintenance, and decommission and destruction of power plants/renewable electricity units. However, the breadth of an LCA study is determined in the study's goal and scope, in which the life cycle may not be cradle-to-grave, but rather shortened e.g. cradle-to-consumer or shop-to-grave. In this paper, a brief overview of the water-related impacts and water footprints of life cycles of electricity production methods, we will be relying on scientific studies based on the EN ISO 14046:2016 standard. Water use, withdrawal and water-related environmental impacts will be identified, when information is available, of the construction, for the three life cycle phases: fuel acquisition, power plant/ technology construction and electricity generation, as shown in Figure 2.

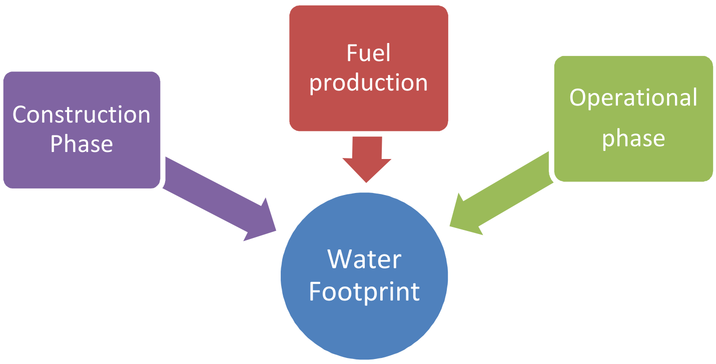

Figure 2 The life cycle phases of electricity production considered in this study.

The following chapter will go over the standard EN ISO 14046:2016, specifically discussing how the standard should be used and how water footprint assessments should be done in order to earn the title of a water footprint assessment that is in accordance to the standard. The chapter will also discuss water-related impact categories and mirror them to the water-related impact categories associated with the construction phase, fuel production phase and operational phases of the various electricity production methods chosen for the brief overview comparison of this project.

2.1 The Definition of Goal and Scope

The goal and scope of the water footprint assessment describe the overall reasons for the study, and the breadth and intricacy of the study. The goal is set by determining the intended application and reasons for carrying out the study and determining the intended audience. The goal also has to determine whether the study is a stand-alone study or part of a life cycle assessment (LCA).

The Scope has to be defined by describing system under study and determining the system boundary. The scope of the study has to be comprehensive in determining the uncertainties and limitations of the study, in discussing which cause-and-effect chains and impacts are covered in the water footprint assessment. It should also discuss the justifications and the foreseeable implications of excluding chosen environmental impact categories from the study. The scope includes information on the temporal and geographical coverage as well as the resolution of the study, including the determining of cut-off criteria, whether or not allocation is done and describing the used procedures. The scope of the study should also discuss the assumptions, value choices and optional elements chosen as well as elaborate on the data and data quality requirements. The scope also describes the impact assessment methodology chosen to be used and type of impacts to be evaluated or not evaluated. (EN ISO 14046, 2016, pp. 17–18)

A functional unit that serves as a reference unit for the unit processes is also determined in the scope of the study. Functional unit is the quantified performance of a product system, process or organization (EN ISO 14046, 2016, p. 7). Water footprint assessment is related to the functional unit and the results calculated relative to it. In the case of water footprint assessments of electricity, the water footprint could be evaluated in units of volume of water per unit of electricity produced. The inputs of and outputs of each unit process should be related to the reference flow. The reference flow in the case of the water footprint of electricity production would have to be determined separately for each electricity production method.

The system boundary should be clearly documented and indicate whether the water footprint is for a process, organization or a specific product. According to section 5.2.3 of EN ISO 14046:2016, the system boundaries should be determined and well justified. Unit processes are determined in the system boundary, including decisions on what unit processes, i.e. inputs or outputs, are included or excluded from the study as well as stating the level of detail to be used. Omissions to the system boundary of the study should only be done if they do not change the outcome of the study. Unit processes should be clearly identified throughout the study, especially in the water footprint inventory analysis. (EN ISO 14046, 2016, pp. 18–19)

The data collected on water should include data on the properties of the water or the process the water goes through, as well as data on the changes or effect on environment due to the water withdrawal, consumption, or degradation. Most importantly, data collected must include data on quantities of water used for both water withdrawal and release. Data should also include information on the types of water resources, water quality, and forms of water used, including water withdrawal, release and water receiving body. Especially, in the assessment of environmental impacts, it is imperative that data is collected on the effects of land use change, land management activities, such as data on the changes in drainage, stream flow, and groundwater flow or water evaporation. Location of the water use and information on the general water-related environment of the area, such as the water availability and seasonal effects on water availability or water quality is also very important.

Data quality is also determines by factors of geographical coverage, i.e. the data collected should satisfy the geographic specifications in the goal of the study. Data collected should also fulfil the specifications on the age of the data. The same applies for the representativeness, reproducibility, consistency and precision of the data collected. Missing data should be well documented, as well as the assumptions made. It is important to note that a water footprint analysis should never include offsetting. (EN ISO 14046, 2016, pp. 19–20)

2.2 Water Footprint Inventory Analysis

A thorough inventory analysis needs to be done of the data collected with regard to the study subject. Calculating the data requires explicit documentation of all calculation procedures and assumptions made. Chosen calculation methods should be used throughout the study. In the process of an inventory analysis (see Figure 2), it may become necessary to revise the chosen calculation methods and system boundaries. (EN ISO 14046, 2016, pp. 20–21)

Water footprint inventory calculations are done according to procedures as described in LCA standard ISO 14044, depicted in figure 3. All procedures need to be explicitly documented and assumptions clearly stated all calculation procedures used should be the same and used consistently. Data validity must be checked during data collection and evidence needs to be provided of data fulfilling quality requirements.

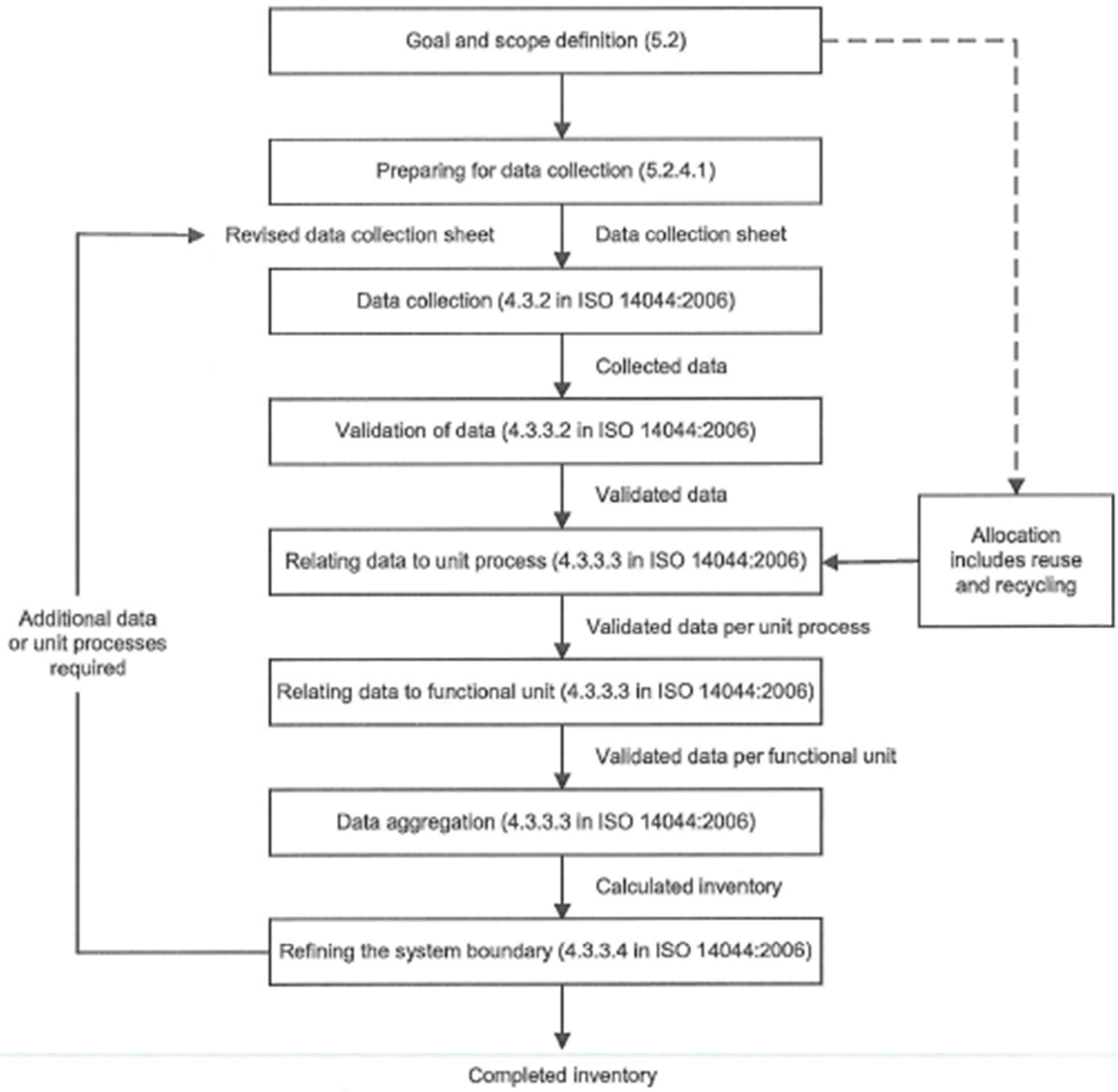

Figure 3 Procedures for water footprint inventory analysis (EN ISO 14046, 2016, p. 22).

A useful check of validity is a mass balance analysis of the process/system. An appropriate flow must be determined for each unit process by relating data to unit processes, reference flows including an evaluation of functions done by calculating quantitative input and output data in relation to flow. Calculated data should relate all flows of all unit processes related to a reference flow and results in all system input and output data referenced to functional unit. The data pertaining to water in the unit processes and material flows being analysed are represent the elementary flows. Information on each elementary flow should include information categories shown in table 1, to the extent of relevance (EN ISO 14046, 2016, pp. 22–23). (EN ISO 14046, 2016, pp. 20–21)

Table 1 Information on each elementary flow should include the following data, where relevant. (EN ISO 14046, 2016, pp. 22–23)

Quantities of water used	Mass, or volume (e.g. water inputs and water outputs)
Resources of water used	Precipitation, surface water, brackish water, groundwater, fossil water, or possible other types.
Water quality parameters and/or characteristics	Physical (e.g. thermal), chemical, and biological characteristics, or functional water descriptors.
Forms of water use	Evaporation, transpiration, product integration, release into different drainage basins or the sea, displacement of water from one resource type to another resource type within a drainage basin, and other forms of water use, e.g. in-stream use
Geographical location of water of affected(incl. withdrawal and/or release)	Information on physical location or assignment of the physical location to a category derived from an appropriate classification of drainage basins or regions
Temporal aspects of water use	Time of use and release if relevant residence time occurs within system boundaries
Emissions to air, water and soil with impact on water quality	-

The system boundaries are refined in the process of the inventory calculation in accordance to ISO 14044:2006, 4.3.3.3. A water footprint assessment has an iterative nature where decisions to include/exclude data are based on sensitivity analyses, which are done to determine the significance of data. The system boundary is then revised when needed in accordance to cut-off criteria and definition of scope. (EN ISO 14046, 2016, p. 21)

The process of refining the system boundary, including the sensitivity analyses, should be well documented. A sensitivity analysis can prove the lack of significance of a life cycle stage or unit process as well as quantify proof for exclusion. The same could be done to prove the necessity of potentially significant new unit processes to be included in the study. (EN ISO 14046, 2016, p. 22)

Allocation in water footprint assessments is done in accordance to ISO 14044. Allocation is the assignment of inputs and outputs to a process when the system/process produces more than one output i.e. product or service. Allocation should be avoided by rather dividing the unit process into one or more sub-processes and relaying the input and output data to these sub-processes or by expanding the system to take into account the sub-processes. If allocation cannot be avoided the inputs and outputs should be portioned between the different products in a way that reflects their physical water-related relationship, and if this is not possible, they should be portioned in a way that reflects their relationship between each part, e.g. by economic value. (EN ISO 14046, 2016, p. 24)

2.3 Water Footprint Impact Assessment

A water footprint impact assessment is to be done according to the guidelines of ISO 14044:2006 “Environmental Management – Life Cycle Assessment”, section 4.4. Water-related environmental impacts of a product system, process or organization are presented and quantified according to type of water-related impacts i.e. impact categories, such as water scarcity. Each impact category assessed will have its own water footprint indicator results, e.g. water scarcity footprint. A water footprint profile is comprised of several impact category related indicator results. The process of conducting a water footprint assessment compared to an LCA has been depicted in figure 4, showing the main phases: inventory analysis, impact assessment and interpretation, with special attention to the steps taken in the impact assessment phase. (EN ISO 14046, 2016, p. 26)

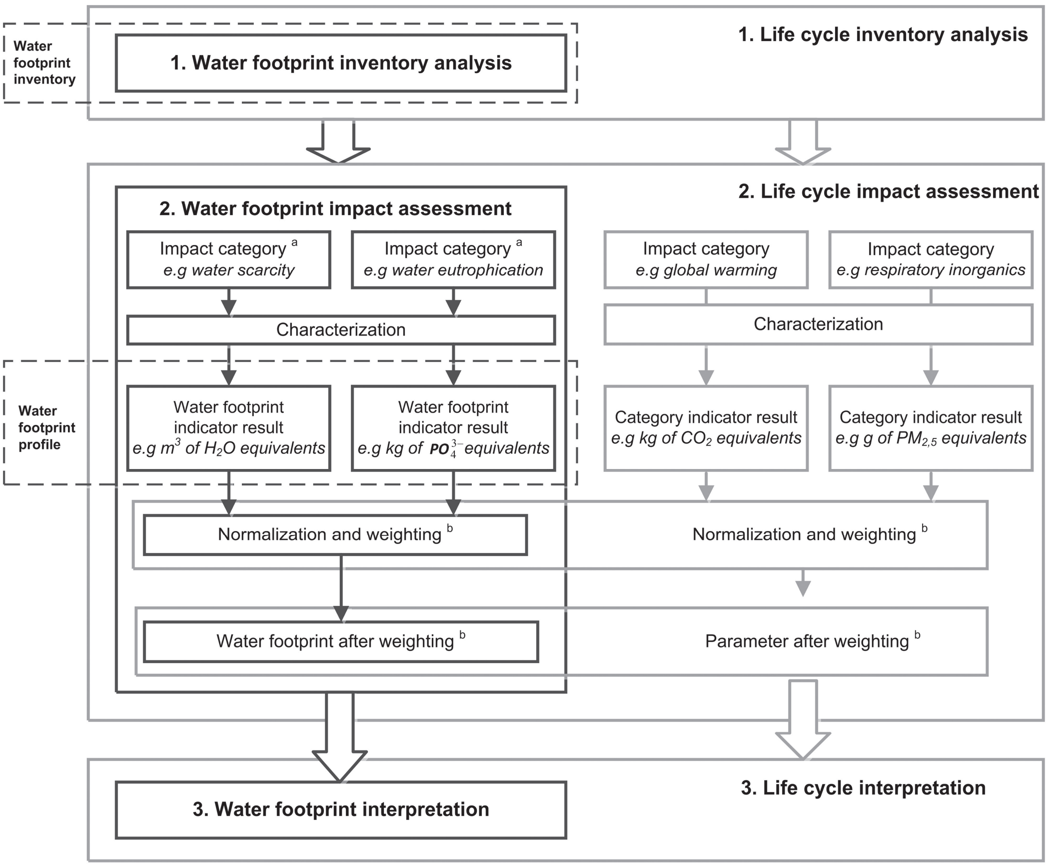

Figure 4 Comparison of a water footprint as a stand-alone assessment to an LCA (EN ISO 14046, 2016, p. 28).

Changes in water availability or quality may affect the possible uses and availability of water in the future. In turn, the changes may affect the local ecosystem, biodiversity and possibilities for human use, which is why it is imperative that the water in question is characterized according to its local geographical characteristics. Geographical characteristics can include descriptions of drainage basin(s), precipitation norms, hydrological characteristics, and environmental conditions for that climate, ecosystem and socio-economic environment. Quantifying the extent of environmental impact a product or service has in each impact category is done in the characterization phase by the use of a characterization model. (EN ISO 14046, 2016, p. 29)

In the characterization step, all water resources are multiplied by a factor, which reflects their relative contribution to the water-related environmental impact category. In doing so, a weighted water footprint is created e.g. water footprint of aquatic toxicity. Changes to water quality and/or quantity caused by the system under study should be described and accounted for by the water footprint impact assessment methods in order to properly depict the potential environmental impact. The selection of category indicators and water footprint impact assessment methods is done according to the goal and scope of the study. (EN ISO 14046, 2016, p. 29)

Water resource types should be distinguished as far as possible throughout the study, e.g. seawater, surface water. The process of characterization, i.e. choice of characterization method and factors for impact categories, should be well explained and justified. The processes of normalization and weighting are the same as in EN ISO 14044:2003, and therefore are not discussed separately in the water footprint standard. (EN ISO 14046, 2016, p. 29)

2.4 Interpretation of Results

A water footprint assessment must include the interpretation of results. Firstly, the interpretation of results should identify the significant anomalies brought to light in the results of the water footprint assessment. These could be, for example, identifying processes or environmental mechanisms which are shown to be affected or elementary processes with the highest contributions to the results of the assessment. (EN ISO 14046, 2016, p. 30)

Interpretation of results should also include an evaluation of the completeness of the assessment, including sensitivity and consistency check. A sensitivity analysis should be conducted to determine the range of changeability of the acquired results.There should also be a discussion on the limitations of the study as well as a qualitative and/or quantitative assessment of uncertainty. (EN ISO 14046, 2016, p. 30)

A water footprint assessment may not be able to properly demonstrate the relationship between impact categories and the indicator results attained for the products, processes or organizations being studies. These limitations of the study may be related to how the functional unit was chosen and established, how the system boundary was determined, or problems related to data availability. Limitations related to the system boudary could be e.g. all inputs/outputs may have not been taken into consideration due to cut-off criteria, unavailable data, or faulty assumptions. There may also be limitation in the inventory analysis due to inadequate quality of data, inadequate availability of representative or appropriate data, or problems in determining uncertainties in allocation and/or aggregation procedures. (EN ISO 14046, 2016, p. 31)

2.5 Water-related Environmental Impact Categories

The water footprint impact assessment categorises changes in water quality and type of water degradation by impact categories. There are multitudes of water-related environmental impact categories depicting the effects of human activities in nature. Thus, there can be a multitude of impact categories related to the life cycle of electricity production. The most common water-related impact categories are as follows: water scarcity, eutrophication, aquatic toxicity, aquatic acidification, thermal pollution, and human toxicity (due to water pollution).

Water scarcity describes the availability, or lack of availability, of water either due to physical shortage or due to lack of access caused by poor infrastructure or failure by institutions to provide regular supply (UN-Water, 2017). According to the water footprint standard (EN ISO 14046, 2016, p. 11), water scarcity is determined as the relative availability of water by water quantity, i.e. it is a relative comparison of water demand and water replenishment of a specified area without accounting for water quality.

Acidification of water bodies is caused by atmospheric pollutants and agricultural land use. Atmospheric pollutants, mainly sulphuric oxides (SO_x), nitrous oxides (NO_x), carbon dioxide (CO_2), ammonia (NH_4), hydrofluoric acid (HF) and hydrochloric acid (HCl), affect the acidity of soils and surface water through acidic precipitation and dry deposition (Curran, 2006, p. 49). These cause further acidification in soils and surface waters when they react with minerals present and cause them to ionise. Nitrous oxide emissions are mainly a result of fossil fuel combustion in industry (~25%), transport (~25%), energy production (~15%) and wastewater treatment (US EPA, 2017). In Finland, agricultural activities, specifically animal rearing (~70-80%) and fertilizer industry (~10%) are the main causes of ammonia emissions to air (MTK, 2017). Hydrofluoric acid and hydrochloric acids are formed in the combustions of fossil fuels, waste and biomass. (Ymparistö hallinto, 2017)

Eutrophication is the over-nourishment of water-bodies, which leads to excessive growth of phytoplankton and algae. Eutrophication is mainly caused by large inflows of nitrogen and phosphorous from agricultural fertilizers, both natural and industrial fertilizers, residential areas, and rainwater contaminated by gaseous emissions of industrial processes. Excess nutrients cause negative effects in the aquatic ecosystem, which are often evident in loss of dominant species or functional groups due to increased sediment porosity and nutrient flux, loss of productivity (i.e. less growth of species) and overall deterioration of water quality. The extra nutrients speed up the production of some organisms, which in turn consume more of the water body’s oxygen and produce more acidic by-products. As some aqueous species being sensitive to the change in water acidity and oxygen levels, they are less likely to survive whilst other species thrive, eventually altering the ecosystem. Eutrophication of water is assessed by determining the concentrations of nitrogen and phosphorus, algal chlorophyll, dissolved oxygen and evaluating water transparency. (Yang et al., 2008, p. 198)

Aquatic ecotoxicity is the build-up of lethal chemicals in lethal concentrations in aquatic organisms (Curran, 2006, p. 49). The toxicity can be determined for three trophic levels of organisms; vertebrates, invertebrates, and plants (EURL ECVAM, 2018). Aquatic ecotoxicity is caused when unwanted chemicals leach into a water body, e.g. heavy metal runoff form mining activities leaching into surface water (Tiwary, 2001, p. 187).

Thermal pollution is caused by activities that change the temperature of the immediate environment. Thermal pollution to water bodies is mainly caused by power plants and industrial processes, which release water of a higher temperature. The effects of elevated temperature can be a change in dissolved oxygen content, thus affecting the aquatic organisms. The change can lead to a change in the ecosystem and species composition as some organisms are sensitive to changes in temperature and dissolved oxygen content. The rise in temperature increases metabolic rates, increasing growth rates of primary producers, such as algae and phytoplankton, which in turn, due to the rise in activity and population size, reduce the water oxygen content even more. In smaller water bodies, thermal pollution may also cause eutrophication, as reduced oxygen content increases the solubility of nutrients from sediment or atmosphere into the water. (Hogan, 2012)

3 WATER USE AND RELATED ENVIRONMENTAL IMPACTS OF FUELS PRODUCTION

The electricity production methods impact categories will be assessed for three stages of the life cycle: construction phase, the fuel production phase and the operational phase. In accordance with the water footprint standard EN ISO 14046:2016, the water footprint of energy generation includes the water usage and related environmental effects of the fuels procured and processed. In this chapter, we will conduct a brief overview of the most common water impact categories affected by the procurement and processing of fuels for electricity production. The task is to understand how water is used and affected in the acquisition and processing of various fossil fuels, biofuels and nuclear fuels.

The fuels overviewed are chosen by their predominance in the production of electricity globally. In 2015, the total primary energy supply in OECD countries was 13 647 Mtoe (158.7 TWh) (IEA, 2018, p. 5) of which a quarter was used to produce electricity. As shown in figure 5 below, the fuel shares of electricity production were as follows in 2016 in OECD countries; 28% coal, 28% natural gas, 18% nuclear, 13% hydro, 11% non-hydro renewables (geothermal, solar, wind, tide, biofuels, waste and heat). In Finland in 2016, nuclear power produced a third (33.7 %) of all electricity, followed by hydropower (23.6 %), biomass (16.3 %), coal (10.4 %), natural gas (5.3 %), peat (4.4 %) , wind power (4.6 %), waste (1.4 %) and (0.3 %) from oil (Energiateollisuus, 2017).

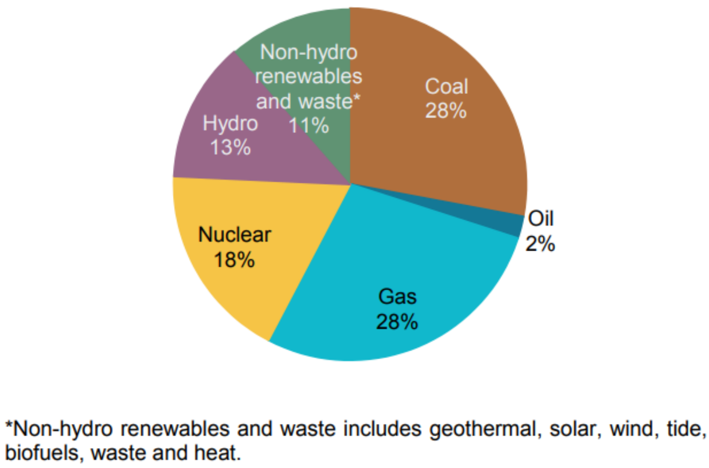

Figure 5 Electricity generation mix of OECD countries in 2016 (IEA, 2018, p. 9)

Due to waste, oil and peat representing very small portions of electricity production both globally and in Finland, we shall not take into consideration their water-related environmental impacts of fuel production and electricity generation. However, since the importance of renewable electricity production has becoming increasingly important due to global warming, we shall include both wind and solar power into the scope of this study. (IEA, 2018, p. 9)

3.1. Coal

Coal is a combustible solid, sedimentary, organic rock, which has formed from organic matter consolidated over millions of years under high pressures and temperatures between other rock strata. Coal is composed mainly of carbon, including small portions of oxygen, hydrogen and sulphur. They vary in form depending on the location, age and composition of the coal. Coal is one of the most popular primary energy resources, accounting for over 40% of the world's electricity needs. The use of coal has more than doubled since the year 2000. Coal also has a very important position in steel and cement production. Over 70 % of all steel produced uses coal, or coking coal, for reducing iron ore to steel. Cement production requires high amounts of heat energy, coal being the most common source. The production of cement 200kg of coal is used to produce 1 tonne of cement, which in turn produces 2.5-3 m^3 of concrete. (World Coal Association, 2017, pp. 1–2)

The amount of water used by coal in the electricity generation depends on many variables, such as type of coal and the technology used to mine and process the coal (Ali and Kumar, 2015, p. 248). Most common coal mining methods are surface mining and underground mining (Ali and Kumar, 2015, p. 249). Surface mining is done for coal reserves close to the surface using methods such as open-pit mining, strip mining and mountaintop removal and underground mining accesses coal reserves under sedimentary rock layer, using methods such as room-and-pillar and long-wall mining (Wilson et al., 2012, p. 14). In underground mining dust is controlled inside the mine by spraying with water, accounting for 70% of the on-site water use (Fthenakis and Kim, 2010, p. 2041). As a result of which underground mining uses more water than surface mining, as the rest of the water used is used in coal beneficiation (Fthenakis and Kim, 2010, p. 2041). Coal is prepared for use in a cleaning and crushing process called beneficiation, in which unwanted impurities, rocks, and ash-forming materials are separated from the coarse coal (Ali and Kumar, 2015, p. 250).

The most common form of water pollution, acid mine drainage, can results from both surface and underground mining (Wilson et al., 2012, p. 15). Acid mine drainage is a result of naturally occurring sulphur in coal mines, which reacts with water and oxygen converted by of a sulphur-oxidising thiobacillus bacteria producing sulphuric acid and an iron precipitate such as iron hydroxide or iron sulphate (Tiwary, 2001, p. 188). Acid mine draining leachate consists of sulphuric acid and dissolved iron, and a myriad of other heavy metals and minerals e.g. calcium, selenium, magnesium and manganese (Wilson et al., 2012, p. 15). Mining water has very high concentrations of TSS, TDS, sulphates, heavy metals, hardness, nitrate, and oil and grease (Tiwary, 2001, p. 187). Mine water and/or acidic leachate often enter a water body as a result of rain or seeping into groundwater (Wilson et al., 2012, p. 15). Water discharged from mining sites cause environmental impacts such as water acidification and aquatic ecotoxicity, causing hardness of water which affects humans as well as aquatic lifeforms.

Many papers (Fthenakis and Kim, 2010, p. 2041; Mielke et al., 2010, p. 20) on the water use and consumption of water in coal mining reference a studies by the U.S. Department of Energy (1983 and 2006). These studies cite the same results published by P.H. Gleick in 1994, in which the data is collected in the 80's (Mekonnen et al., 2015, p. 287; Meldrum et al., 2013, p. 2). A more recent paper by Meldrum et al. (2013) reviewed and harmonized data available literature reports on water use, withdrawal and consumption in various life cycle stages for most common electricity production methods (Meldrum et al., 2013, p. 2). All references where assessed through a three-tier screening process evaluating method quality, completeness, current technology relevance, reasonableness of estimates and excluding duplicates and evaluating age and thoroughness of documentation(Meldrum et al., 2013, pp. 2–3). The goal of harmonization is to reduce analytical variability of the wide range publications by adjusting old estimates with more recent estimates (Meldrum et al., 2013, p. 4). Harmonized statistics of selected and harmonized estimates for coal fuel production life stage of surface mining water consumption of at 22.7-219.6 L/MWh with median of 83.3 L/MWh, and underground mining water consumption at 64.4- 870.6 L/MWh with a median of 212 L/MWh, for both withdrawal equalling consumption (Meldrum et al., 2013, p. 6).

The water related effects of coal mining are largely dependent on miming method, surface or underground. Water-related risks, aquatic toxicity and aquatic acidity, to environment or water bodies are dependent on the water management at mining sites and coal beneficiation locations. The rather large variation in water consumption and withdrawal in coal mining, as seen from values provided by Meldrum et al. (2013), leads to the assumption that the extent of water use or degradation seems to be site-specific.

3.2. Natural Gas

Natural gas is the third of global total primary energy supply, holding a share of 22% (IEA, 2017, p. 5) and is tied with coal holding a 28% share of OECD electricity production (IEA, 2017, p. 9). There is a global trend of coal consumption decreasing and being switched to natural gas, as seen in figure 6 below (IEA, 2017, p. 9). Natural gas has had growing popularity of 2% yearly increase in consumption since the early 2000’s. Increased production of natural gas from unconventional sources, especially shale gas in the U.S., China, Canada, and Argentina, has provided the market with an alternative source of natural gas to the depleting conventional natural gas; in fact, natural gas production increase in the U.S. is almost entirely from shale gas production increase (IEA, 2018). Sourcing oil and gas from unconventional reservoirs producing shale gas and oil, and tight gas and oil, has become increasingly more common in the U.S. accounting for about 50% of production in 2013-2014 (Scanlon et al., 2016, p. 10273).

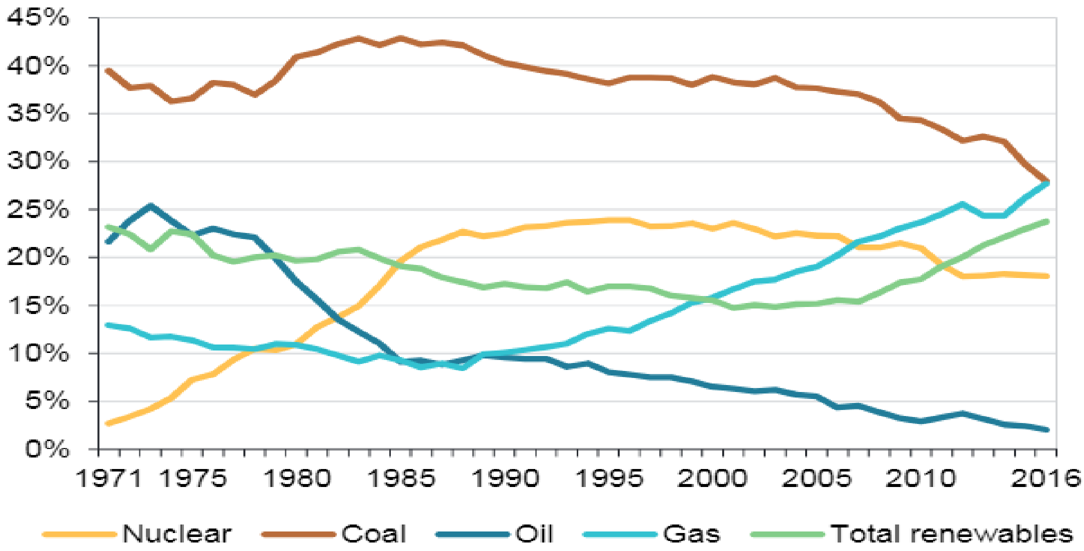

Figure 6 OECD electricity mix 1971-2016 (IEA, 2017, p. 10).

Conventional wells for natural gas procurement require water in the drilling phase in cementing the constructions and in drilling mud, which is used for lubrication and cooling, transporting drill cutting from the lowest part of the bore hole to the surface and upkeep hydrostatic pressure (Clark et al., 2013, p. 11831; Mielke et al., 2010, p. 16). Hydraulic fracturing is done by pumping large amounts of fracking water, water with additive chemicals and proppant material, at high pressure, pressures generally 14-83 MPa (U.S. EPA, 2016, p. 23). Fracking water has small amounts chemical additives which are added to water to change the properties, e.g. to alter pH, liquid thickness and anti-bacterial properties. Some of these additives add significant risk of drinking water contamination, either via on-site spilling of the chemicals or fracturing fluid at the mixing station or via when hydraulic fracturing fractures straight into the drinking water supply source. (U.S. EPA, 2016, pp. 16, 18, 29).

Another component of hydraulic fracturing is the management of flowback water, water that is produced from the well immediately after hydraulically fracturing, and produced water, water that is produced along with the gas over the life of the well (Clark et al., 2013, p. 11832). Flowback water will generally contain fracking fluid constituents, the chemical additives and proppants, as well as chemicals created by the chemical additives reacting in the well, and small amount of formation water(U.S. EPA, 2016, p. 30). Formation water is naturally occurring water in the gaps inside the rock bed. Produced water, consisting mainly of formation water with a small portion of fracking fluid and chemical transformation products, generally contains salts (chloride, bromide, sulphate, sodium, magnesium and calcium), metals (barium, manganese, iron and strontium), naturally occurring organic compounds (benzene, toluene, ethylbenzene, xylenes, oil and grease), radioactive materials (e.g. radium), and hydraulic fracturing chemicals including their transformation products. Amounts of each chemical constituent vary depending on the location of the well, the type of rock formation, and the original chemical consistency of the fracturing fluid. (U.S. EPA, 2016, p. 29).

In the states, over 90% of the flowback and produced water from hydraulic fracturing is deposited in Class II wells. A Class II well is a man-made deep well for the specific task of disposing of contaminated water in underground formations away from drinking water resources. Only 10-20% of the water is treated at water treatment facilities. On some plays the wastewater is reused as fracking fluid, accounting for 5-20% nationally used fracking water. (U.S. EPA, 2016, pp. 34–36). An analysis of the life cycle water consumption of shale and conventional gas production done by Clark et al. (2013) shows that conventional production uses between 0.56-5.3 L/MWh (litres of water per gigajoule of natural gas produced) and shale gas production uses between 3.6-10.3 L/MWh, as shown in Figure 7 (Clark et al., 2013, pp. 11832–11833). Meldrum et al. (2013) harmonized research estimates conclude water consumption for natural gas procurement at 3.8-98.4 L/MWh and median 15.2 L/MWh and overall withdrawal at 15.2-128.7 L/MWh and median 64.4 L/MWh (Meldrum et al., 2013, p. 8).

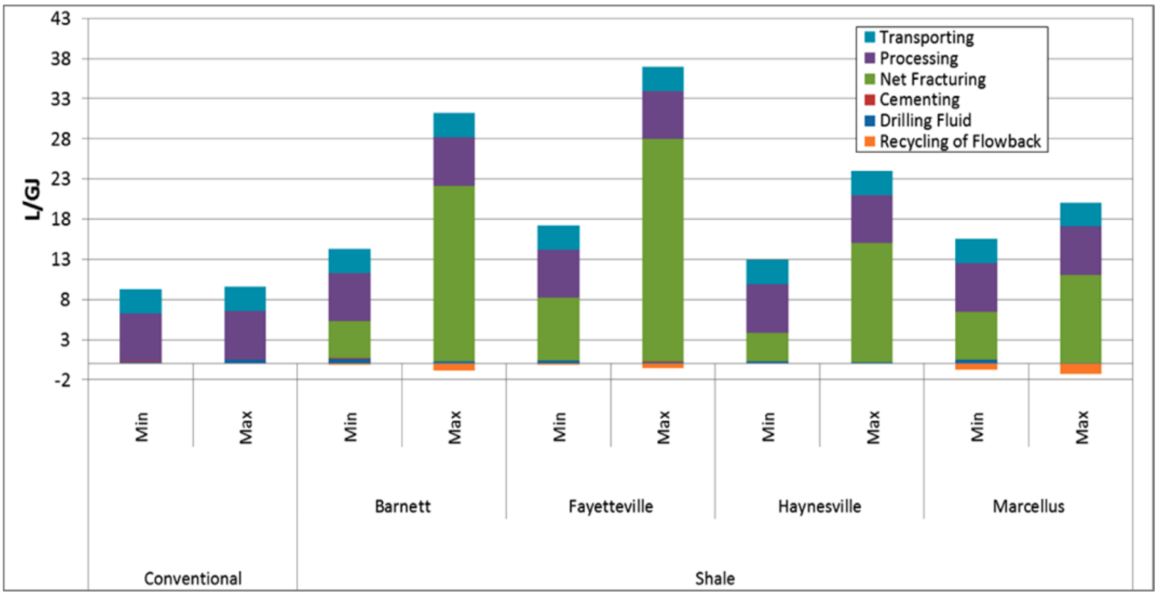

Figure 7 Life cycle water consumption of conventional and shale gas by life cycle stage within production phase of natural gas (Clark et al., 2013, p. 11833).

Over 1600 different chemicals have been identified in flowback and produced water in the United States, but analysis of their environmental effects, specifically to drinking water resources is difficult to determine due to lack of reliable data sources or data availability (U.S. EPA, 2016, p. 41). According to the U.S. EPA's findings, 98 of the chemicals identified in flowback and produced water had potential human hazards related to chronic oral exposure (i.e. digestion through drinking water) causing adverse health effects such as kidney/renal toxicity, developmental and reproductive toxicity, decreased body weight, cardiotoxicity, neurotoxicity, changes in immune system and cancer (U.S. EPA, 2016, p. 38).

3.3. Uranium

Uranium fuel life cycle includes extraction, processing, and end-of-life stages. Uranium is mined much like coal, open-mined or underground-mined (Mielke et al., 2010, p. 22). Uranium is found in nature usually as U-235 and U-238 isotopes, shares of which are 0.7% and 99.3% respectively. The natural uranium is enriched in order to gain a higher share of the fissile isotope U-235 either by a gaseous diffusion process or a centrifuge process. Uranium is mines in the form of a stable oxide U_3O_8 or as uranium peroxide in a concentrate which has to be converted into a gaseous uranium hexafluoride UF_6 as a preparatory step to enrichment. The enrichment processes are physical separation processes where the targeted U-235 UF_6 weighs 1% less than the U-238 UF_6. Nuclear power requires 4-5% U-235 concentration. According to Mekonnen at al. (2015) water use is most significant in the enrichment process of the in uranium procurement and processing life cycle stage (Mekonnen et al., 2015, p. 286). (World Nuclear Association, 2017)

Uranium is weakly radioactive and once enriched to the form of UF6 has a more significant chemical toxicity (World Nuclear Association, 2017). Environmental effects of mining are very similar to other mining processes (aquatic toxicity, acidification, human toxicity) where the main risk is contaminated runoff water or process water seeping through to the ground water streams. Uranium mining affects the quality of surface water, ground water and soil resulting in ecological effects such as aquatic ecotixicity and human ecotoxicity if contaminated water from the mining site enter water bodies via spills, leaching and surface runoff. Mine water and treated processing effluent can have high concentrations of salt, selenium, copper, aluminium, vanadium and iron, which affect the metabolism of and can be toxic to various aquatic lifeforms. Acid mine drainage (AMD) has the greatest potential for ecological damage as acidic mine water contains heavy metals (iron, manganese, aluminium, copper, chromium, zinc, lead, cobalt and nickel), metalloids (selenium and arsenic) and radionuclides decay series from U-238 (uranium, radium, thorium, and radon). Without proper environmental management of mining sites, there is significant environmental contamination potential related to risks of extreme natural events such as hurricanes, heavy rain, and droughts or accidents from human error or technical failures. (National Research Council, 2012, pp. 181, 194, 211–212, 221)

The OECD and NEA (2014) report current practices at uranium mining sites to be far more advanced in water management and claim the previously mentioned environmental risks related to water contamination to be a problem of past mining practiced (OECD, 2014, p. 60). Current leading practices in uranium mining aim at prevention and minimization of contamination by intercepting or diverting water flows from the mineralized zones, and treatment of contaminated waters either by merely reducing concentration of suspended solids or by multi-phased treatment and filtering processes which may be aimed to target specific contaminants (OECD, 2014, pp. 61–62). Successful management of mining impacts on ground water includes practice of prevention, site characterisation, monitoring, and remedial action. Proper practices of prevention include proper siting, a tailings management facility, long-term surveillance and management of the closed mining site. Site characterization entails the determining of geological structures, groundwater flows, and the velocity and depth of groundwater zones. Monitoring is responsible of detecting potential leaks and sampling soil with the aim to prevent and predict potential leakages. Remediation actions include enforcing a corrective action plan in case of leak or spill, stopping the leak or spill, and preventing further migration of contamination. (OECD, 2014, p. 63).

Water consumption and withdrawal for nuclear upstream stage, i.e. uranium mining, processing and enrichment, is dependent on enrichment process. Water consumption in centrifugal enrichment varies between 49-1135 L/MWh, with a median consumption of about 211 L/MWh. Diffusion enrichment withdraws between 234-1550 L/MWh with median withdrawals at around 529 L/MWh and consumes between 158-1249 L/MWh with a median of around 329 L/MWh (Meldrum et al., 2013, p. 10).

3.4. Biomass

Biomass has become a popular fuel in energy production in the energy sector to cut down fossil emissions in order to mitigate global warming effects. However, there are concerns as to how environmentally conscious, carbon neutral or sustainable biomass for energy is in the long run. Biomass was used to produce 462 TWh of electricity in 2013 globally, predominantly in the Americas and Europe, 80% of which was produces in cogeneration plants (World Energy Council, 2017, p. 7). Biomass for electricity is predominantly by-product, waste and residues from food, fibre and wood production (World Energy Council, 2017, p. 6). Woody biomass holds the share of 90% of all biomass primary energy supply globally (World Energy Council, 2017, p. 5), for which reason this section will concentrate on the water-related environmental effect of forest industry sourced biomass for energy. In Finland, 35TWh of cogenerated heat and electricity from biomass was produced from forest industry by-products. (Energiateollisuus, 2015)

The environmental impacts of wood harvesting include loss of biodiversity, possible forest degeneration, as well as acidification and eutrophication of surface waters from excelled bio-degeneration in soil. However, effective gathering of all forest residues at forest felling sites decreases the possible negative environmental impacts. (Energiateollisuus, 2014)

Wood is commonly sourced from economic forests which are part of the natural hydrological cycle (Salminen et al., 2017, p. 82). Forest evaporation causes 45-58% of water vapour into air from ground. There is discussion in the scientific field as to whether or not the green water footprint of boreal forest should be accounted for. As forests provide other ecosystem services than just a source for wood, it can be argued that the evaporation appropriated to roundwood should represent only a fraction of the whole. Some studies have accounted fully the forest evaporation into the footprints of wood products, whilst others argue that since rain-fed economic forests do not differ from natural forests the wood should not be attributed the forest evaporation (Salminen et al., 2017, p. 82). However, Hoekstra argues that the water evaporation appropriated by roundwood production should be accounted as total water consumption, as the water is no longer available for other uses. (Schyns et al., 2017, pp. 490–491)

The water footprints of roundwood production are calculated using forest evaporation rates. In the comparison of sub-tropical, tropical, temperate and boreal forests water evaporation rates, rather unintuitive results were found, as represented in the following figures, Figure 8 and 9. Figure 8 shows the water footprint per unit of roundwood for the biggest producing countries of roundwood and Figure 9 shows the water footprints on a global map, depicting the variations between different climate zones. (Schyns et al., 2017, p. 494).

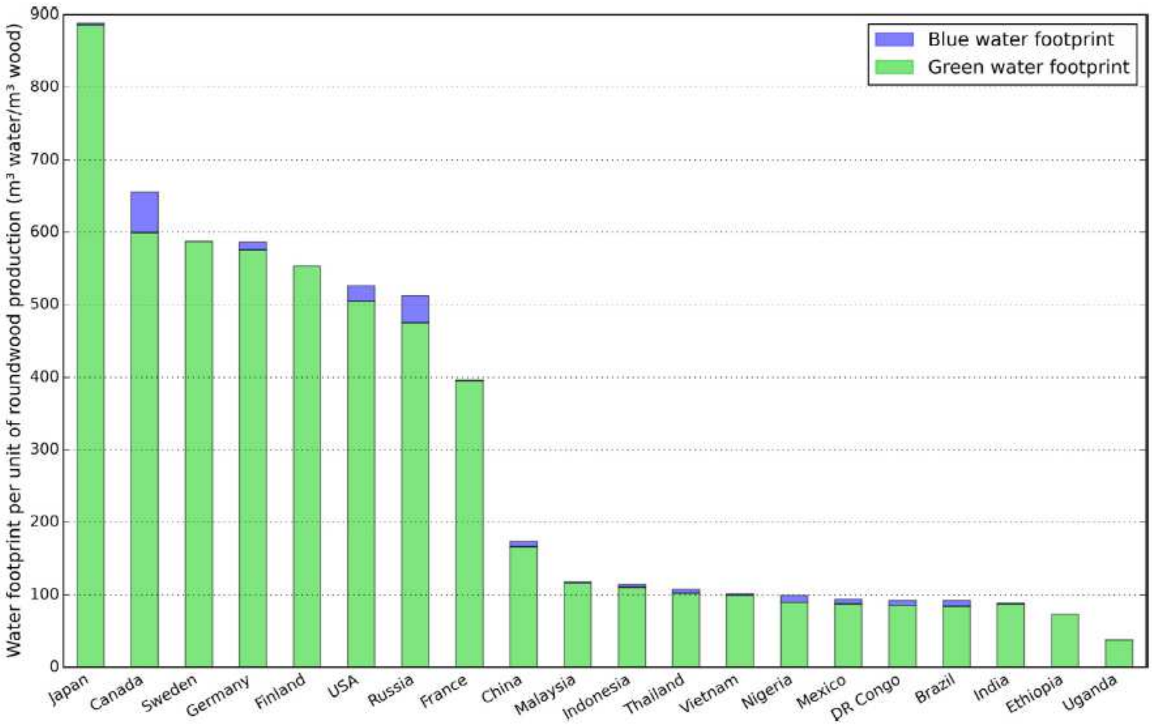

Figure 8 The water footprint per unit of roundwood production (m3 water/ m3 roundwood) for the biggest producing countries roundwood. The values represented are based on production-weighted averages. Period 1961-2010. (Schyns et al., 2017, p. 496)

According to the findings of Schyns et al. (2017) the water footprint of roundwood in boreal forests, such as found in Finland, Russia, and Canada, generally varies between 130-700 $m^3_{water}/m^3_{roundwood}$. As shown in figure 9, the water footprint of Scandinavian roundwood falls in the range of 400-600 $m^3_{water}/m^3_{roundwood}$ and averages at around 448 $m^3_{water}/m^3_{roundwood}$. Temperate forests, such as those found in the U.S., Europe and the Japans, have a higher water footprint ranging from 700 $m^3_{water}/m^3_{roundwood}$ to as high as 1631 $m^3_{water}/m^3_{roundwood}$. Tropical and subtropical forests had low water footprints, varying between 1-130 $m^3_{water}/m^3_{roundwood}$. According to the calculations by Mekonnen et al. (2015) the water footprint of wood biomass, mainly firewood, pellets, briquettes, bark, chips, charcoal, stands at a range of 172 800 – 180 000 L/MWh (Mekonnen et al., 2015, p. 5; Schyns et al., 2017, p. 499) (Schyns et al., 2017, p. 495)

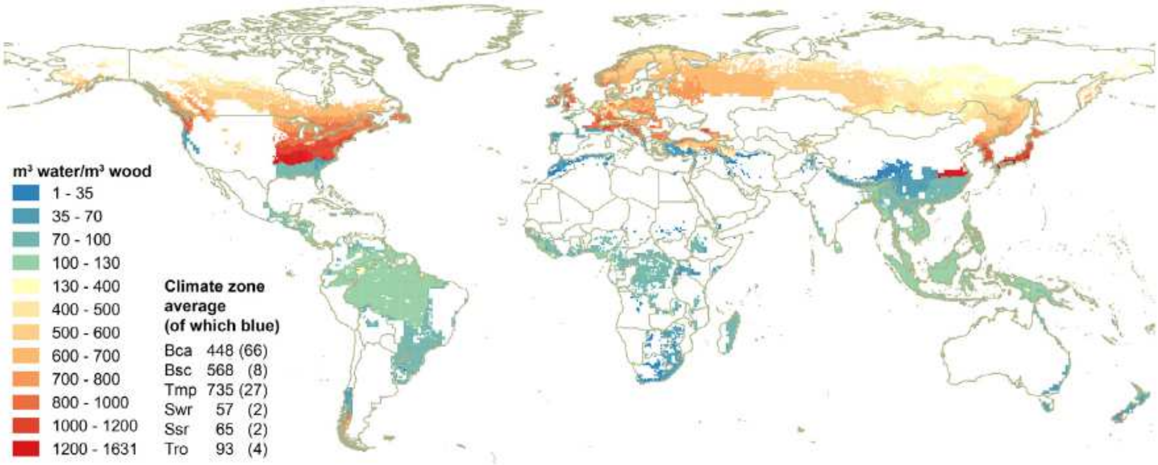

Figure 9 The water footprint per unit of roundwood production ($m^3_{water}/m^3_{roundwood}$) with legend presenting the water footprint per climate zone. The values presented are production- weighted averages calculated from data evaluated from the period 1961–2010. The presented abbreviations are: Bca - boreal, continental & arctic, Bsc - boreal, oceanic & sub-continental, Tmo – temperate, Swr - subtropics, winter rainfall, Ssr - subtropics, summer rainfall, Tro - tropics. (Schyns et al., 2017, p. 495)

Currently the issues revolving around biomass for energy are related to the loss of biodiversity, induced eutrophication and acidification and the carbon-neutrality of using biomass for fuel. As mentioned above, it is still under debate by scientists and policy-makers, whether or not the evaporation of water by forests should be allocated to the roundwood retrieved. The water footprint of roundwood presented by Schyns et al. (2017) is very substantial and may be heavily questioned as it topples the basis of biomass being a sustainable source of energy.

4 CONSRUCTION PHASE WATER-RELATED IMPACTS

This chapter will discuss the water-related environmental impacts of the three main construction materials, cement, steel and glass, used in the construction of electricity power plants or renewable technologies such as wind and solar power. Nuclear power, coal and biomass power, gas power and hydropower plants are all quite large buildings constructed of concrete and steel with large steel structures and technological machines inside and out. Solar power, both thermal and PV use steel and glass, and crystallised silicon in PV. Wind power plants are tall steel structures with a fibreglass nacelle and fibreglass blades. Concrete is often used to secure the base of the tower.

4.1 Water Use in Cement, Steel and Glass Production

Water use in the production processes of cement, steel and glass are accounted for in the whole production chain, from mining raw materials to the ready product. The production chain for steel has six steps, each with energy and process water inputs and product output. There stages are the mining of raw materials, processing (i.e. beneficiation, calcination, or coking), iron ore reduction, air separation, and steel production. Water is used in the production chain for dust suppression, cooling, BOF gas treatment, vacuum generation and washing. (Gerbens-Leenes et al., 2018, p. 3)

The consumption of fresh groundwater or fresh surface water are represented in the blue water footprint and the amount of polluted freshwater is represented in the grey water footprint (Gerbens-Leenes et al., 2018, p. 2). The amount of water considered polluted is evaluated based on the amount of pollutants discharged into the water body (Gerbens-Leenes et al., 2018, p. 2). The study by Gerbens-Leenes et al. (2018) studied the water footprint of the most common types of steel (unalloyed steel), cement (Portland cement) and glass (flat glass). About 89% of steel produced globally is unalloyed steel and chromium-nickel steel is the most common type of unalloyed steel. Most commonly used cement types are Portland cement and Portland composite cement holding an 85% share of cement used in the EU. Flat glass, used for windows and building exteriors is the most common produced glass, float glass being the most common type of flat glass. Figure 10 represents the blue water footprints of these. (Gerbens-Leenes et al., 2018, p. 4)

The grey water footprint is determined by the largest amount of critical pollutant in the polluted effluent; cadmium for unalloyed steel and chromium-nickel unalloyed steel, mercury for Portland cement and Portland composite cement, and suspended solids for glass (Gerbens-Leenes et al., 2018, p. 9). The grey water footprint was calculated using values from Ecoinvent database 3.2, and the study assumed that these values depict the grey water footprint of the contaminated water after water treatment. However, this may not be the case and the Ecoinvent values may represent untreated polluted water, thus the results for the grey water footprint presented in the study by Gerbens-Leenes et al (2018) would be a lot larger than in reality. The grey water footprints of these are presented in figure 11 below. (Gerbens-Leenes et al., 2018, p. 10)

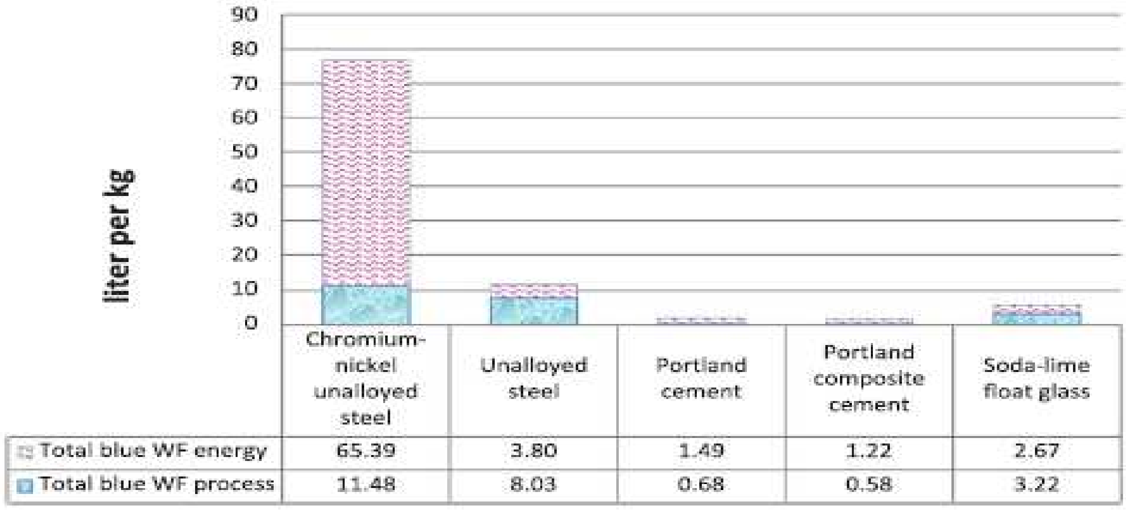

Figure 10 Blue water footprints of chromium-nickel unalloyed steel, unalloyed steel, Portland cement, Portland composite cement and soda lime float glass for production and energy related to production process. (Gerbens-Leenes et al., 2018, p. 7)

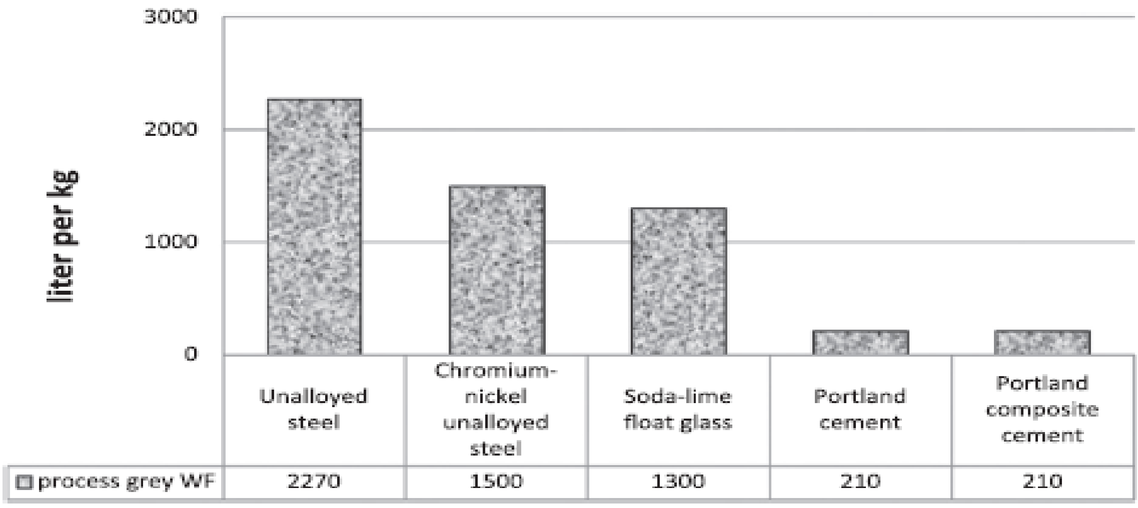

Figure 11 Grey WF of the production process of unalloyed steel, chromium-nickel unalloyed steel, soda-lime glass, Portland cement, and Portland composite cement. (Gerbens-Leenes et al., 2018, p. 8)

Wind power turbines are largely constructed from fiberglass. Fiberglass production does not differ much from flat glass production, except in the forming step. In both cases water and air is used for cooling the molten glass. The water footprint for flat glass may not be applicable to fiberglass, as fiberglass fibres would cool faster than larger float glass slabs. Fiberglass products require many resins and other binding agents, which may require water to produce, to hold together the thin fiberglass strands. However, it is not known how much more or less water fiberglass production requires compared to float glass; we will assume they are the same. (Gerbens-Leenes et al., 2018, p. 4)

In a research paper by Mekonnen et al. (2015), the water footprint for construction of different energy production technologies were acquired from research done by Meldrum et al. (2013). The values for were calculated by dividing the water of construction by energy produced in a lifetime, including heat energy. Thus, the values in Table 2 for the water footprints of construction may not be fully descriptive for electricity production in the instances of fuels, which are commonly used in cogeneration. One should also take note that the rather large water footprint values for some of the construction materials, become small when compared to the lifetime length and energy produced during this time. (Mekonnen et al., 2015, p. 4)

Construction	Consumption (m3/MWh)			Withdrawal (m3/MWh)		
	Median	Min	Max	Median	Min	Max
Thermoelectric						
Coal	0.0038	0.0011	0.0984	0.0038	<0.0004	0.0454
NG	0.0038	<0.0004	0.0038	<0.0004	<0.0004	0.0038
Biomass*	0.0038	<0.0004	0.0946	0.0038	<0.0004	0.0454
Nuclear	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Renewables						
Hydro**	0.00108	0.00108	0.00108	-	-	-
PV	0.3066	0.0379	0.7949	0.3558	0.0038	6.0567
CSP	0.6057	0.3028	0.6435	0.6057	0.3748	0.6435
Wind	0.0038	<0.0004	0.0341	0.0984	0.0492	0.3142
* Same as for coal	** (Mekonnen et al. 2015, p.5)					

Most power plants are constructed with cement, steel. Solar power and wind power differ, as PV solar power technologies are constructed from a metal and glass frame with crystalized silica inside, and wind power plant are constructed from metal and fibreglass. In table 2 we can see that almost all construction require rather little water, besides solar technologies which require 100-200 times more water per produced electricity (life time)

(L/MWh) than other electricity production forms. Though the water footprint values (L/MWh) may seem small, the water is usually used within a short amount of time, rather than over the span of a lifetime. Water consumption of construction can be quite substantial, especially when location and water availability are taken into consideration.

5 OPERATIONAL PHASE WATER-RELATED IMPACTS

In this chapter, we will evaluate the water usage of power plants. We take into consideration the water use related environmental affects the power generating activities could cause. With regard to the water footprint assessment, one needs to identify the elementary water flow, the drainage basin, water availability, the water quality, amount of water withdrawal, water degradation and water consumption. Research results on operational water use of power stations have not made a distinction between use of fresh, waste or sea water, though such a distinction would shed light on the environmental effects e.g. water stress, thermal changes and effect on aquatic life (Mielke et al., 2010, p. 29).

For some energy generation technologies water has an integral part in power plant operations. Hydropower plants rely fully on water to turn its generators, while thermoelectric power plants, power plants relying on steam turned turbines to power the generators, rely on water as steam in the turbine and water for cooling. Thermoelectric power plants can be powered by combustion heat, e.g. burning coal, natural gas, biomass, powered by heat released in nuclear fission, or heated by concentrated solar radiation in CSP. Wind turbines and photovoltaic solar panels barely use water in the operational phase as during their operational phase water is used in the occasional cleaning of the surfaces, however the amounts are considered to be negligible (Mielke et al., 2010, p. 37).

5.1 Water Use in Conventional Power Plants

In thermoelectric power generating processes, high-pressure steam drives a steam turbine to generate electricity. Distilled water is used in this closed loop process as follows; heating in boiler or by other heat source, passed through turbine, converted back to liquid water in condenser and returned to boiler/or other heat source. The amount of water lost in evaporation depends on the condenser duty of the plant, which in turn is dependent on electricity generation type, and the cooling system. Environmental factors of the plant such as elevation, temperature, humidity, wind speed, and ambient water temperature affect both condenser duty and evaporation rate (Diehl et al., 2013, p. 3).

As shown in figure 12, cooling systems are categorised as once-through or closed-loop cooling, where once-through systems are wet cooling systems, and closed loop cooling systems can be wet of dry. Once-through cooling systems, also referred to as open loop cooling, withdraws water from a water body, such a river, lake or sea, passes the water through the condenser/heat exchanger and discharges the water back to the water-body. The water is returned unchanged at a slightly higher temperature and possibly some trace residual chemicals. Some water is consumed due to increased evaporation because of the water being of a higher temperature on return to the natural water body. Figure 13 below shows a depiction of a once-through cooling system. (IAEA, 2012, p. 22)

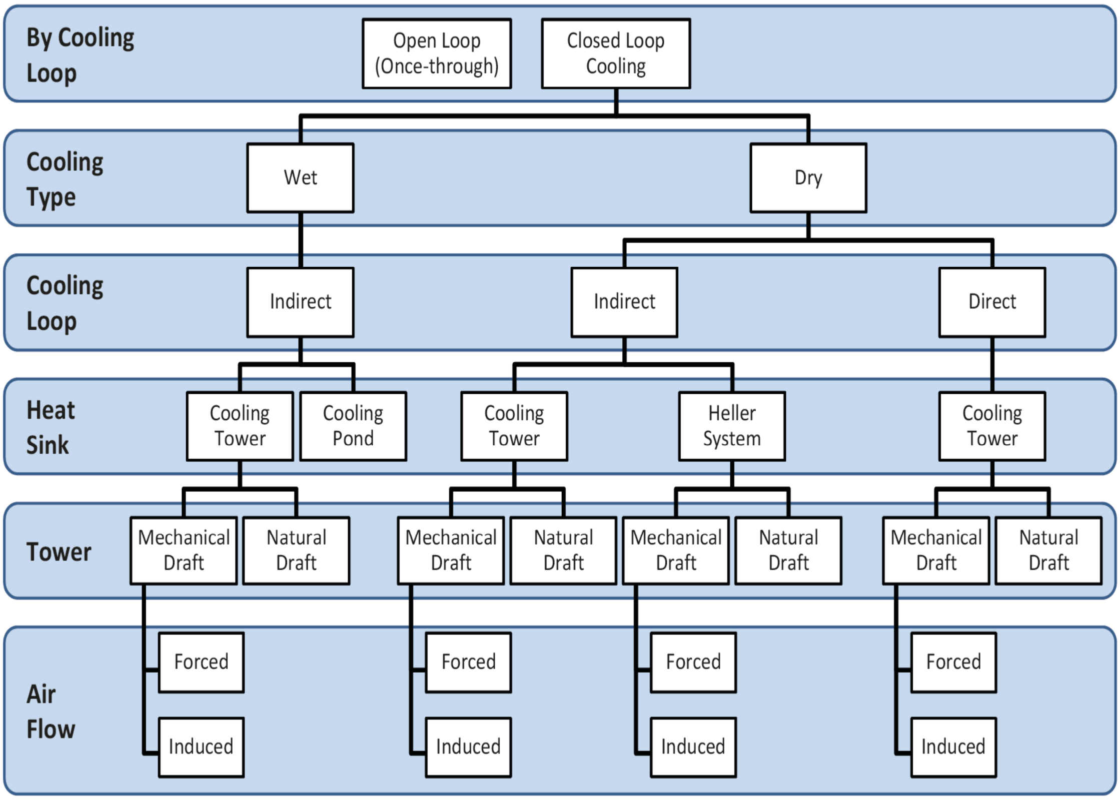

Figure 12 Classification of cooling systems for thermoelectric power plants.(IAEA, 2012, p. 21)

In closed loop cooling, also referred to as closed-cycle cooling, the water is passed via a condenser and further pumped to a cooling source, cooling tower or cooling pond, where the heat of the water transfers to ambient air. Closed-loop cooling can be wet, dry or a hybrid (both wet and dry), however we will mainly consider wet tower cooling, as depicted in figure 14. Closed loop cooling withdraws less water from the environment than open loop cooling, but the evaporation is much larger, which often translates to higher water consumption, as seen in table 4 later in this section.

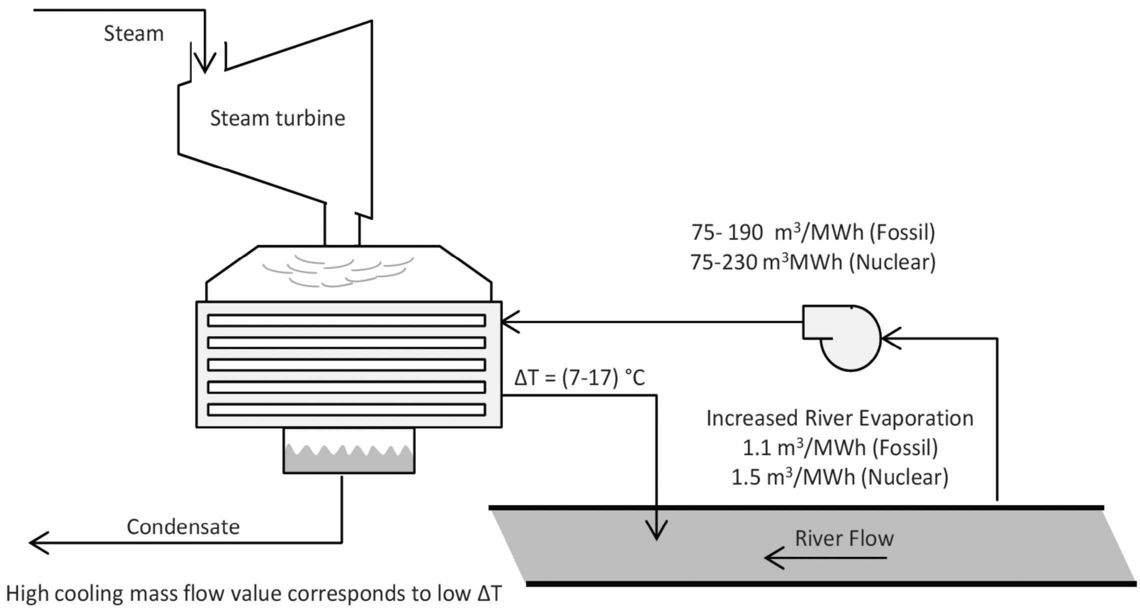

Figure 13 Once-through, also known as open loop cooling.(IAEA, 2012, p. 22)

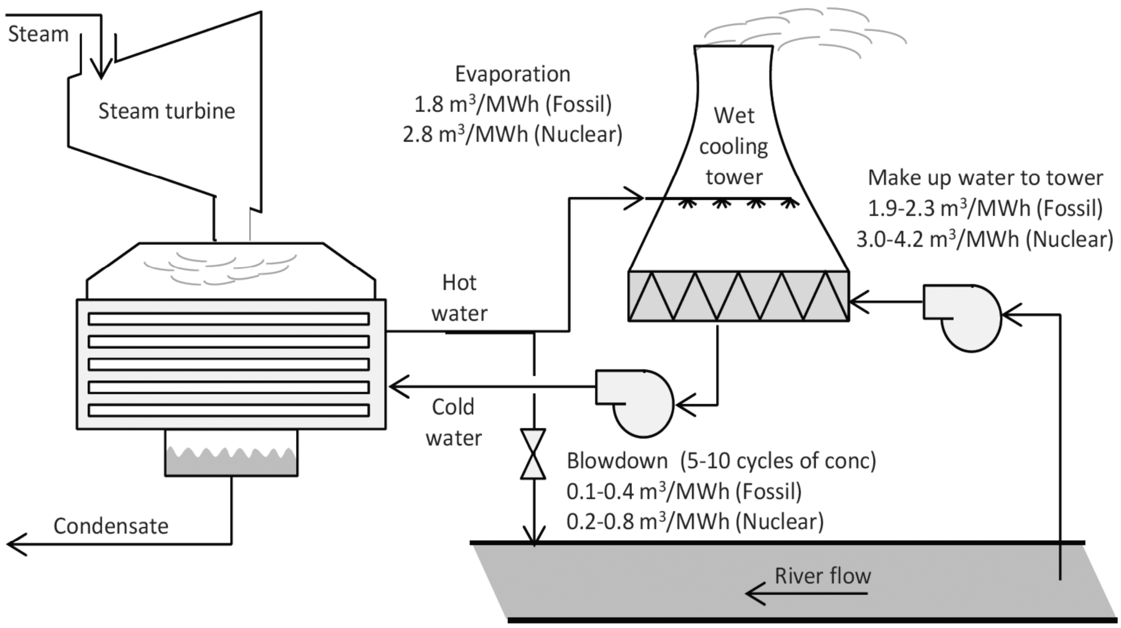

Figure 14 Closed-loop cooling with wet cooling tower (natural draft).(IAEA, 2012, p. 24)

Once-through cooling methods have extremely large withdrawal factors. The once-through cooling system withdraws 178 000 L/MWh in nuclear, 132 500 L/MWh in coal and 34 000 L/MWh in natural (NGCC) (Meldrum et al., 2013, p. 14). Water withdrawal of closed loop systems vary depending on whether they have pond cooling or tower cooling. Pond cooling withdraws more water e.g. 378 000 L/MWh for coal, 22 700 L/MWh for NGCC, but only 4 350 m3/MWh for nuclear. Tower cooling systems withdraw far less, e.g. 550 L/MWh for coal and only 950 L/MWh for NGCC. However, actual consumption of water is largest with cooling tower or pond-cooling systems, whilst the open-loop cooling systems consume only a fraction in comparison. (Meldrum et al., 2013, p. 13)

Water may also be used in other power plant processes such as, pollution control of NO_x, SO_x, FGD (flue-gas desulphurization) in coal plants, and CSS (carbon capture and storage) at plants using fossil fuels (Macknick et al., 2012, p. 2). U.S. National Energy Technology Laboratory reported the water use these additional power plant processes of flue gas treatment and ash handling, as shown in table 3 below.

	Coal-ash handling	NOx control	SOx scrubbing	Dry FGD	Wet FGD
m3/MWh	0.587	0.045	0.227	0.151	0.265

It is unclear, however, as to whether or not the water-use of additional power plant operations has been included in the relayed water footprint of coal and biomass burning thermoelectric power plants provided by Meldrum et al. (2013). Meldrum et al. (2013) also analysed the data of coal and natural gas power plants water use with and without CSS, and found operational water consumption increased by 75-80% , and water withdrawal increased by about 80-104% with CSS due to lower power plant efficiencies and additional process demands. (Meldrum et al., 2013, p. 7)

5.2 Water Use in Nuclear Power Plants

Nuclear power plants are thermoelectric power plants, which generate electricity from the turning of the turbine with steam, in this case heated by nuclear fission. Thus, nuclear power plant water consumption and withdrawal is also dependent on condenser duty and cooling system type. Nuclear power plant operational water withdrawal and consumption are shown in figures 15 and 16 in the previous section. Nuclear power plants have a larger consumption of cooling water because heat is dissipated solely by cooling water, and does not leave the plant in flue gas, unlike in combustion power plants (Diehl et al., 2013, p. 21).

However, nuclear power plants also use water in other power plant processes. Spent nuclear fuel is stored in large constructs, spent fuel pools. Spent fuel pool can be in-reactor pools, as in fuel pools in the fuel building or in independent buildings ISFSI's (independent spent fuel storage installations). These spent fuel pools are also actively cooled due to due to decay heat from the fuel and are cooled in the same way operational steam is cooled; the pools will often have a series of cooling circuits, each connected to their own set of heat exchangers connected to the cooling system. Unfortunately, there does not seem to be data on how much water is consumed into the use of these spent fuel pools. (IAEA, 2012, p. 10)

5.3 Hydropower

Hydroelectric plants cause significant environmental impact on the immediate environment. The change in water flow both upstream and downstream changes the ecosystem balance. Habitat diversity is affected due to the changes in flow and sediment regimes, and the distortion of the natural temperature layering. The altered temperature regime increases the productivity of certain species causing in a decrease in species diversity. The change in sediment regimes caused by the turbulent flow of water affects the nutrient balance of the water, which in turn has resulted in an increase in phytoplankton populations. The diversity of fish species is also affect, where some populations grow and others dither. (Goodwin et al., 2006, pp. 255–257)

The water consumption of hydroelectric power plants can be determined as the amount of evaporation caused by the creation of damns and large artificial water reservoirs. The water footprint is thus the amount of evaporated water (yearly) divided by the amount of energy generated (that year). There is a large variation in the water footprints of hydroelectric stations around the world, ranging from a mere 1080 L/MWh in San Carkos Colombia, to a vast 3 081 596 L/MWh in Akosombo-Kpong in Ghana. However, a study of 35 power stations shows common evaporation rates between 2000-3000 mm/year, with the subtropics having slightly higher evaporations rates than the more temperate areas. Mekonnen and Hoekstra (2012) find that the amount of evaporation, i.e. water consumed, is not linear to the amount of electricity produced, but rather the water footprint is influenced by the reservoir area flooded per installed capacity of the hydroelectric power plant. Although, evaporation is also affected by local climate, in the end, the water footprint increases with the area flooded per installed capacity. (Mekonnen and Hoekstra, 2012, pp. 179–180, 182, 185)

The water footprint of hydroelectricity is rather large, in fact, according to a comparative study by Mekonnen et al. (2015) on the consumptive water footprint of select electricity production methods, hydroelectricity has the highest consumption. As the size of a water footprint depends on the size of the flood plain and not electricity production, the values vary on a wide spectrum from 1 080 - 666 000 L/MWh, with median values falling between 3 420 - 497 000 L/MWh (Mekonnen et al., 2015, p. 5). Some may argue, that since the flood plains caused by the hydropower reservoirs create added value, such irrigation, water supply and leisure qualities, it may not be reasonable to allocate the full evaporative consumption to hydroelectricity production (Mielke et al., 2010, p. 38).

5.4 Solar and Wind Power

Wind and photovoltaic (PV) solar power do not use water in their operational processes, which is why their water consumption and withdrawal are negligible. Washing PV panels frequently increases efficiency of electricity production; it also leads to economic losses. Wind turbines also require little no washing and maintenance. Concentrating solar power (CSP) uses mirrors to reflect solar thermal heat from a wider area to heat one small concentrated area. The heat is used to convert process water into steam in conventional thermoelectric power plant. Water footprint values for Wind, PV and CSP are presented in table 6 below. (Meldrum et al., 2013, pp. 11–12)

Table 2 Water consumption footprint (gal/MWh) of wind and solar (PV and CSP). Conversion 1 gal/MWh = 3.78541 L/MWh (Macknick et al., 2012, p. 5) *(Meldrum et al., 2013, p. 13)

Fuel type	Cooling	Technology	Median	Min	Max
PV	N/A		3.79	0.00	18.93
Wind	N/A		3.79	0.38	34.07
CSP	Tower	Trough	3429.58	2744.42	4198.02
		Power tower	2975.33	2842.84	3452.29
		Fresnel	3785.41	3785.41	3785.41
	Hybrid	Trough	1279.47	442.89	1502.81
		Power tower	643.52	386.11	22.71

Concentrating Solar Power is one of the most common large-scale solar thermal power generation methods, has very high water consumption. CSP as thermoelectric power stations use water for cooling likewise to conventional power plants. CSP facilities also use water for cleaning mirrors and heliostats (Macknick et al., 2012, p. 2). Only about 10% of operational water-use of CSP is used for mirror cleaning, and the remaining 90% of water used is consumed in the cooling systems. The most common CSP technology is the parabolic trough with re-circulating cooling. (Mielke et al., 2010, p. 36)

5 CONCLUSIONS: THE OVERVIEW OF LIFE CYCLE WATER FOOTPRINT OF ELECTRICITY GENERATION

This chapter will discuss the information provided in previous chapters in an attempt to evaluate the overall water consumption and water-related environmental impacts. In previous chapters, we have discussed the water-related environmental impacts of the production of fuels, of the construction of power plants and technology and of operational electricity generation. Below, Figures 15 and 16, present the life cycle water withdrawal and consumption of electricity production by generation type and fuel type, including these 3 life cycle phases, not including biomass.

Section 2 discussed the water footprint of the procurement of roundwood biomass for fuel, which concluded that the water footprint of biomass is substantial. The water footprint of Natural gas was the smallest 15 L/MWh, shale gas values were generally about double that of NG, and followed by coal at 212 L/MWh, uranium at 329 L/MWh and lastly roundwood biomass at a whopping 172 800 – 180 000 L/MWh. The water footprint of roundwood stands orders of magnitude larger than fossil fuels or nuclear, to which end Mekonnen et al. (2015) argue that using wood to fuel electricity and heat production is not a sustainable solution to the problems facing our planet. (Schyns et al., 2017, p. 499)

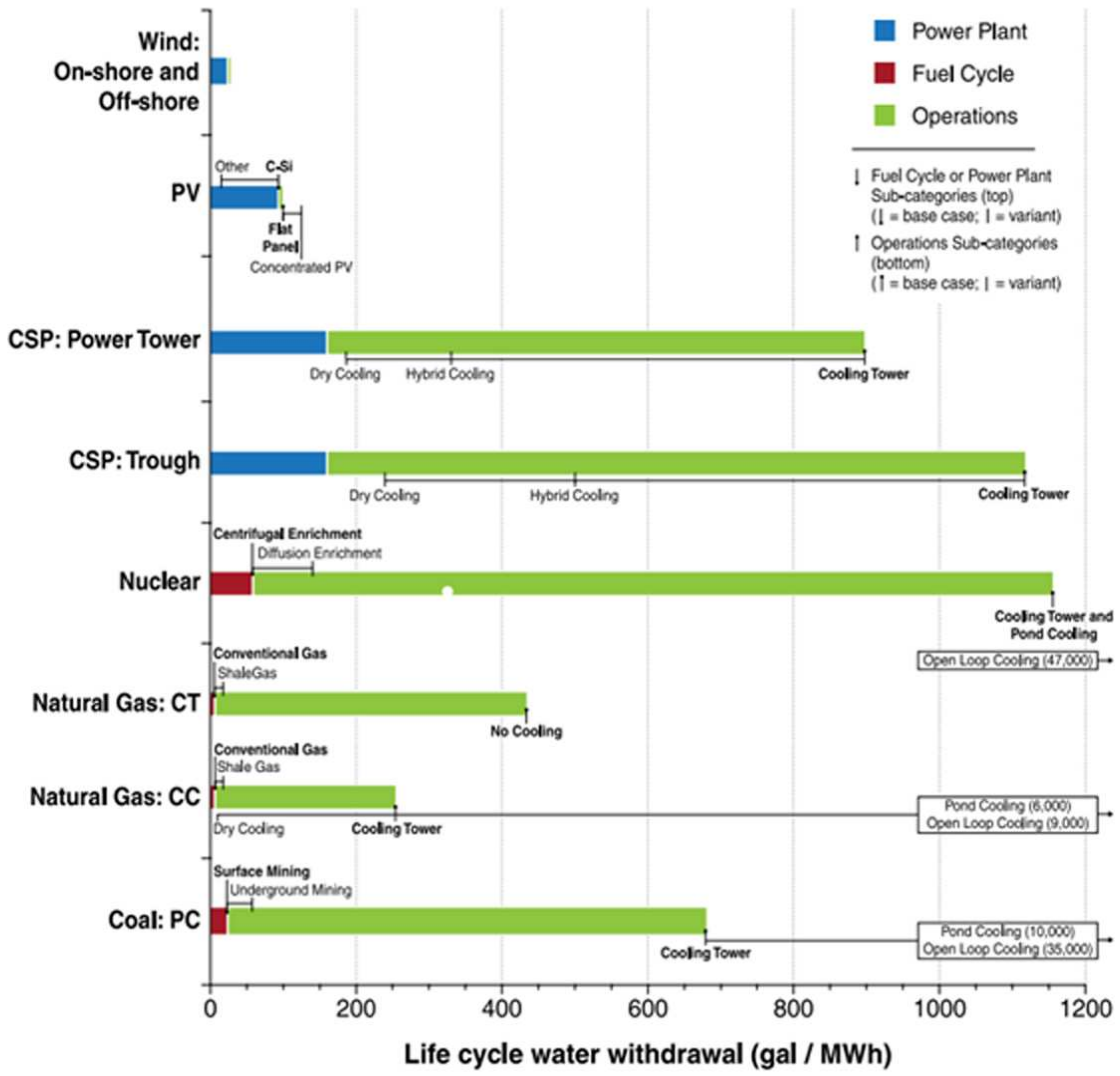

Figure 15 Life cycle water withdrawal of electricity production systems. The green bar shows operational water use, separately marked with the median harmonized estimates of each cooling system. (Meldrum et al., 2013, p. 14)

As concluded in Section 4, the weightiest water footprints seem to be caused in the operational phase, not taking into account bioelectricity. For thermoelectric power plants, the extent of operational water consumption and withdrawal was dependent on the cooling system. Open-loop, or once-through cooling, had the largest withdrawal, but turned out consumed far less water than the closed-loop cooling systems. The closed loop cooling systems does not affect the local environment with thermal pollution, whilst open-loop cooling causes rather substantial thermal pollution.

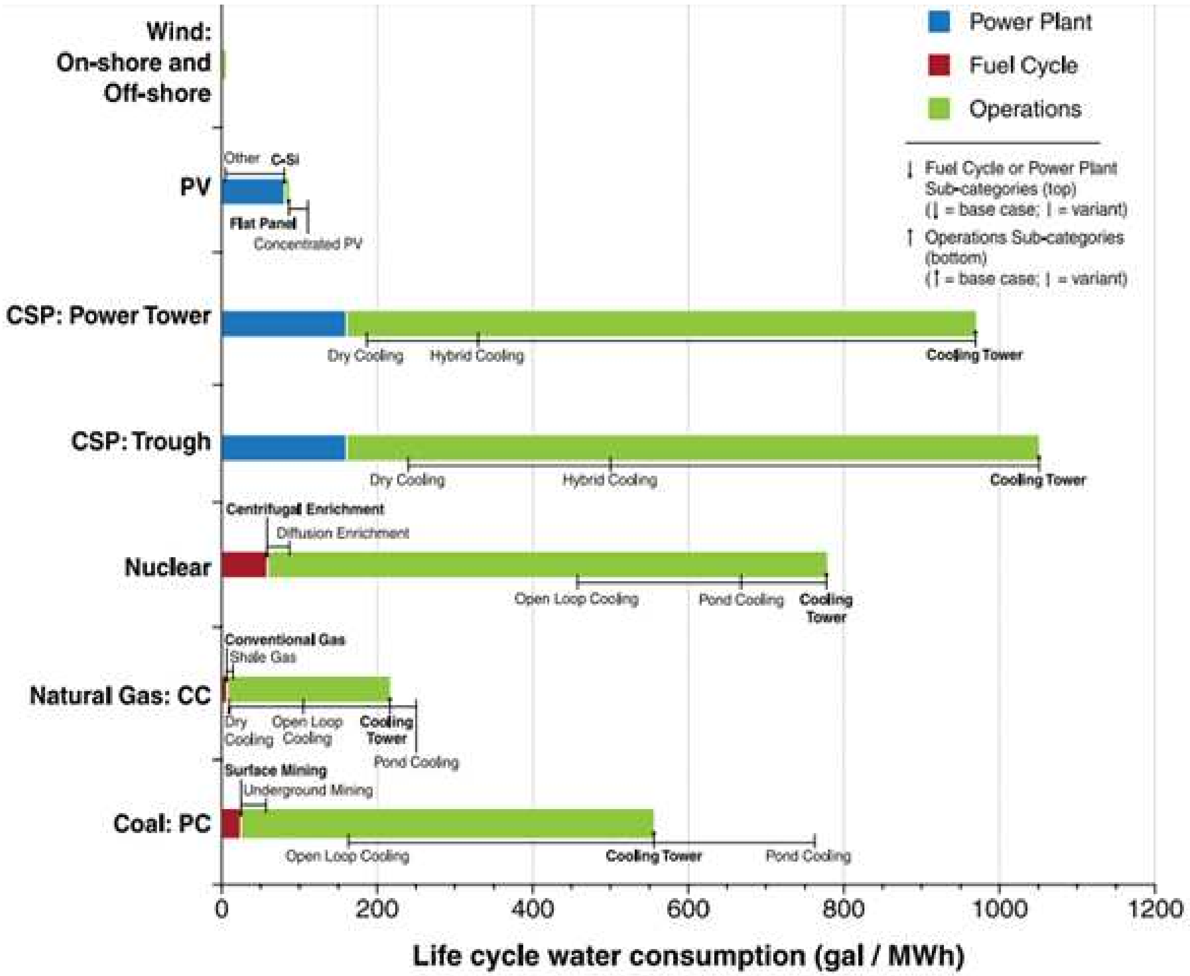

Figure 16 Median harmonized estimates of life cycle water consumption of electricity generation technologies, showing consumption of water in construction (blue), fuel production (red) and power plant operations (green). Also depicted are values for the operational water consumption by cooling system. (Meldrum et al., 2013, p. 13)

The life cycle environmental water-related impacts of each electricity generation method were evaluated based on the literature referenced in this work and graded each water-related impact category. The scale of the chart ranges from insignificant impact to excessively high impact in order to depict the relatively large differences. The shades in the first column, water footprint, are deduced based on the life cycle consumptive water footprint values represented in figure 16, with changes in interpretation to biomass and nuclear power. The overall consumptive water footprint of biomass electricity production is slightly higher than that of traditional coal. The water footprint of biomass was about 5-10 times that of coal, but since the fuel production phase of the life cycle water footprint of coal represented a small fraction (see figure 16), the added water footprint of biomass fuel brought the life cycle water footprint of biomass electricity production to similar levels as nuclear electricity. However, nuclear electricity is dedicated a darker shade for water footprint due to the unaccounted, yet probably rather substantial, amounts of water being used in spent fuel pools globally.

Table 3 A summary of the water-related environmental impacts of different electricity production technologies

	Water footprint	Water Scarcity	Eutro-phication	Aquatic Toxicity	Acidifi-cation	Thermal Pollution	Human Toxicity
Coal							
Natural Gas							
Shale Gas							
Biomass	Extremely High						
Nuclear							
Solar PV							
Solar CSP							
Wind							
Hydropower							

Legend:

Very High Impact	High Impact	Noticeable Impact	Somewhat Impact	Some Impact	No impact	No info

Water Scarcity category has been left empty since the water scarcity is tied to location and water availability. Hydropower reservoirs cause excess nutrients in the water, and the deforestation affects the soil's nutrient retention capacity, causing more nutrient runoff to surface water, which eventually leads to a water body. In mining coal, uranium, iron ore and pumping for natural gas and shale gas, the waters used were contaminated with heavy metals and acid leachate among other things. Shale gas is darker than the others are as produced waters from fracking shale contained a litany of salts, metals, and unhealthy biological compounds, as well as radioactive particles. Due to this shale also scores high in human toxicity and aquatic toxicity. Coal and uranium mining both had high risk and high probability of acid leachate reaching natural water bodies, for this reason they are marked with orange. All thermoelectric power plants using once-through cooling or wet closed-loop cooling cause thermal pollution.

In conclusion, the electricity generation systems with smallest life cycle water footprint and least impact on environment were photovoltaic solar power and wind power. Natural gas follows these, with lowest environmental impacts and lower water footprint values of all the thermoelectric power options. Solar CSP, though owning a larger water footprint than conventional power plants, showed to have the smaller environmental impact than shale, nuclear and coal powered electricity generation. Shale had a rather low water footprint, but fares worst of all fuel options in environmental impacts in fuel procurement. Nuclear power fares a little worse than coal due to higher slightly higher water footprint and larger environmental impacts in fuel procurement. Unsurprisingly, the consumptive water footprint of hydropower was among the largest and the environmental impacts of hydropower were to be expected. The water footprint of biomass places wood based bioelectricity last on the list. Some researchers argue that taking into account the evaporative water footprints by damns and forest is taking environmental sustainability assessments too far. Without the heavy weight of their water footprints, hydropower and bioelectricity would be among the least consumptive electricity generation technologies, right after wind and solar power.

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