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Energy-Water Nexus: An overview of the Finnish case

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Energia-Vesi Nexus: Yleiskatsaus Suomen tilanteesta

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Energialla ja vedellä on tärkeä merkitys yhteiskunnassa, joita ilman yhteiskunnan on haastava tai jopa mahdoton toimia. Kestävä veden- ja energiankulutus sekä tuotanto ovat tärkeitä tavoitteita tulevaisuudessa. Yksi energiatuotannon suuria haasteita on energian varastointi, mihin veden ja energian nexuksella on mahdollista luoda ratkaisuja. Lisäksi Suomessa energian tuotanto on muuttumassa entistä enemmän hajautetuksi tuotannoksi, joka tuo omat haasteensa säätökykyyn.

Työn tavoitteena on tehdä kirjallisuuskatsaus Suomessa toimiviin energia- ja vesijärjestelmiin nexus näkökulmasta tarkastellen. Termi nexus tarkoittaa asiayhteyksien kytköstä ja sanan alkuperä pohjautuu latinan kielestä. Energia-Vesi Nexus tarkoittaa energian ja veden yhteyttä, mikä pohjautuu energiantuotannon vedenkäyttöön sekä veden ja jäteveden energiankulutukseen. Työn alkupuolella tarkastellaan veden ja energian yhteyttä teorian näkökannalta. Työn toisessa osiossa tarkastellaan Suomessa käytettäviä energia- ja vesijärjestelmiä. Pääasiassa tarkasteltavia energianlähteitä ovat vesivoima, biomassa, aurinkoenergia, tuulivoima ja ydinvoima. Energia- ja vesijärjestelmiä tarkastellaan työssä saatavissa olevan datan ja tutkimusten avulla. Lopussa energia-vesi nexusta tarkastellaan lyhyesti joustavuuden näkökulmasta. Kun tarkastellaan energia-vesi nexusta Suomen näkökulmasta, otetaan huomioon Suomen energia- ja ilmastostrategia. Työssä pyritään selvittämän, kuinka merkittävä vaikutus energia-vesi nexusella on Suomessa. Lisäksi selvitetään, kuinka tehokkaasti energia-vesi nexus:ta olisi mahdollista hyödyntää Suomessa.

Tutkielmassa tarkkaan lopputulokseen ei päästy, mutta huomattiin aiheen lisätutkimuksen tarve. Kuitenkin suuntaa antavia päätelmiä saatiin kuten, että biomassan tuotannolla on suuri vedentarve verrattuna muihin energianlähteisiin. Biomassan tuotannon vedenkulutusta on tärkeä tutkia, koska Suomen energiantuotanto hyvin riippuvainen bioenergiasta. Suomessa tulevaisuuden energiastrategioiden muodostamisessa olisi mahdollisesti tarve huomioida paremmin vedenkäyttö ja energianlähteiden joustavuus mahdollisuudet. Lyhyessä Tampereen Vesi case-tutkimuksessa huomattiin, että energiakäyttö vesi- ja jätevesilaitoksilla on pysynyt lähes samana vuosien ajan, mikä voi indikoida energiatehokkuuden tasaantumista. Kuitenkin lisätutkimuksia vaadittaisiin vesi- ja jätevesilaitosten energiatehokkuudesta ja energiantuotannon omavaraisuudesta sekä jätevedenpuhdistuksesta biomassaa tuottavilla laitoksilla.

Asiasanat: Nexus, Energia, Vesi, Suomi

ABSTRACT

Energy-Water Nexus: An overview of the Finnish case

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Energy and water have a significant relationship in energy and water systems. Sustainable energy and water consumption and production are becoming increasingly important. In today’s world, energy and water are basic needs for humans. The Finnish government aims to be carbon neutral by 2035, which will significantly impact the energy sector. Finland is moving away from fossil fuels and increasing renewable energy production. Renewable energy production commonly needs greater system flexibility since flexibility depends on circumstances, conditions, and resources. The increasing amount of renewable energy and decentralized production will create challenges for the Finnish energy system. Finnish water system requires energy during each process stage. Biogas is also produced from sewage in Finland. Thus, water system can impact the energy system in many ways.

The thesis will discuss the Energy-Water Nexus from a Finnish perspective. The word nexus denotes connection between systems or situations. Energy-Water Nexus means connection between water system and energy system. Research methods include a literature review and a briefcase study. The first chapter discusses nexus at a theoretical level: energy use for water and water use for energy. The second chapter includes the Energy-Water Nexus in Finland, where energy and water systems are described and evaluated. Energy sources chiefly included are hydropower, solar power, wind power, biomass, and nuclear power. The end of the second chapter shortly discusses Energy-Water Nexus from a flexibility perspective. Lastly, results are analyzed and discussed. Finnish energy and climate strategy are used as a peer material when results are analyzed. The thesis aims to convey, how efficiently Energy-Water Nexus is utilized or could be utilized in Finland.

The thesis suggests biomass, nuclear power, and hydropower to have the most significant water demand during the full life cycle. However, reached results are estimations and cannot be considered utterly correct. Biogas production from sewage will unlikely offer significant benefits to the Finnish energy industry, but it might offer on-site flexibility for treatment plants. Finnish water and wastewater treatment plants' energy efficiency occurs to have remained at an even level during recent years. However, further studies are required to investigate water and sewage treatment plants' energy efficiency, self-sufficient energy production, and effective wastewater treatment in biomass plants. Further research on Energy-Water Nexus is required in the future.

Keywords: Energy-Water Nexus, Flexibility, Finland

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LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
CHP	Combined Heat and Power
DR	Demand Response
EWN	Energy Water Nexus
GDP	Gross Domestic Product
GW	Gigawatt
GWh/a	Gigawatt-hours per annum
kWh/m^3	Kilowatt-hours per cubic meter
L/kWh	Liters per kilowatt-hours
Mm^3 /a	Cubic megameters per annum
MWh/a	Megawatt-hours per annum
PJ	Petajoule
TWh	Terawatt-hour
WCC	Water Consumption Coefficients

1 INTRODUCTION

Energy and water are strongly linked in today's world since energy production relies on water usage and vice versa. By 2035 the Finnish government aims to become carbon neutral, which increases the demand for flexible energy systems. Aim to be carbon neutral will also increase multi-energy-system use since it likely increases renewable energy usage. (Ministry of Economic Affairs and Employment, 2019) Energy-Water Nexus signifies the relationship between water and energy: water used for energy and energy used for water. Energy production requires water during the construction, extraction, and generation stage. Vice versa, water and wastewater treatment and distribution require energy during the transmission, wastewater collection, treatment, distribution, and sludge disposal. (Adamovic et al., 2019)

The European Union's target for renewable energy was 20% by 2020, and the target increases to 32% by 2030 (European Commission, 2020). Finland has reached both targets since the renewable energy share of total primary energy was 38 % in 2019, as shown in Fig.1 (Official Statistics of Finland, 2019b). Finland's energy demand has not significantly changed in recent years. However, renewable energy production has increased, and fossil fuel production has slightly decreased. (Official Statistics of Finland, 2020) In general renewable energy production systems are less flexible since many renewable energy technologies depend on weather conditions and are poorly predictable. (IEA, 2018)

Finland's extensive water resources are used sustainably if sustainability is defined by the water availability per citizen. The use of Finnish water resources could make water-intensive energy production justified. The Energy-Water Nexus (EWN) might have beneficial opportunities in Finland since water-intensive energy production is highly used, for example, nuclear power and hydropower. Hydropower is one of the most flexible energy systems in today's Finland. However, hydropower is highly regulated, why it has limited opportunities in Finland. (Klimstra and Hotakainen, 2011) New energy and water technologies will likely increase energy system flexibility in Finland, for example, new heat storage systems such as rock cavern heat storage (Helen Oy, 2018).

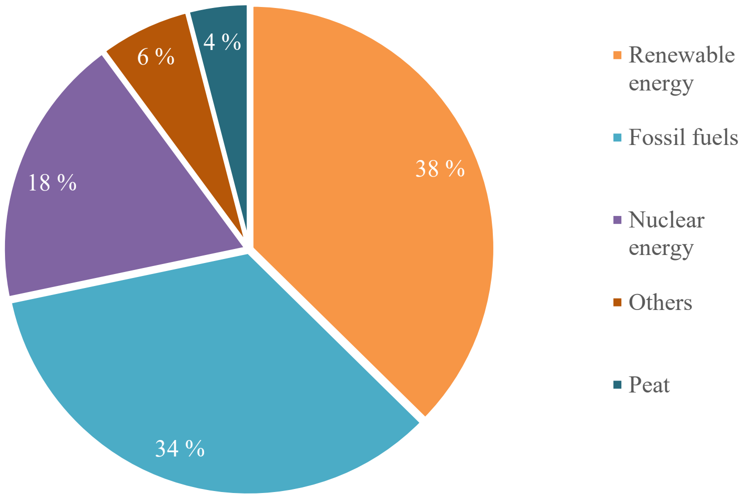


Figure 1. Primary energy sources in Finland 2019. (Official Statistics of Finland, 2019b) (retell)

Key issues the thesis will aim to examine are, how is Energy-Water Nexus used in Finland? Which EWN systems are already flexible, and have they reached their full potential? How extensive is the potential for Energy-Water Nexus in Finland? The thesis will shortly investigate the future of Finland's energy production and consumption. The target of being carbon neutral by 2035 will be the guideline for the energy sector's improvements, and consequently, it will be shortly discussed in the thesis. The thesis will discuss Finnish water demand, utilization, and energy production relations by utilizing previous research literature. Energy sources discussed are biomass, nuclear power, hydropower, solar, and wind power, but some other energy sources will be shortly mentioned in the thesis. Finnish water and wastewater treatment will be discussed by utilizing data from the treatment plants. In Addition, a case study about Tampereen Vesi is made to investigate water and sludge treatment plants' water demand, energy demand and energy efficiency.

2 ENERGY AND WATER

2.1 Water use for energy

Today, the global energy sector has a relatively low water demand; water consumption accounts for roughly 3 % of the global water consumption and water withdrawal accounts for 10%. (International Energy Agency, 2018a) However, the energy sector is a significant water user in Europe; for example, energy sector's water usage is more considerable than water use in agriculture. Energy-related water consumption has many challenges since water availability issues have increased around the world. Globally, energy consumption has increased, and water availability decreased, which has significant consequences on multiple levels. Both energy and water are crucial resources, which are linked to each other. (Adamovic et al., 2019) Water efficiency also correlates with energy production's water demand since high water efficiency will likely reduce water demand. The energy sector can improve water efficiency by water recycling, improving non-freshwater use, increasing power plant efficiency, and making changes to technology and fuel mix. Many current energy scenarios expect the energy sector's water consumption to increase by 2030 since some low-carbon technologies have comparatively high-water demand. (International Energy Agency, 2018a)

Water can be utilized directly or indirectly for energy. Direct use of water is, for example, the amount of water required for cooling. Indirect use of water is, for example, the water demand for producing energy technology and equipment. Furthermore, water can be utilized either by using or relocating water during energy production. For example, hydroelectric energy is produced by generating electricity from the water movement. Water use during energy production is, for example, water use during cooling of the energy production plant. Hydropower highly relies upon the inflows to the reservoirs, but the reservoirs can also be utilized as energy storage. Hydropower provides the most remarkable connection between energy and water; for example, it is able to provide flexibility for energy balancing and serve energy storage purposes. (Adamovic et al., 2019)

The European energy sector can be divided into four parts: extraction of fossil fuels, energy infrastructure construction, manufacturing of energy equipment and electricity, steam, gas, and air supply. During the extraction of fossil fuels, water is required for oil and gas extraction and coal mining. Coal mines mainly require water for dust suppression, washing, and transportation. Water is needed to provide primary energy and can also be utilized for cooling and heating purposes. (Adamovic et al., 2019)

Energy sector's water use is defined by estimating water consumption factors and withdrawals. Operational constraints for water are driven by water availability and water temperature. Water withdrawal was 74 billion m^3 by the European Union's energy sector in 2015, which included electricity transformation, transformation into derived fuels, and primary energy production. However, the energy system consumes 6 % of the required water withdrawal, and the remaining 94 % could be returned to water reclaiming. (Adamovic et al., 2019) Globally, the energy sector consumed about 50 billion m^3 and withdrew 340 billion m^3 in 2016. Most of the water was withdrawn by the power sector since coal-fired power generation utilizes over one-third of the water withdrawals. Primary energy production consumes the highest amount of water, over two-thirds, when biofuel production consumes about 30% and fossil fuel production 40% of the energy sector's water use. (International Energy Agency, 2018a)

Thermal power plant's performance depends on the amount of water available for cooling. During cooling processes, the water temperature will affect the efficiency of the thermal plant. (Adamovic et al., 2019) The chosen cooling system may impact water efficiency, but two factors must be considered: water withdrawal and consumption. Tower cooling has a low water withdrawal rate, but the consumption rate is high. Once-through cooling systems are considered the most efficient, but the water withdrawal rate is high. (International Energy Agency, 2018a)

Power generation is commonly divided into dispatchable and non-dispatchable power generation. Distribution systems are highly dependent on the form of power generation, dispatchable or non-dispatchable power generation. Dispatchable power generation includes primary energy sources, such as biomass, hydropower, and natural gas. Wind and solar power are considered non-dispatchable power generation sources. Dispatchable power generation corresponds with demand flexibility since dispatchable power generation has a few comparable properties with energy storage systems. Dispatchable power generation offers some flexibility for energy balancing; for example, hydropower plants can release power generation during low electricity demand. Commonly water use during operation is low for non-dispatchable power generation compared to dispatchable power generation. Some studies anticipate water use for energy to increase in the future because of biofuels and unconventional fossil fuels. Water may also be utilized for handling solid waste, which is utilized in some power plants. (Meadow, 2014)

2.2 Energy use for water

The water sector utilizes multiple different processes, such as groundwater and surface water extraction and distribution, water treatment, and wastewater treatment. Each process has a specific energy demand; for example, the water supply demands a high amount of electricity. (Adamovic et al., 2019) Water cycle technologies and location determine the needed intensity of energy consumption in each stage. (Lienhard V, Plappally, 2012)

Water extraction begins with water pumping from lakes, rivers, groundwater aquifers, and oceans. Location and water flow impacts the energy consumption during water pumping. More specially, the energy efficiency in water pumping might depend on the friction factor, pump technology, pipeline, and the diameter of pipeline and pipeline material. (Lienhard V, Plappally, 2012) Commonly surface water requires less energy to access than groundwater due to longer pumping distances. (Dale et al., 2017) In 2016, industrial water withdrawal was 1 417 000 000 m^3 per year in Finland. (Food and Agriculture Organization of the United Nations, 2016) Extracted water commonly requires multiple different treatments to remove micro-organisms, solids, and organic compounds. Usually, water extraction requires a low amount of energy. However, more saline seawater requires demanding desalination treatments due to dissolved ions. Hence, seawater desalination demands higher consumption of energy compared to less saline waters. (Lienhard V, Plappally, 2012)

After treatment, water usually must be either cooled down or heated up. During water heating and cooling, the temperature difference defines the amount of energy required for heating and cooling of the water. However, different heating and cooling solutions may have a significant impact on electricity demand. High energy factor reflects a high energy efficiency in water heating; for example, heat pump heaters own a high energy factor. (Lienhard V, Plappally, 2012)

During wastewater treatment, energy consumption depends on location, plant size, type of impurity, used process type for treatment, received quality of water, discharge quality, and end-user type. Wastewater comes from residential, industrial, or commercial use, and the quality of wastewater may vary significantly. Treatment may include three stages that are primary, secondary, and tertiary treatment. A tertiary process will be utilized if wastewater contains higher amounts of phosphorus and nitrogen. Usually, the primary treatment process consists of wastewater collection, chemical treatment, removal of hard materials, and sedimentation. Stabilization, aeration, clarification, and membrane bioreactor processes are used in the secondary process. Energy consumption during wastewater treatment may be determined by the impurity type. (Lienhard V, Plappally, 2012)

3 ENERGY-WATER NEXUS IN FINLAND

3.1 Finnish energy system

Finnish energy production is highly decentralized and consists of various energy sources such as nuclear energy, coal, and hydropower. Fossil fuels cover about one-third of Finnish primary energy, and nearly 40 percent becomes from renewable energy sources. (Official Statistics of Finland, 2019b)

In 2018 total energy consumption in Finland was approximately 1375 PJ (Official Statistics of Finland, 2020). Furthermore, The Gross Domestic Product in Finland (GDP) was 275,9 billion US dollars, and GDP in Germany was 3,949 trillion in 2018 (The World Bank, 2020). Compared to Germany's 12 963 PJ energy consumption in 2018 (AGEB, 2018), energy consumption per GDP is approximately 50% times higher in Finland than in Germany. Furthermore, a similar result is received by counting energy consumption per capita. Energy consumption per capita is approximately 60% times higher in Finland than in Germany (Eurostat data browser, 2020; AGEB, 2018; Statistics of Finland, 2020). Finland's energy consumption is reasonably high because of the cold climate and energy-intensive industries. However, total energy consumption has remained at the same level for years in Finland, which indicates that energy efficiency has increased, as shown in Fig. 2. (Statistics of Finland, 2020)

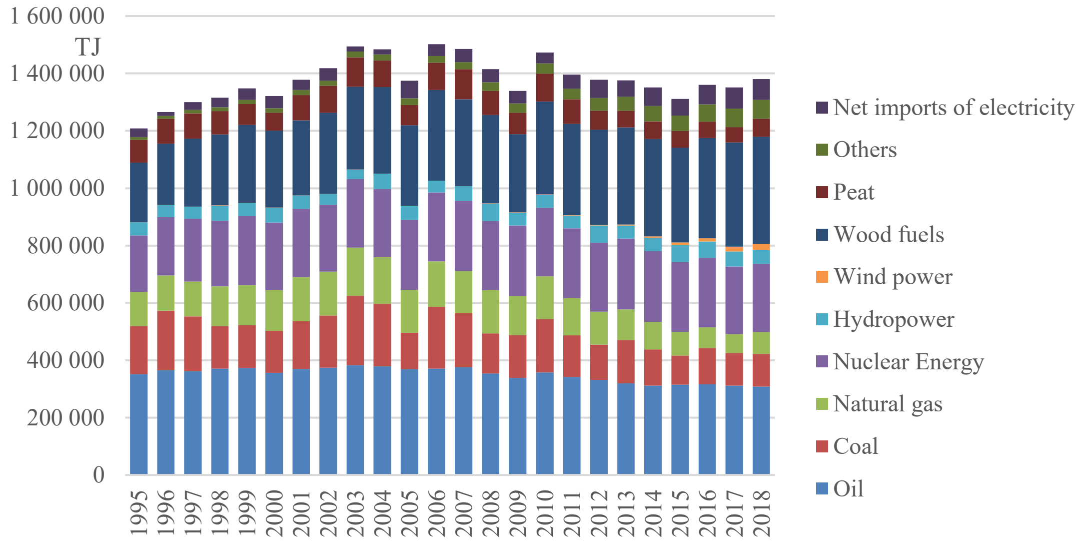


Figure 2. Energy consumption in Finland, 1995-2018 (Official Statistics of Finland, 2019a). (retell)

Energy-intensive industries, for example, the forest and steel industries, have excellent energy efficiency in Finland. For example, if energy consumption by manufacturing from the year 2007 is compared to 2018, manufacturing consumed 16% less energy in 2018 with approximately the same industrial output. (Official Statistics of Finland, 2018) Finnish industry consumed 47.8% of the overall final energy consumption in Finland, but energy consumption has dropped about 8% since the peak in 2006 (International Energy Agency, 2018b). For example, Wood fuels are the most used energy source in manufacturing, covering approximately 40% of the entire manufacture industry's energy consumption in Finland 2018. Since 2007, fossil fuel consumption has decreased, but wood fuel utilization had increased by 10% in 2018. (Official Statistics of Finland, 2018) In 2016, 57% of the total final energy consumption was consumed by the paper, print, and pulp industry. However, biofuels control industrial heat production, but fossil fuels still account for 24% of the produced industrial heat. (International Energy Agency, 2018b)

The transport industry consumes energy generally from oil, but the share of biofuels has risen. The share of oil was 94.3% of the energy consumed by domestic transport in 2016. A small share of electricity and natural gas is utilized in domestic transport. The amount of biofuel consumed by the transport industry can vary annually. In 2016, biofuels accounted for 4.1% of the transport sector's energy consumption. (International Energy Agency, 2018b)

In Finland, buildings typically use electricity and district heating as an energy network source. One-third of the overall energy consumption by buildings was supplied by district heating, which is generally generated in co-generation plants. Two-thirds of the entire residential heating was consumed by space heating and one-third by water heating in 2016. Energy-efficient technology is highly used in new buildings, but older buildings commonly have lower energy efficiency. Over 60% of the energy consumed in residential buildings is utilized for water and space heating. Fossil fuel consumption accounted for 36% of the overall energy consumption by buildings in 2016. The remaining 64% was consumed by low-carbon energy. Fossil fuel consumption has decreased from 80% to 54% between 2006 and 2016 in district heating production. In the climate and energy strategy, district heating production's use of wood-based fuels is estimated to increase from the current 14 TWh to approximately 30 TWh by 2030. Other renewable energy sources have been estimated to increase to 5 TWh, which primarily replaces coal-based energy production, which will be phasing out. The public and commercial sectors also utilize district cooling, which accounted for 205 GWh in 2016. However, district cooling use is low compared to district heating, but demand is increasing. The increase of district cooling depends on competitiveness while being compared to other cooling technologies, such as heat pumps. (International Energy Agency, 2018b)

Finland has a well-structured energy system, which has a diverse production mix. Used electricity and heat production systems are CHP-systems, district heating, district cooling and electricity generation systems. A diverse production mix eases demand response during peak hours and therefore increases energy system flexibility. Nearly 80% of generated electricity were emission-free in Finland, 2015. The Finnish energy sector is aiming to be carbon neutral and utilize multiple renewable energy sources. (Energiateollisuus, 2020) Electricity consumption peaks are commonly from 7 to 9 am and from 6 to 9 pm in Finland; during that period, coal power plants are frequently utilized to respond to electricity demand. (Sitra, 2017) However, the Finnish energy sector also utilizes the Nordic energy market to import electricity during peak hours (Ministry of

Employment and the Economy, 2014). Finnish electricity generation is based on alternating current, and the frequency of alternating current describes the balance between electricity consumption and production. Thus, balance is required between energy demand and production. (AFRY, 2019)

Biomass, nuclear power, and oil account for most of the primary energy supply in Finland. Finland has one of the largest shares of waste and biofuels in the total primary energy supply, which covers over half of the domestic energy production. Domestic primary energy production accounted for slightly over half of the Finland's overall primary energy supply in 2017. Renewable energy production has increased steadily during the last decade, and waste and biofuel production's average annual growth is approximately 3%. However, the share of solar energy has remained at a low level in primary energy production. Combustion fuels are used to respond to seasonal variations of electricity demand. Hence, during winters, the district heating demand is the highest, and it is often generated by combustion fuels. Biofuel use varies between seasonal changes, but the variations are relatively low. Hydropower, nuclear power, and the share of imported electricity remain comparatively stable during seasonal changes. (International Energy Agency, 2018b)

Approximately 200 hydroelectric power plants are located in Finland, which is crucial to the Finnish energy system. The annual share of hydropower is controlled by water supply, reflecting upon fossil fuel use in electricity generation. In Finland, hydroelectric power production might vary 10%-20% annually since water availability varies. The total hydropower capacity is 3 190 MW, but 13 137 GWh of electricity were generated by hydropower in 2018 (Motiva, 2020a). Hydropower production is very decentralized in Finland, which improves electricity supply security. If required, electricity is imported from the Nordic electricity market, commonly from Norway or Sweden, where hydropower has a large share of the total electricity production. (Energiateollisuus, 2020) Hydropower is the only energy technology that offers electricity flexibility for all periods from the second to annual level. (AFRY, 2019)

Finland’s national energy and climate strategy depends on nuclear power and biomass energy. Nuclear power will most likely peak in 2030 since new investments, besides currently under development projects, are unlikely due to current political acceptance and high cost. The basic scenario predicts wind power to reach an off-shore capacity of 6 TWh and an on-shore capacity of 30 TWh. However, the prediction of potential wind power production varies considerably in different reports. The growth of solar energy depends on the economic viability of small-scale production. However, photovoltaic energy has great potential in Finland. Thus, solar electricity capacity would correspond with 13 TWh/a if all rooftop areas would be utilized. (Ministry of Economic Affairs and Employment of Finland, 2017)

3.1.1 Water withdrawals and consumption for energy pathways

The Study from 2018 estimates water consumption coefficients for renewable energy power generation. The paper assets the total life cycle water footprint for different renewable energy pathways. However, nuclear power is included in the paper. The United States and Canadian electricity generation and water systems differ from the Finnish energy system and water system, which causes difficulties in data comparison. Data about water consumption for electricity generation is commonly limited by data quality and availability. Water consumption factors are determined by calculating water consumption coefficients (WCC), including 6 merit factors and different conversion efficiencies. Merit factors 3 and 5 are required to calculate WCC, and merit factor five is used to wind, hydroelectricity, and solar photovoltaic technologies. Merit factor 3 includes the rest of the technologies, but all the merit factors were established from the conversion efficiencies and water demand coefficient's base case values. Data were collected from several different literature sources, but some technological methods differ from Finland's technological methods. (Ali, Kumar, 2017)

Water consumption factors for renewable electricity technology pathways differ significantly across and within technology groups. Electricity generation technologies were sorted by cooling technology. Biomass has the highest water footprint, which varies within feedstocks and cooling technologies, as shown in Fig 3. Biomass power generation pathways vary between 260 – 1289 L/kWh. Biomass power generation has the most negative effect on the water requirements since water is required during the agriculture stage. Biomass is divided into four classifications by the main raw materials: corn stover, wheat straw, wood chips, and switchgrass. Furthermore, biomass power generation is divided into different pathways: direct combustion and bio-oil combustion. Bio-oil has the highest water consumption if produced from wood chips and utilized by once-through cooling. (Ali, Kumar, 2017) In Finland, biomass production commonly utilizes wood-based feed. (Motiva, 2020b)

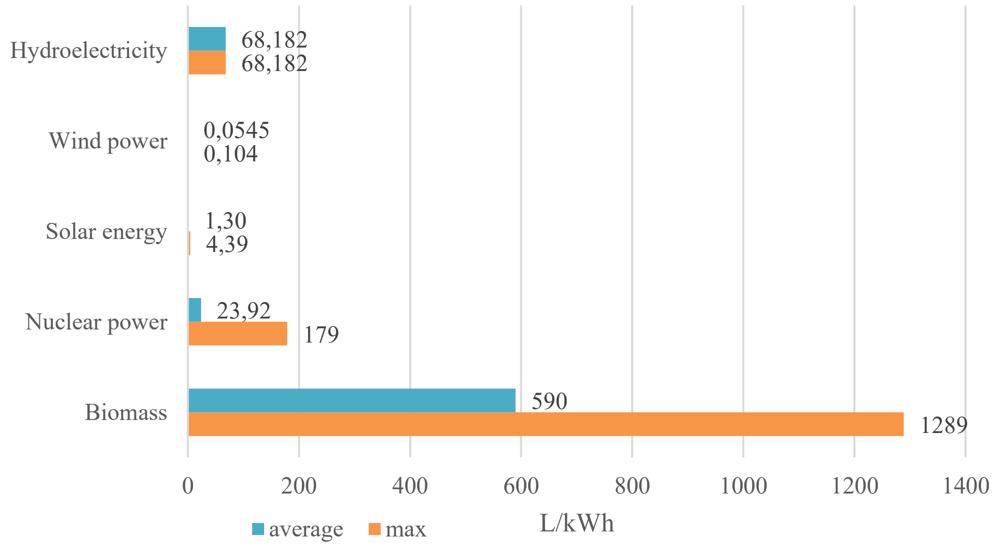


Figure 3. Calculated water consumption coefficients for renewable energy and nuclear power pathways. (Ali, Kumar, 2017)

PV and wind power technologies utilized a moderate amount of water compared to other technologies. Furthermore, wind power and solar power mainly consume water during material extraction, manufacturing, and construction stage. Solar power generation includes solar-thermal and photovoltaic technologies, and within both occur multiple different technological solutions. In the operational phase, photovoltaic power requires a minimal amount of water for panel washing. Solar-thermal power generation consumes a moderate amount of water during operation, water for cooling. Wind power does not require a cooling system, but the operation period requires a minimal amount of water. Most of the water is required for the construction and cleaning of the turbines. (Ali, Kumar, 2017)

The paper states that nuclear power has a high-water withdrawal coefficient because of the steam cycle. Choice of cooling technology can also affect on water demand, especially for power generation. Most of the water is consumed by evaporation from reservoirs in hydropower generation, but the initial construction stage requires water since the upstream construction stage, mining, and extraction demands water. If power generation is solely considered, the maximum water consumption coefficient is in hydropower generation. The highest consumption coefficient is due to the high amount of water consumed by evaporation in reservoirs. (Ali, Kumar, 2017)

The life cycle water footprint of nuclear power can be calculated, but nuclear power's determination should be considered. Uranium has been estimated to support the world's energy requirements for about 1000 years, but by this definition, nuclear power cannot be a long-term energy solution. However, the quantity of uranium required to produce 1 GW of energy is extremely low compared to other energy sources, such as biomass or coal. (Cohen, 1983; Ali, Kumar, 2017) Uranium also occurs in water, rocks, and soil, but in very low quantities. Hence, uranium for nuclear power is mined as a uranium ore since extraction from the lower quantity sources is not commercially viable. (U.S Department of Energy, 2020) If the lower quantity sources would be considered, nuclear power might perhaps be considered sustainable. From this perspective, nuclear power might be considered sustainable if the cost and the quantity of energy sources required during the production would be considered in the evaluation.

As shown in the paper, the choice of cooling technology significantly impacts water demand for power generation. Especially biomass and nuclear power can highly benefit from suitable cooling technology choices. (Ali, Kumar, 2017) Biomass as an energy source consumes a high amount of water (Ali, Kumar, 2017), which could be concerning since biomass is highly used in Finland. However, most of the forest-based energy is produced either as a part of the pulping process or by wood by-products, such as bark and sawdust. The sustainable energy use of wood is an essential part of a versatile and resource-efficient forestry industry in Finland. In the future, forestry-based energy is predicted to increase, and especially the amount of residual forestry liquor is likely to increase. (International Energy Agency, 2018b)

An increase in forest-based energy would compensate for fossil fuels and peat energy since it will be required to aid the phase-out of oil and coal. However, biomass has limitations because of availability and sustainability. (International Energy Agency, 2018b). In Finland, many CHP-plants have changed input from fossil fuels to biomass due to climate strategy. Biomass resources can be utilized competitively, which can threaten the increase of bio-CHP. Biomass has many benefits, for example, it can respond to high electricity demands during winter, and it has the capacity of dispatchable generation. These predictions are based on basic scenarios shown in the Energy and Climate report for 2030. Nowadays, forest-based energy is already utilized more than other forms of renewable energy. (Ministry of Economic Affairs and Employment of Finland, 2017)

3.2 Finnish water system

The Finnish water system can be divided into wastewater and sludge treatment, water treatment, and water supply. Energy consumption is highest in wastewater and water treatment since treatments require different mechanical, biological, and chemical treatment. (Motiva, 2019a) Sewage sludge may be further utilized as biogas, which can be used on- or off-site (Lantz et al., 2007).

In water treatment plants, energy consumption consists of raw water pumping to the treatment plant, electricity generation in water purification, water pumping between water treatment units, and pumping required for distribution network. However, electricity is required for chemical supply, but it requires a slight amount of electricity. Energy consumption and the amount of treatment required for water treatment depends on the raw water source. The Finnish water supply database (VEETI) indicates that the average energy consumption of surface water treatment plants was 0,97 kWh/m^3 and groundwater treatment plants' average energy consumption was 0,78 kWh/m^3 in 2015 (VVY, 2020). Groundwater sources are not available at every site, but surface water quality is excellent in Finland compared to many other countries. If groundwater quality is excellent, moderate water purification or even no purification is required. Nonetheless, surface water requires treatment in several stages since surface water contains impurities and humus. Different water disinfection methods: chlorination, ozone, and ultraviolet require electricity depending on the utilized technology. (Motiva, 2019a)

Finland uses multiple different wastewater treatment technologies, for example, simultaneous biochemical precipitation and mechanical wastewater treatment. In Finland, wastewater treatment consumes over 50% of the energy during aeration process, and the total energy consumption is between 0,1 to 2 kWh/m^3 in wastewater treatment, as shown in Fig. 4. Energy consumption decreases if oxygen demand and air supply are optimized. The required amount of aeration depends on the wastewater impurities, plant type and technology, temperature, nitrogen load, and BOD load. Moreover, pumping consumes energy between 5 to 15 % of the total energy consumption in wastewater treatment, and the highest amount of energy is consumed during intake pumping. (Motiva, 2019b)

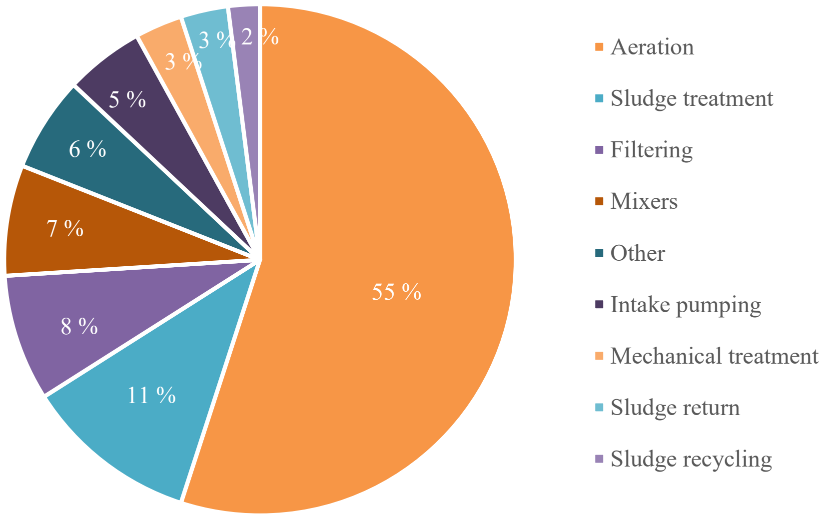


Figure 4. Aeration consumes the highest amount of energy in wastewater treatment. Pie chart illustrates energy consumption in each wastewater treatment stage. (Motiva, 2019b) (retell)

About 70% of the sewage sludge is decomposed in Finland; hence biogas production may be profitable in wastewater treatment (Motiva, 2019b). Approximately 0,583 PJ of biogas is produced annually by wastewater treatment plants, but it merely covers 0,000424% of Finland's total energy consumption. However, industrial wastewater treatment and co-digestion plants produce biogas, but the production is more small-scale in Finland. (Huttunen, Kuittinen and Lampinen, 2017) Biogas from sewage sludge can merely serve a small degree of flexibility for the total Finnish energy demand since it produces less energy than other forms of energy production. (Lazarevic, Valve, 2020) The energy contained in wastewater can be recovered by digestion or heat recovery. Biogas production can cover 50-70% of the energy requirements for the process. Biogas production and utilization is an excellent example of EWN in wastewater treatment. However, if biogas production is to be maximized, inorganic material must be minimized in sludge digestion. (Motiva, 2019b)

Data comparison from the Finnish water supply database, VEETI, shows that biogas production can nearly cover some water supplier's electricity demand, as shown in Fig 5. However, not all water suppliers perform well in this comparison, which could be due to the high cost of biogas production. Increasing self-sufficient energy production water suppliers could produce energy that has a low water demand, such as solar energy. However, the VEETI database did not specify the categories of electricity generation. (VEETI database, 2020).

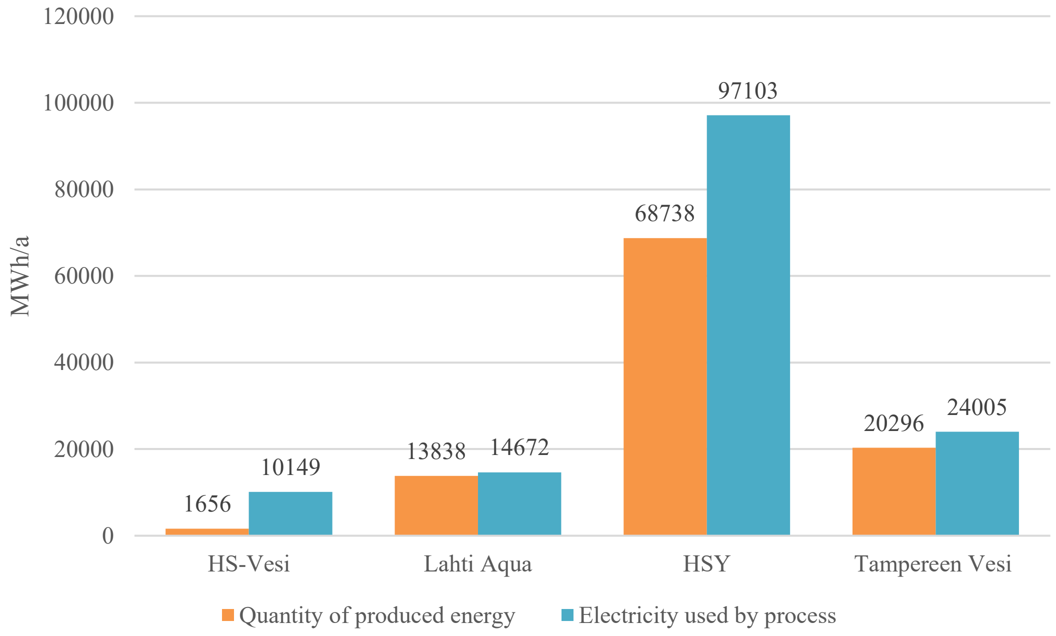


Figure 5. Energy production and electricity use by four different Finnish water suppliers in 2019 (VEETI database, 2020).

Some water suppliers utilizes a share of the produced biogas for onsite use; for example, HS-Vesi used 1273 MWh/a for onsite use, when total energy production was 1656 MWh/a in 2019 (VEETI database, 2020). Biogas production from sewage sludge has a great benefit since biogas can serve multiple end-use options. Biogas can be utilized for on-off-site energy production, for example, to electricity or heat production. Biogas can also be refined into transport fuel or industrial fuel. When energy demand is high, biogas from sewage sludge could be utilized for off-site use. Biogas for on-site use could be utilized during low demand. Hence, biogas from sewage sludge can offer energy demand flexibility. (Lantz et al., 2007) VEETI database also specified fuel oil and natural gas consumption, but many water suppliers did not utilize natural gas or fuel oil during production. (VEETI database, 2020)

Sewage sludge can be utilized for biogas production, but biogas plants are merely profitable for large wastewater treatment plants. In Finland, 18 sludge digesters are located next to wastewater treatment plants. However, smaller size treatment plants can utilize sewage sludge into biogas in Co-treatment plants. In Co-treatment plants, sewage sludge is commonly utilized with municipal bio-waste. Biogas plants have a high investment cost; therefore, biogas plants are economically viable for large wastewater plants. Biogas from sewage sludge contains 60% methane and 40 % carbon dioxide, and the average heat value is about 6,0 kWh/m^3. (Motiva, 2019b) Biogas plays an essential role in Finnish energy and climate strategy since it is a valuable renewable biofuel and energy source. It has been estimated that biogas production from sewage sludge can only increase slightly in the Future. (Ministry of Economic Affairs and Employment of Finland, 2017)

3.2.1 Case study: Tampereen Vesi

Tampereen Vesi has gathered a small energy report about energy consumption in water treatment plants. In 2015, Rusko, the main water treatment plant, distributed 12,5 Mm^3/a to the water network, and the water treatment plant utilized electricity 6,9 GWh/a. (Motiva, 2019a) About two-thirds of the domestic water is from surface water, and one-third is generated from groundwater to Rusko water treatment plant (Tampereen Vesi, 2020a). In Rusko water treatment plant, water pumping and treatment consumes approximately 77% of the required energy for water treatment and distribution.

Viinikanlahti wastewater treatment plant consumes electricity 9,0 GWh/a. The amount of sewage disposed is 26 Mm^3 /a in Viinikanlahti wastewater treatment plant. (Motiva, 2019a) The wastewater treatment plant produces biogas as a disintegration product from the digestion, which is utilized for electricity and heat purposes. (Tampereen Vesi, 2020b)

Rusko water treatment plant and Viinikanlahti wastewater treatment plant consume two-thirds of the total energy consumption in Tampereen Vesi. (Motiva, 2019a) As shown in Fig 6, sewage treatment and water treatment consume nearly the same amount of energy. Energy consumption has remained at the same level for years, and consumption will unlikely increase or decrease much in the Future, as shown in Fig.6.

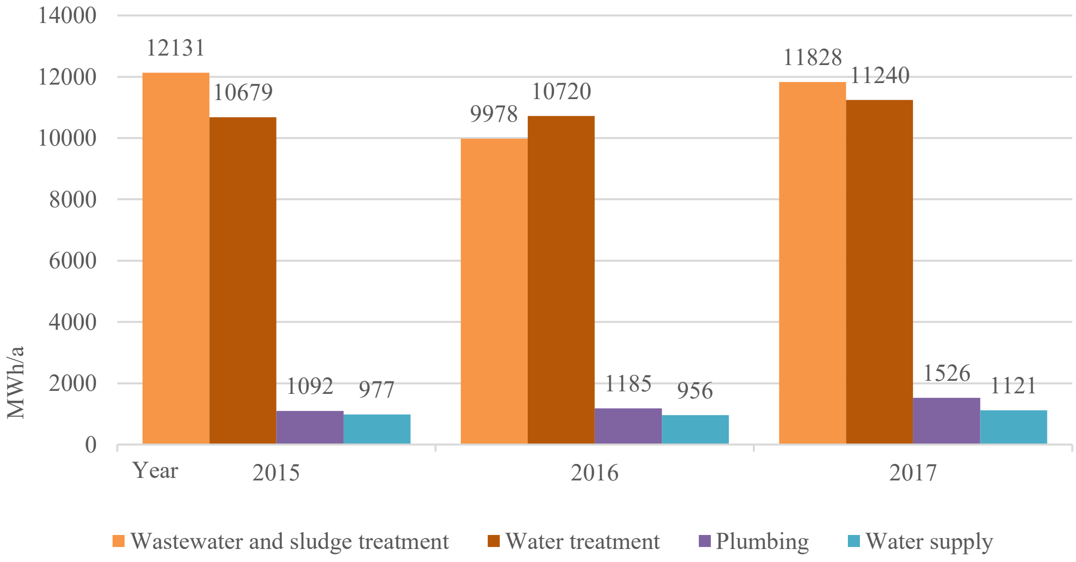
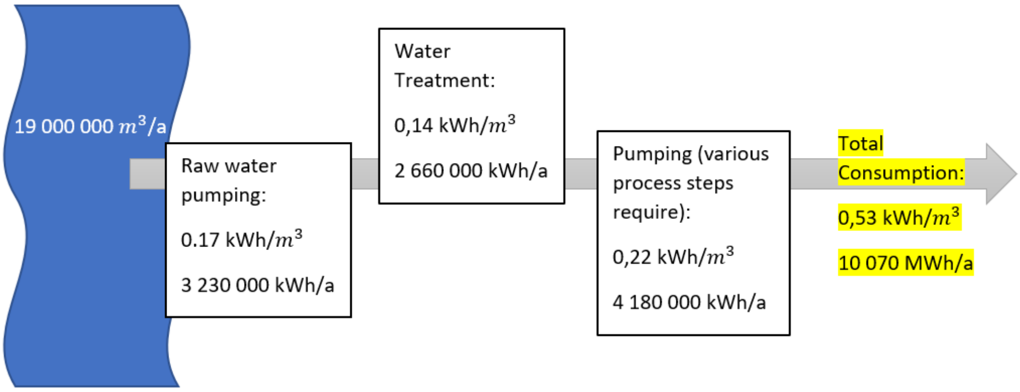


Figure 6. Calculated energy consumption in different water supply and sewerage process stages at Tampereen Vesi (VEETI database, 2020).

Power usage was determined in each water treatment process stage. Pumping from freshwater sources consumed cumulative energy of about 0.17 kWh/m^3 as shown in Pic.1. The least amount of cumulative energy was consumed in the processing stage, about 0,14 kWh/m^3. However, water pumping is required in various process steps during the water treatment process, which causes it to consume the most amount of electricity during the water treatment process. Pumping during different process stages consumes 0,22 kWh/m^3, and the total power consumption was around 0,53 kWh/m^3. (Motiva, 2019a)



Picture 1. Cumulative energy consumption is illustrated in different water treatment stages by using Tampereen Vesi as an example. (Motiva, 2019a)

3.3 Energy-Water Nexus and Flexibility in Finland

Energy flexibility term can be defined to describe the potential to balance demand and generation by regulating power generation and demand when an unusual deviation occurs in the system. Load fluctuation, outages, and power fluctuations might be due to flexibility issues in power generation. Renewable energy sources are commonly less flexible than other energy sources, which might cause issues. Flexibility can be divided into heat production flexibility and electricity generation flexibility. Furthermore, flexibility procedures can be divided into categories: energy storage, dispatchable generation, increased interconnection, and demand management. (Siemonsmeier et al., 2018)

Flexibility can be further divided into short-, mid- and long-term flexibility. Short-term electricity flexibility is commonly from seconds to few hours, which batteries and industrial demand response can provide. Short-term flexibility is utilized to balance errors on demand and supply and optimize daily grid. Distributed resources can benefit from short-term flexibility. Mid-term flexibility varies between hours to weeks. Mid-term flexibility need will most likely increase due to renewable energy. Hydropower accounts for the majority of daily flexibility demands, which can be provided from the domestic or Nordic electricity market. On weekdays, energy consumption is 1500-3000 MW times higher than during nights in Finland. Short-term and mid-term flexibility is required to balance those variations each day. Energy production must be able to respond to demand fluctuations. Long-term electricity flexibility is defined to cover demand from weeks to months. Long-term flexibility is frequently required to cover electricity demand during winter since cold weather increases energy demand, and wind and solar power availability will decrease during winter. Commonly dispatchable generators offer the best capacity for storing a generous amount of energy, such as bio-fired CHP plants or hydropower. (AFRY, 2019)

Commonly, the primary source of flexibility is traditional power plants since the operation can be altered when a deficit or surplus of energy is detected in the system. The flexibility type depends on start-up time, ramp rate, and operation minimum and maximum. Quick reaction to renewable energy generation fluctuations is becoming vastly important since renewable energy generation balancing demands a quick turn-on and off time frame, within minutes and even various times during a day. Fossil-fueled power plants have offered mid-term and long-term flexibility, but renewable power plants have become an alternative to fossil-fueled power plants. Hydropower has the potential to cover baseload. Thus, it has already been used widely to cover base loads in Nordic countries. However, the output depends on water availability, which differs during seasons and depends on the location. Wind and solar power are considered climate-friendly since they can generate electricity while producing no greenhouse gas emissions and consuming no natural resources. When no sun or wind is available, occurs no power generation and no flexibility. In the future, solar and wind power might not operate on the highest power, but they could be reduced when desired. (Siemonsmeier et al., 2018)

Industrial demand response has a great potential since Finnish industries have been estimated to have roughly 1000 MW's flexibility abilities for a few hours. However, these estimations are theoretical. Industrial DR also depends on the process capacity, production targets, environmental restrictions, and interim storage utilization. (AFRY, 2019) Most of the energy is consumed during aeration and water pumping in wastewater treatment, which could offer flexibility potential for DR. Part of the wastewater treatment could be switched-off during peak hours, thus it would create possibilities for DR. For example, the aeration process can be shut down for a limited timeframe without causing vital fluctuations to effluent. Shutting down the aeration process could offer flexibility for short periods, but plant equipment might affect on the technical flexibility possibilities. Sludge recycling pumps can offer the switch-off possibility for a short timeframe without causing a negative change to effluent. However, the potential for DR in sludge treatment is under-researched. (Kirchem et al., 2020)

Solar and wind power production presents additional variables and insecurity in the power system operation. Hence, more flexibility can be required by the power system. The required amount of flexibility depends on the existing flexibility and the amount of solar or wind power integrated into the system. The most flexible electricity production source is hydropower, which has the potential to offer better integration of variable electricity generation, such as wind power. Flexibility from heat generation was studied for Finland's future power system. The results inferred that heat storages provided better flexibility for wind power integration. CHP units and electric boilers were utilized to balance peak demands by enabling CHP units to shut down and utilizing electric boilers to absorb excess power. Heat storage measures increased the wind power optimization from the cost perspective from 35% to 47%. (Bessa et al., 2016)

Term flexibility is commonly associated with electricity, but the term can also be used for water. Water availability is overall at a decent level in Finland, but water demand may fluctuate seasonally and daily. Daily water demand for residential, commercial, and industrial use would require evaluation when determining flexibility opportunities and challenges. Flexibility options during the water and sludge treatment process might require assessments.

4 DISCUSTION AND CONCLUTIONS

Energy and water, two closely related topics, will most likely attract much more attention in the future. Today's society revolves strongly around energy and water; for example, transportation requires fuels, housing requires water and energy, and clean drinking water is a basic human need. The aim towards sustainability will require energy production to utilize more renewable energy and increase energy efficiency in the future.

EWN utilization could offer solutions for many issues, such as energy and water demand peaks. However, EWN issues, solutions, and questions should be examined universally from national and international perspectives. EWN studies and applications face many difficulties, for example, a wide range of various technological applications in the energy and water industry and availability issues. Thesis conclusions are only indicative since the EWN questions are not widely studied in Finland. However, the thesis can offer questions and direction for future studies. The lifecycle water footprint for energy pathways raised some concerns and questions for Finnish energy production. Finnish energy and climate strategy aims towards sustainable energy production and consumption, but water demand could become an obstacle for the goals. Finland has overall excellent water availability, but water availability must remain exceptional in the future.

From Finland's perspective, the paper indicates an increase in water demand since biomass production is predicted to increase in the future. Compared to other energy pathways, biomass has by far the highest life cycle water footprint. The study examined in this thesis indicates that biomass can consume nearly 300 times more water than solar power. A high amount of water is especially required during the construction and operation. Can biomass be used sustainably from a water consumption perspective? However, biomass can be utilized in various ways, for example, utilizing CHP and thermal power, which will matter if flexibility is considered. CHP can create flexibility for a long period since CHP-plant can be restarted for winters. However, after restarting, CHP-plants must be run by constant power, which does not offer rapid flexibility.

Renewable energy sources, such as wind and solar power, have the lowest water footprint than other energy sources. From the EWN perspective, renewable energy production is a beneficial choice since it has low water demand. However, renewable energy production must be highly decentralized from the perspective of flexibility and water demand. Hydropower has a significantly higher water footprint than wind and solar power, but the power is derived from the water movement. Water footprint calculations for hydropower are much complex than for wind and solar power, which causes difficulties in comparison. However, hydropower can offer versatile flexibility since it can offer flexibility in real-time or for months. Wind and solar power have a considerably lower capacity factor than, for example, nuclear power plants. Thus, wind and solar power are commonly difficult to adjust. Can wind and solar power play an important role by reducing energy production's water demand?

Tampereen Vesi case study demonstrates the current situation in larger Finnish cities, but the case cannot be directly compared to other cities. The case study indicates that energy efficiency has remained at the same level for years. Tampereen Vesi processes a significant amount of wastewater annually, which creates efficient biogas production conditions. Thus, profitable biogas production requires a large amount of waste or sewage. Biogas production from sewage will likely not significantly increase power grid flexibility, but it could increase on-site flexibility. Co-operation plants produce biogas in Finland, which allows smaller wastewater treatment plants to reuse sewage into biogas. Produced biogas can also be sold for commercial use, for example, for transportation fuel purposes. Wastewater and water treatments could increase self-sufficient energy production by utilizing solar panels or windmills. However, the annual biogas production is low compared to the total energy demand in Finland. Biogas produced from sewage has many benefits, but production will unlikely offer significant benefits to the energy industry. Further studies are required to investigate water and sewage treatment plants' self-sufficient energy production and effective wastewater treatment in biomass plants.

Energy and water efficiency play an essential role in EWN. Thus, increasing energy and water efficiency could reduce energy and water demand. Increasing energy efficiency during the water and wastewater treatment could reduce plant’s energy demand.

However, this would require further studies and extensive data collection from the Finnish water and wastewater plants.

The thesis suggests biomass, nuclear power, and hydropower have the most significant water demand during the full life cycle. However, the numbers indicated in the thesis are estimations and cannot be considered entirely correct. Hence, further studies are required.

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