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Overview of Water Use in Renewable Electricity Generation

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This work provides an overview of water resources' roles in the development of renewable energy-fueled electricity generation. It shows that the specific water consumptions of electricity from renewable sources vary significantly due to the setting of the system boundary, data availability, and data quality. Hydroelectricity has a relatively more significant water consumption compared with other renewable energy sources due to surface evaporation. The current studies mainly cover the water consumption of the operational stages of renewable energies. The unit water consumption of hydropower ranges from 0.2 to 245 L/kWh, for solar PV ranges from zero to 0.11 L/kWh, wind power from 0 to 0.64 L/kWh, and geothermal from 2.5 to 6.8 L/kWh. Future studies should put effort to provide a unified and comparable database of renewable energy-related water consumption and water pollutant generation. An implication is that renewable energy generation planning should account for local natural conditions, particularly water availability.

1. Introduction

Water and energy are intricately connected as the two primary natural resources that are essential for global development (Varbanov, 2014). However, the increasing human activities, especially industrial development, have been the primary cause of water and energy (fossil fuels) scarcity issues. Driven by these issues, new theoretical and practical technologies have been developed to reduce water and energy consumption, increase water and energy use efficiency, as well as to explore new alternative resources. Seawater desalination has been an emerging technology to generate freshwater for drinking or industrial use, and renewable energy has been intensively investigated to replace conventional fossil fuels to reduce greenhouse gas (GHG) emissions.

The water-energy nexus exists in the exploitation and use phase of water and energy and their environmental impacts (Wang et al., 2020). The nexus is not always favourable but can aggravate each other’s ecological issues. According to the UN (2021) that 90 % of the global power generation is water-intensive and can cause chemical and physical pollution from the process and cooling water.

Figure 1 shows the contribution of renewable sources in energy generation in Europe from 2015 to 2019. Among the 37 studies countries, 23 of which has an overall increase share of energy from renewable sources, and eight countries maintained at a stable level of renewable energy production, and only six countries showed a decreasing rate of powers from renewable sources, including Montenegro, Moldova, Romania, Slovenia, North Macedonia, and Hungary. On the contrary, Iceland, Norway, and Sweden are the top three countries with more than 50 % renewable source contributions to energy generation. Especially in Iceland and Norway, the energy generation from renewable sources in 2019 was already more than 70 %. For most of the countries, the percentage of renewable sources in energy production has an increasing trend. Figure 2 shows the contribution of renewable sources in power generation. Norway and Iceland reached 100 % renewable power generation in 2019, and Sweden has an increasing percentage of closing to 60 %. Romania, Spain and Slovakia are the only three countries that showed a decreasing trend of power generation from renewable sources, while most of the countries showed an increasing role of renewable energies in power generation. The development and utilisation of renewable energies are proved to reduce greenhouse emissions and other air pollutants, but some of them are very water-intensive and more dependent on the water-energy nexus (Tsolas et al., 2018).

Water scarcity and heatwaves have already compromised power generation in the world (The Power, 2018). Drought and climate change affect main the cooling water availability for power generation, and can even

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impacts electricity prices (Byers et al., 2020). Droughts in Brazil during 2013–2016 and in California during 2011–2017, significantly affected the availability of hydropower and resulted in higher usage of more expensive thermal power plants (Byers et al., 2020). The drought in California in 2012-2016 led to a substantial disruption (Power Technology, 2018) in hydroelectric power output (Lund et al., 2018). Drought and river water temperature increase caused by climate change can hit the aging power plant, especially those ones with older cooling system (Science Daily, 2019). CO_2 emission in ASEAN recorded almost double increment (4.1 %) compared to 2016 (2.6 %) due to dependency on carbon-emitting sources like natural gas and coal to meet the energy needs under water-scarce conditions (Ibrahim, 2021). These impacts can be exacerbated by environmental regulations that limit water use. The European Environment Agency (2019) reported that the water availability is projected to further decrease as a side effect of climate change (Steffen et al., 2018), and this being especially the case in southern regions of Europe, affecting thermal power plants, hydropower, bioenergy potential, and fuel transport on rivers.

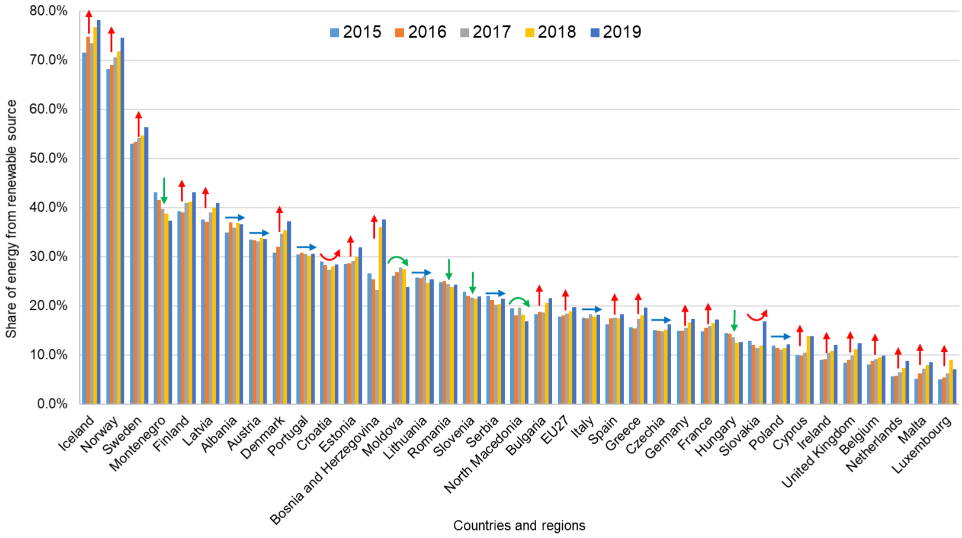

Figure 1: Share of energy from renewable sources in selected countries (2015-2019) based on data from (Eurostat, 2021a)

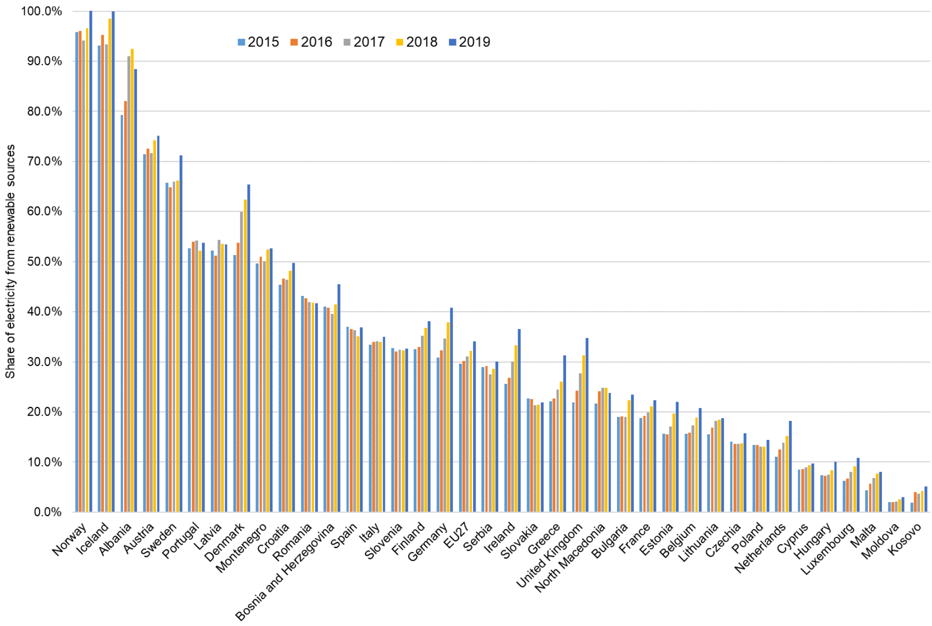

Figure 2: Share of electrical power from renewable sources in selected countries (2015-2019), based on data from (Eurostat, 2021b)

There has been challenges and opportunities to implement a de-carbonised energy system to adapt to the climate change (European Environment Agency, 2019). It has been reported that renewable energy technologies consume less water than conventional power plants. The operating stage of solar PV and wind power generation require marginal quantities of water for solar PV modules and wind turbine blades cleaning (Meldrum et al., 2013). Although high penetration of renewables into the energy mix has been promoted as the future, their life cycle environmental impacts have not been adequately investigated. In particular, attention on impacts on water resources and pollution has been limited. The operational water footprint of some renewable energies might be smaller than conventional energies, but many types of them still have an intensive life cycle water consumption under the current technologies. Studies claim that the water footprints of the operating stages of windmills and solar panels are near zero, but the (direct and indirect) water footprint of the construction process has not been well addressed. The water footprint of the windmills and solar PV can be considered as a water footprint debt", which can be paid back by consuming less water during the operating stages. In addition, the water consumption of specific renewable energies is even higher than conventional energies under the best-practice technologies. In fuel production, the water footprint of biofuel cultivation from sugarcane can be 2,000 times higher than from fossil fuel (Spang et al., 2014), and nuclear power with a cooling tower can be higher than coal-fired power plant with a cooling pond (Macknick et al., 2012).

As water scarcity has become an essential issue that could have a direct impact on human security, in many cases, it is worth discussing if it's water for energy or water – to energy. A more systematic assessment of energy-related water consumption will elevate the discussion of the sustainability of 100 % renewable energy systems from a broader perspective. There is an urgent need to look at the roles of water and wastewater in the development, generation, and use of renewable energies to provide a more systematic perspective in terms of the water-energy nexus and facilitate the development of both water and energy. To provide a more focused and detailed discussion, the scope of this review is majorly focused on the studies of European countries.

2. Review method

This review mainly covers studies of water consumption and wastewater discharges in electricity generation from renewable energy sources. The reviewed articles are selected by searching in Scopus and Google Scholar with the Keywords "Water" & "renewable energy". As the review focus on the environmental aspect of the topic, subject areas such as "Medicine", "Pharmacology, Toxicology and Pharmaceutics", "Immunology and Microbiology", "Biochemistry, Genetics and Molecular Biology" etc. are then excluded. Until this step, 621 documents were found. A screening by reading the title and abstract is then carried out to select the quantitative research articles under the reviewed topic. A total of 23 research articles from Scopus have remained for the final detailed review, and other papers selected from Google scholar have also been reviewed.

3. Water for renewable power generation

Water footprint (Mekonnen and Hoekstra, 2012) is one of the most widely used indicators for water use assessment in energy generation. The water footprint concept has been elaborated with the Life Cycle Assessment (LCA) (Lee and Atsushi, 2004) and used following a similar framework in recent years. The water consumption accounting results have been very diverse due to the different settings of system boundaries of the assessments. Specific water consumption (SWC) is also used to describe the water consumption of generating 1 unit of electricity.

Water resources is a crucial element in the life cycle of renewable power generation. The energy sources supply, transportation, power plant construction and operation, electricity generation, power distribution, and disposal of wastes generated in the supply chain are directly or indirectly connected to water use and pollution. The proportions of water use or wastewater generation of these stages can vary for different types of renewable energy sources. The water consumption in the operational stage of wind power is negligibly small, but the windmill's water consumption construction and transportation are relatively large (Yang and Chen, 2016). For hydropower plants, the surface evaporation of the reservoir in the operational stage is determined as the significant water-consuming stage (Mekonnen and Hoekstra, 2012). A complete life cycle water footprint assessment should cover all these stages and provide more accurate and comparable results. Due to the major limitations of data availability, most of the studies limits the system boundary to the "cradle to gate" level, which means from raw material collection to the generation per unit of electricity (e.g. 1 kWh). Bluewater footprint determines the blue water consumption, which is the surface and groundwater consumption. When the functional unit is set as water consumption of 1 kWh electricity generated, the blue water footprint is comparable with specific water consumption. Greywater footprint evaluates the water pollution impacts of the power generation and has not yet been widely implemented.

Table 1 presents the specific water consumption (SWC) of power generation from renewable sources, including hydropower, solar photovoltaics, wind power, and geothermal (steam). The functional units, system boundary, and geographical coverage are also compared. The summary showed that the water footprint (or SWC) values vary depending on the selection of system boundaries and the studied area. For example, the water footprint / SWC of hydropower varies from 0.2 to 245.0 L/kWh (as shown in Table 1) with different system boundary setting. Surface evaporation dramatically increased the value based on the results from Mekonnen and Huekstra (2012). Larsen and Drews (2019) determines the share of freshwater in hydropower cooling water of EU28 and claimed that the percentage already reached zero in 2019. This is because hydropower generation consumes a larger volume of freshwater for the operational stage cooling comparing with other renewable energy sources.

Table 1: Summary of SWC of electricity generation from renewable energy sources

Type of renewable energy sources	SWC/Water footprint	Functional Unit	System boundary	Covered geographical area
Hydropower				
Mielke et al. (2010)	17.0	L/kWh	Operational cooling water	World average
Macknick et al. (2012)	17.0			World average
Mekonnen and Huekstra (2012)	245.0	L/kWh	Operation stage blue water footprint	Average of 35 sites covering 8 % of the global installed hydroelectric capacity
Bakken et al (2016)	0.2	L/kWh	Cradle to gate*	Norway
Larsen and Drews (2019)	0.0	Share of fresh cooling water in power generation, %	Operational stage cooling water	EU-28
Solar photovoltaics (PV)				
Macknick et al. (2012)	0.004	L/kWh	Operational stage	World average
Spang et al. (2014)	0.000	L/kWh	Operational stage	World average
Wind				
Saidur et al. (2011)	0.004	L/kWh	Operation stage	Malaysia
Li et al. (2012)	0.64	L/kWh	Life cycle	China
Larsen and Drews (2019)	0	Share of cooling water in power generation, %	Operation stage cooling water	EU-28
Geothermal power generation				
Mielke et al. (2010)	2.5	L/kWh	Operational cooling water	World average
Clark et al. (2011)	1.9	L/kWh	life cycle*	US
Macknick et al. (2012)	6.8	L/kWh	Operational cooling water	World average

**Water consumption of all raw materials and production processes are included, but power distribution is not included. **The geothermal power plant construction with 30 y of operation is covered.*

For power generation from solar PVs, the functional unit is L/kWh, and the system boundaries in the three studies are all set as the operational stage. The SWC value range from 0 to 0.11 L/kWh for the world average. Saidur et al. (2011) determined that the SWC of the wind power in the operational stage is 0.004 L/kWh, which is about 0.6 % of the water consumption in the cradle-to-gate life cycle (Li et al., 2012). The cooling towers in the operational stage of wind power generation in EU28 are no longer consuming freshwater (Larsen and Drews, 2019). As another widely applied renewable energy source, geothermal (steam) has the second-highest water consumption for cooling in the operational system. The water footprint of the geothermal plant construction + 30 y operation in the US is 1.9 L/kWh, which is lower than the operation stage cooling water (world average). The operation stage cooling water consumption of power generation from renewable sources follows Hydropower > Geothermal > Solar PVs > Wind.

As the system boundary setting and definition of the existing studies differ considerably, the assessment results are hardly comparable. Most of the studies have been focusing on the water footprint quantification of the operating stages of renewable energy productions, namely from the cradle to the gate. The water-use results from only the operational stages cannot strictly represent the water use performance of the renewable energy sources because the water use intensity of different stages of different types of renewable sources various dramatically. Wind power's operational stage water footprint is often determined as zero, but the direct and indirect water consumption of the windmill construction, transportation, disposal, etc., have not been accounted for. The water footprint of solar panels production, transportation, and potential water footprint from solar panel disposal is also not investigated.

In addition to water quantity, water pollution and wastewater discharge, as well as other aquatic environmental impacts in renewable energy generation, needs further study. The wastewater from solar PV panel cleaning and the increase of evaporation caused by the hydropower construction and its other impacts on the aquatic organisms should be further investigated. The quantification of water used for renewable energy development should cover a more standard system boundary to enable the comparability between renewable and non-renewable energy production, as well as among various types of renewable energy alternatives, to facilitate the selection of sustainable energy sources.

4. Water challenges in renewable energy development

As GHG emission reduction becomes the major task globally, the promotion of renewable energy has also become a default option for various countries in the world. The renewable energy development scheme should be carefully evaluated in countries with limited favourable conditions.

As a country in central Europe, the Czech Republic has a limited condition in developing hydro- and wind power due to its natural and geographical conditions. Electricity from renewable sources takes 15.8 % of total electricity generation (Figure 3(a)). Water scarcity has been one of the major issues in the Czech Republic since 2014, and the energy sectors took 49 % of the total surface water abstractions (Figure 3(b)). Considering the high water consumption via cooling water and evaporation indicates that further development of hydropower might not be the optimal option. Similarly, the development of renewable energy-fuelled power generation should be designed in line with the specific condition of the country, including the economic development level, resources availability, geographical conditions, etc.

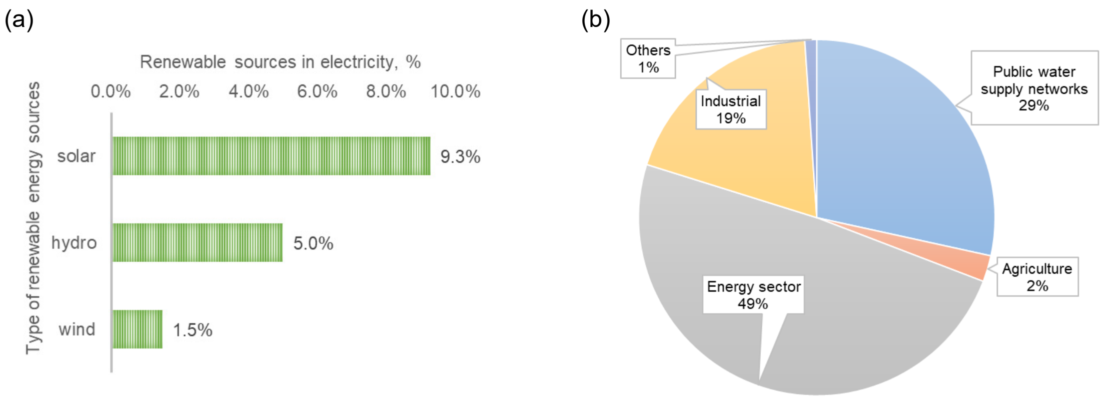

Figure 3: (a) Share of renewable sources in electricity generation in the Czech Republic in 2019 (Czech Statistical Office, 2020); (b): Surface water withdrawals in the Czech Republic by industry in 2019, based on data from (Ministry of Agriculture of the Czech Republic, 2020)

5. Conclusions

This work provided an overview of the water consumption of electricity generation from renewable sources and discussed the challenges faced by the water sectors during the development of renewable energy fuelled power plants. The specific operational water consumption of hydropower ranges from 0.2 to 245 L/kWh, for solar PV ranges from zero to 0.11 L/kWh, wind power from 0 to 0.64 L/kWh, and geothermal from 2.5 to 6.8 L/kWh. These figures do not include the water footprint of capital stocks, such as those incurred during the manufacture of system components. It is found that a unified and comparable water consumption database for renewable energy sourced power generation has not been provided in the existing studies. Limited by data availability, the current studies rarely cover the whole life cycle of the power generation process. In addition to the water quantity, water and thermal pollution, wastewater generation, and other related environmental impacts of power generation using renewable sources still need to be further investigated. Methodologies to optimise electricity trade under water footprint constraints should also be developed.

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