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The consumptive water footprint of the European Union energy sector

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The consumptive water footprint of the European Union energy sector

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Abstract

Energy security for the EU is a priority of the European Commission. Although both blue and green water resources are increasingly scarce, the EU currently does not explicitly account for water resource use in its energy related policies. Here we quantify the freshwater resources required to produce the different energy sources in the EU, by means of the water footprint (WF) concept. We conduct the most geographically detailed consumptive WF assessment for the EU to date, based on the newest spatial databases of energy sources. We calculate that fossil fuels and nuclear energy are moderate water users (136–627 m³/terajoules (m³ TJ⁻¹)). Of the renewable energy sources, wood, reservoir hydropower and first generation biofuels require large water amounts (9114–137 624 m³ TJ⁻¹). The most water efficient are solar, wind, geothermal and run-of-river hydropower (1–117 m³ TJ⁻¹). For the EU territory for the year 2015, our geographically detailed assessment results in a WF of energy production from domestic water resources of 198 km³, or 1068 litres per person per day. The WF of energy consumption is larger as the EU is to a high level dependent on imports for its energy supply, amounting to 242 km³ per year, or 1301 litres per person per day. The WF of energy production within the 281 EU statistical NUTS-2 (Nomenclature of Territorial Units for Statistics) regions shows spatially heterogeneous values. Different energy sources produced and consumed in the EU contribute to and are produced under average annual and monthly blue water stress and green water scarcity. The amount of production under WS is especially high during summer months. Imported energy sources are also partly produced under WS, revealing risks to EU energy security due to externalisation. For the EU, to decarbonise and increase the share of renewables of its energy supply, it needs to formulate policies that take the water use of energy sources into account. In doing so, the spatial and temporal characteristics of water use and water stress should particularly be considered.

1. Introduction

In 2015, energy consumption in the European Union (EU) amounted to 1184 million tonnes of oil equivalent (Mtoe), whereas primary energy production was 779 Mtoe (figure S1 is available online at stacks.iop.org/ERL/14/104016/mmedia) [1]. The EU’s energy sector is heavily dependent on fossil fuels, nuclear energy and imports. Therefore, one of the European Commission’s priorities is the Energy Union strategy [2], which focuses on boosting energy security, creating a fully integrated internal energy market, improving energy efficiency, reducing greenhouse gas (GHG) emissions and increasing the use of renewable energy. To that purpose, the EU has agreed upon a series of intermediate targets, including increasing the share of renewable energy in final energy consumption to 20% by 2020 and 27% in 2030 [3]. The 2050 long-term strategy calls for a climate-neutral Europe by 2050 [3].

The EU energy sector is responsible for many environmental pressures, the latter being resource use...
and pollution [4, 5]. The most obvious one is the emission of GHGs, mostly CO$_2$. In 2015, the EU emitted 4461 million tonnes (Mt) CO$_2$-equivalent, of which 3371 Mt CO$_2$-equivalent related to energy [6]. Induced climate change has many impacts, including in the EU [7–9]. Another important pressure, the use of water resources, is generally not considered when formulating energy related policies [2, 3, 10, 11].

Due to human freshwater use in different economic activities, both blue (surface and groundwater) and green (soil moisture) water resources are scarce [4, 12, 13]. Blue water refers to water in rivers, lakes and aquifers. Green water is the soil water held in the unsaturated zone, formed by precipitation and available to plants. These resources are essential for food security [14–18], energy security [19–21], water security and the environment [22]. Interactions and trade-offs between these sectors are referred to as the water-energy-food-nexus (WEFE) nexus [22], a framework which is increasingly acknowledged by different institutions as important for policy making [23, 24].

A vast body of literature on the interactions between the water and energy systems exists, dealing with water quantity, water quality and/or climate change, among others [25–28]. The water footprint (WF) of energy has been analysed for specific world regions [19, 29]. This includes a first assessment of the WF of production of Europe, not the EU, by Mekonnen et al [19], based on geographically coarse data, while excluding the WF of energy consumption as well as specific energy sources like biofuels. A comprehensive, geographically detailed assessment of the consumptive WF of energy production as well as consumption of the EU, including all energy sources and based on the newest developed databases, to a level of detail required as input to guide EU policies, has never been done before. Here we close this knowledge gap.

We calculate the water footprint (WF) of EU energy production and consumption for the year 2015, based upon a geographically detailed quantification of the WF of different energy sources, using newly developed databases and analyses. The WF is a pressure indicator, which quantifies consumptive (green plus blue) water use along a supply chain [30]. We use three stages in our assessment—(1) fuel supply or energy production, which includes oil refining; (2) construction and (3) operation or energy power generation—with the first two as supply chain stages. First, we calculate WF unit amounts for the different energy sources inside and outside the EU, expressed as (m$^3$ TJ$^{-1}$). For production within the EU, the WF unit amounts are based on detailed data within 281 so-called NUTS (Nomenclature of Territorial Units for Statistics) 2 level statistical regions [31], based on newly developed geographical databases of energy production such as the JRC-power plants database [32]. Second, we assess the WF of production of the EU energy sector and the WF of energy consumption in the EU. The former quantifies the WF of energy production from domestic water resources. The latter quantifies the WF related to energy consumption from domestic and foreign water resources, as a significant part of energy consumed in the EU is imported. We account only for freshwater, not saline or brackish water. We use blue and green WF components in our analysis.

2. Methodology

For energy production and consumption in the EU and its 28 member states, we use as reference year 2015, as included in the EU energy reference scenario [33, 34]. This scenario has been crosschecked and validated by EU member states and is publically available. It is calibrated by means of EUROSTAT statistics.

With respect to the WF of the EU energy sector, a differentiation needs to be made between the WF of EU domestic energy production and the WF of EU energy consumption. The first relates to the energy produced within the EU, the second refers to the energy consumed in the EU. The WF of EU domestic energy production thus relates to consumptive water use (green and blue) along the supply chain of the energy sector for energy production within the EU area. It quantifies the direct and indirect water consumption of domestic freshwater resources. The WF of EU energy consumption, on the other hand, quantifies the total volume of freshwater consumed along the supply chain to produce the energy consumed by the inhabitants of the EU. It is the sum of direct and indirect water use of domestic and foreign water resources through domestic consumption. It equals the WF of energy production plus virtual water imports (virtual water associated with import) but minus virtual water exports (virtual water associated with export). Import and export data of the different energy sources are obtained from EUROSTAT [35–37].

The three stages we assess in the energy production chain are: (1) fuel supply or energy production; (2) construction; (3) operation or energy power generation.

To compute the WF of energy production in the EU, we use geographically detailed databases on energy production, including the newly developed JRC-Power Plants Database [32], the JRC-Coal Mines Database [38] and Rystad Energy UCube [39]. Unit WF values are assembled from different data sources [19, 20, 40–45], with a differentiation between specific types of energy production and power plant technologies (e.g. tower steam, one-through steam or pond steam cooling for nuclear power plants). WF amounts are computed per location according to the technology used, then aggregated to NUTS-2 level and in a following stage summed to EU level. A detailed description of this methodology can also be found in a recent JRC report [46].
For energy sources that are imported, national average WF unit quantities per energy source of the country of origin are used as well as imported quantities. As an example, for maize bioethanol imported from the US, the national average US values blue WF \(6 \text{ m}^3 \text{TJ}^{-1}\) and green WF \(52 \text{ m}^3 \text{TJ}^{-1}\) \([42]\) are used for the imported quantity.

An overview of all databases used, is presented in table 1. A detailed description of the methodology per energy source can be found in the SI.

We only account for fresh water (hence only on-shore activities), not for brackish water (such as in estuaries) or sea water (along the coast or off shore activities). We are able to distinguish between these types of water resource due to the use of geographically detailed databases on energy production, which account for this information. As an example, seaside nuclear power plants generally use seawater, as in the UK, Sweden and Finland (figure 4). Brackish water from the Scheldt river is used by the nuclear power plant of Doel near Antwerp in Belgium, and is therefore not included in the WF accounting (figure 4).

3. Results

3.1. EU level

We calculate for fossil fuels and nuclear energy average unit WF amounts that range from 136 m\(^3\) TJ\(^{-1}\) for gas, over 249 m\(^3\) TJ\(^{-1}\) for oil up to 572 m\(^3\) TJ\(^{-1}\) for coal and lignite. Nuclear energy has an average WF of 627 m\(^3\) TJ\(^{-1}\) (figure 1).

Substantially larger average unit WF amounts are calculated for the renewable energy sources reservoir hydropower (9114 m\(^3\) TJ\(^{-1}\), due to evaporative losses of water from reservoirs), as well as the biomass resources wood (61 762 m\(^3\) TJ\(^{-1}\)), 1st generation bioethanol (61 032 m\(^3\) TJ\(^{-1}\)) and 1st generation biodiesel (137 624 m\(^3\) TJ\(^{-1}\)). These biomass resources have a large green water component. Biofuels also have a large blue WF component from the production phase, due to irrigation. Based on economic allocation, the WF of reservoir hydropower only quantifies blue water consumption for power generation, and not for other reservoir water uses like irrigation or recreation \([40]\). Similarly, the WF of wood only quantifies consumptive water use for wood production, not for other ecosystem services \([20]\).

The most water efficient in terms of water resource use are the renewable energy sources solar (117 m\(^3\) TJ\(^{-1}\)), geothermal (35 m\(^3\) TJ\(^{-1}\)), wind (1 m\(^3\) TJ\(^{-1}\)) and run-of-river hydropower (1 m\(^3\) TJ\(^{-1}\)).

The total annual WF of energy production in the EU amounts to 198.2 km\(^3\), the WF of energy consumption to 241.5 km\(^3\) (figure 2 and supplementary table S7). Green water dominates with 93% these total amounts, due to the biomass energy sources wood and 1st generation biofuels. Wood accounts for about two thirds of the total WF of production and consumption, 1st generation biofuels for about 20%–30%. Energy consumption WF amounts are larger than energy production WF amounts for these three energy sources, as the EU net imports them. Especially for biodiesel, the net import compared to domestic production is high, with a green and blue WF of production of 34.4 km\(^3\) respectively 0.9 km\(^3\) compared to a green and blue WF of consumption of 64.2 km\(^3\) respectively 1.0 km\(^3\) (supplementary tables S1, S2 and S7). Imported rapeseed from Australia and Ukraine as well as imported palm oil from Indonesia and Malaysia account for the bulk of total WF import amounts. For wood and bioethanol, the proportion of domestic production in the WF of energy consumption is higher, as the EU is less dependent on import for these energy sources. For wood, the green and blue WF of production are 145.1 km\(^3\) respectively 2.0 km\(^3\), compared to a green and blue WF of consumption of 154.1 km\(^3\) respectively 2.3 km\(^3\) (figure 2, supplementary tables S5 and S7). About 50% of wood import originates from the USA, Russia and Canada. For bioethanol, the green and blue WF of production are 4.7 km\(^3\) respectively 3.7 km\(^3\), compared to a green and blue WF of consumption of 6.8 km\(^3\) respectively 0.8 km\(^3\) (figure 2, supplementary tables S3, S4 and S7).

The total blue WF, 13.9 km\(^3\) for the WF of energy production and 16.4 km\(^3\) for the WF of energy consumption, represents 7% of the total WF of energy production and consumption (figure 2 and supplementary table S7). Renewables account for the largest share of the blue WF, that is 74.1% for the WF of energy production and 67.8% for the WF of energy consumption. The remaining share is for fossil and nuclear energy. With 6.76 km\(^3\), the WF of reservoir hydropower has the largest blue WF. Electricity from biomass accounts with 0.28 km\(^3\) for 2.0% and 1.7% of the blue WF of energy production respectively consumption. The renewable energy sources solar, wind, geothermal and run-of-river hydropower account combined with a blue WF of 0.02 km\(^3\) and 0.06 km\(^3\) for only 2.0% and 1.7% of the blue WF of energy production respectively consumption.

Due to high reliance on imports for fossil fuels, the WF of energy consumption is higher than the WF of energy production for solids (2.67 km\(^3\) respectively 1.94 km\(^3\)) and oil (1.03 km\(^3\) respectively 0.20 km\(^3\)). For gas, the difference is negligible. Also nuclear energy shows with 1.40 km\(^3\) respectively 1.26 km\(^3\) a difference between production and consumption, because 98.4% of uranium used in the EU is extracted outside of its territory.

3.2. NUTS-2 level

The EU energy sector unit and total WF numbers are based upon detailed geographical databases and analyses, as e.g. shown for the blue WF of solids production and solid-fired power plants (figure 3). A blue WF of solids production is only located in 32 of 281
Table 1. Overview of databases used in the study.

<table>
<thead>
<tr>
<th>Data and resulting statistics</th>
<th>Supply chain stage (1, 2, 3)</th>
<th>Data source</th>
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<tbody>
<tr>
<td>Energy production and consumption in the EU and its member states, year 2015</td>
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</tr>
<tr>
<td>WF of fossil fuels: solids (coal, peat, oil shale)</td>
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<td></td>
<td>2</td>
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<td>JRC-Power Plants Database [32]; WF unit amounts from Macknick et al [45]</td>
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<tr>
<td>WF of fossil fuels: oil</td>
<td>1</td>
<td>oil production database Rystad Energy UCube [39], Worldwide Refinery Survey [47]; unit WF amounts from Macknick et al [45]</td>
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<tr>
<td></td>
<td>2</td>
<td>Mekonnen et al [19]</td>
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<td>JRC-Power Plants Database [32]; WF unit amounts from Macknick et al [45]</td>
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<td>WF of fossil fuels: gas</td>
<td>1</td>
<td>Location and characteristics of gas fields from Rystad Energy UCube [39]; unit WF amounts from Macknick et al [45].</td>
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<tr>
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<td>2</td>
<td>Mekonnen et al [19]</td>
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<td>JRC-Power Plants Database [32] and WF unit amounts from Macknick et al [45]</td>
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<td>1</td>
<td>Meldrum et al [44]</td>
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<tr>
<td></td>
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<tr>
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<td>JRC-Power Plants Database [32]; WF unit amounts from Macknick et al [45]</td>
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<td>Reservoir hydropower from Hogeboom et al [40]</td>
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<tr>
<td></td>
<td>3</td>
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<tr>
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<td>2,3</td>
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<tr>
<td>WF of renewable energy: geothermal</td>
<td>2</td>
<td>EGES Geothermal Market Report [48] for characteristics and location; WF unit amounts from Macknick et al [45]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>JRC-Power Plants Database [32]; WF unit amounts from Macknick et al [45]</td>
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<tr>
<td>WF of renewable energy: 1st generation biofuels</td>
<td>1</td>
<td>Biodiesel and bioethanol production and consumption statistics for the EU from EUROSTAT [49] and the EU Agricultural Outlook report of DG AGRI [50]; Feedstocks and their origin derived from different data sources [49–51]. Country of origin of imported feedstocks as well as bioethanol and biodiesel from a combination of EUROSTAT databases [35–37]; average EU feedstock specific WF amounts from an international database [41, 42]; biofuel processing unit WF from [43]</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<tr>
<td>WF of renewable energy: wood</td>
<td>1</td>
<td>Detailed description of methodology to compute the WF of energy from wood for the EU by Schyns and Vanham [52], based upon Schyns et al [20]</td>
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<tr>
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<td>2,3</td>
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<td>WF of renewable energy: electricity from biomass</td>
<td>2</td>
<td>JRC-EU-TIMES model [53]; WF unit amounts from Macnind et al [45]</td>
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<td>Blue WS as well as location and production (Tonnes) crops</td>
<td>3</td>
<td>JRC-Power Plants Database [32]; WF unit amounts from Macknick et al [45]</td>
</tr>
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<td>Green water scarcity</td>
<td>Mekonnen and Hoekstra [54] and [42]</td>
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NUTS2-regions, concentrated in the middle and eastern EU, with five German (Köln, Münster, Düsseldorf, Brandenburg and Dresden), two Polish (Śląskie and Lódzkie) and two Czech (Moravskoslezska and Severozápad) NUTS2-regions amongst the ten regions with the highest WF (table S8). A blue WF of solid-fired power plants is spread more over the EU, in 81 of 281 NUTS2-regions. Four German (Köln, Düsseldorf, Brandenburg and Arnsberg) and three Polish (Śląskie, Lódzkie and Mazowieckie) are amongst the ten NUTS-2 regions with the highest WF. A blue WF of nuclear energy operation is only located in 28 of 281 NUTS2-regions (figure 4 and table S8). Nuclear energy is produced in 46 of 281 NUTS2-regions however, but in many regions seawater or brackish water is used for cooling, which do not account for a WF. The five NUTS2-regions with the highest WF are all located in France (Centre, Rhône-Alpes, Champagne-Ardenne, Lorraine, Poitou-Charentes) (figure 4(b)). Schwaben in Germany has the sixth highest WF. Other detailed spatially distributed maps (NUTS2 level) for the blue WF of production for different
energy sources with a total lower amount as compared to solids and nuclear energy, are included in the SI: Supplementary figures S2 and S3 for oil production and refinery; S4 for oil-fired power plants; S5 and S6 for gas production and gas-fired power plants; S7 for geothermal power plants and S8 for biomass/waste power plants. Table S8 provides all these data on NUTS2 level, as well as on country and EU level. For wood national WF of production amounts are presented in table S5. These graphs and tables show substantial differences in proportional production of energy sources and related WFs amongst countries.

4. Discussion

4.1. WEFE sectors

With respect to the EU population, the WF of production and consumption of the energy sector amount to 1068 litres per person per day (l/cap/d) respectively 1301 l/cap/d (figure 5). These amounts are substantially higher than the WF of the water sector for municipal water supply (23 l/cap/d) [55], the consumptive part of municipal water withdrawal. In other words, the water required for energy use by EU citizens is much higher than the water they use at

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**Figure 1.** Average blue and green WF related to energy production in the EU (m³ TJ⁻¹). Note that the scale is logarithmic. The values in the table show the three stages in the energy production chain: (1) fuel supply or energy production; (2) construction; (3) operation or energy power generation. The blue bars show the blue WF, the green bars the green WF.
home. However, these amounts are considerably lower than the WF of a third pillar of the WEFE nexus, the food sector. The WF of production and consumption of the food sector amount to 2521 l/cap/d respectively 3687 l/cap/d (figure 5). The sum of these three sectors leads to an EU WF of production and consumption of 3612 l/cap/d respectively 5,011 l/cap/d. When only considering the blue WF, these amounts are 296 respectively 391 l/cap/d. This quantification accounts for the WF of the EU energy sector, not the energy embedded in imported or exported products. Both perspectives are relevant for the WEFE nexus.

Figure 2. The annual absolute WF of energy production (a) and consumption (b) in the EU, in km$^3$ for the year 2015. The left part shows the green and blue WF (in colours green respectively blue), with proportions equal to amounts. The right part shows the different components of the blue WF, again with proportions equal to amounts. The differentiation between the groups renewables on the one hand and fossil and nuclear on the other hand is shown.

Figure 3. Blue WF of solids production (left) and solids-fired power plants (right) (third stage—operations or energy transformation) in EU NUTS-2 regions. Only freshwater is accounted for. Total amount 828 (left) and 1106 (right) million m$^3$ yr$^{-1}$. Location of power plants as in the newly developed JRC-Power Plants Database [32].
4.2. Blue and green water scarcity

Competition for blue and green water resources between these three sectors and the environment as well as between different users within these sectors, has led to widespread water scarcity both in the EU and regions the EU imports products from [54].

Blue water stress [56] quantifies the ratio between water use and environmentally available water, the latter being total water availability minus environmental flows. In the SDG framework, this value is monitored with indicator 6.4.2 [57]. When environmental flows are not met any more, this leads to serious disruptions in important ecosystem services [28, 57, 58].

As the WF quantifies consumptive water use, related WS needs to be computed with consumptive use, as e.g. done in the global study of Mekonnen and Hoekstra [54]. In the EU, the Water Exploitation Index plus (WEI+) is often used to compute WS for consumptive water use. WS differs both spatially and temporally [57].

Attributing the global WS raster data (5°x5 arc Minutes) of Mekonnen and Hoekstra [54] to the NUTS2
regions of the EU, shows average annual WS (values exceeding 1) in many Mediterranean regions (figure 6(a)). In some regions, severe WS (WS $>$ 2) is observed. In August (figure 6(b)), monthly WS values are generally the highest of all months throughout the EU, and WS extends through large parts of the EU territory. The production of nuclear and fossil energy sources contributes to and occurs under WS (figure 6(c)). Regarding average annual WS, 18% of nuclear energy production (operation, blue WF $1207 \times 10^6$ m$^3$, table S7) contributes to and occurs under WS. The values are 2% for solids fuel supply (WF $828 \times 10^6$ m$^3$), 6% for solids operation (WF $1106 \times 10^6$ m$^3$), 0% for gas fuel supply (WF $0.2 \times 10^6$ m$^3$), 13% for gas operation (WF $204 \times 10^6$ m$^3$), 13% for oil fuel supply (WF $171 \times 10^6$ m$^3$) and 7% for oil operation (WF $4 \times 10^6$ m$^3$). The highest monthly proportions under WS are observed during summer: 34% for nuclear energy in September, 20% for solids fuel supply in August, 26% for solids operation in August, 5% for gas fuel supply in August, 36% for gas operation in August, 38% for oil fuel supply in August and 17% for oil operation in August. The lowest monthly proportions are observed in winter, respectively: 2% in January, 0% in January, 2% in January, 0% during 10 months, 2% in January, 5% in January and 23 from January to April. Different energy sources contribute to and occur under different levels of WS in a spatially very heterogeneous way, as displayed during August (figure 6(d)). The highest total amount of energy production under WS during August occurs for oil energy fuel supply (19 681 ktoe), of which 12 895 ktoe under severe WS. About 2000 ktoe of nuclear energy operation and solid energy production occur under WS, whereas for solid energy operation and gas production the amounts are about 1500 ktoe. For nuclear energy operation e.g. WS occurs in Spanish (severe WS) and French (moderate to severe WS) NUTS 2 regions, as well as the Romanian Sud-Est region (severe WS) and the Belgian Province of Liège (moderate WS). For solids production, WS occurs in German (moderate WS), Greek (severe WS), Spanish (severe WS), Italian (severe WS) and UK (significant WS) NUTS regions. For solids operation, WS occurs in Bulgarian (moderate to severe WS), German (moderate to severe WS), Greek (severe WS), Spanish (severe WS), French (severe WS), Hungarian (moderate WS), Italian (severe WS), Dutch (moderate to severe WS), Portuguese (severe WS) and UK (moderate to significant WS) NUTS regions.
Biofuel production accounts for high blue and green WF amounts, both in the EU and from regions the EU imports biofuels from. It also contributes to and occurs under blue WS in a spatially and temporally heterogeneous way. As an example, irrigated maize, for which bioethanol accounts for a blue WF of $311 \times 10^6$ m$^3$ (table S3), is predominately grown in the Mediterranean region as well as in France, Portugal and Romania (figures 7(a) and (b)). Total annual EU maize production in 2000 was 55 million tonnes, with a related blue WF of 5.9 km$^3$ yr$^{-1}$ and a green WF of 35 km$^3$ yr$^{-1}$ [42, 55], of which 24 million tonnes was to some extent irrigated. Irrigated maize contributing to and produced under local annual average WS (figures 7(a) and (c), WS > 1) amounts to 9 million tonnes, of which 4 million tonnes under severe WS (WS > 2). During the summer season (figures 7(b) and (d)) the highest amounts of local WS conditions are observed. In August, 16 million tonnes are produced under WS, of which 13 million tonnes under severe WS. During other months and especially winter, the proportion of maize under WS is lower. Also other biofuel feedstock is partly produced under WS, such as rapeseed or soybeans.

Also ethanol from irrigated maize and biodiesel from irrigated soybeans imported to the EU (table S4), contribute to and are produced under local WS, as is the case for the USA (figure 8). Significant parts of irrigated maize and soybean in the USA contribute to and are produced under different levels of WS, violating environmental flows and accounting for groundwater depletion such as in the Ogallala aquifer [16]. Of a total annual irrigated production of 54 million tonnes of maize, 46 million tonnes are produced under WS, of which 39 million tonnes under severe WS. For soybeans, 6 million tonnes are produced under WS, of which 2 million under severe WS. Monthly WS can show even higher amounts. WS is not accounted for in the sustainability assessment of biofuels [10], as shown in a new recognition by the Commission stating technical requirements to be met by US soybeans in order to be used in biofuels in the EU [11]. In other words, relying on the import of energy resources produced under WS, could have negative effects on EU energy security.

The Commission already indicated that biofuels, bioliquids and biomass fuels produced from food and feed crops should gradually be phased out and replaced by advanced biofuels, including notably...
cellulosic ethanol and diesel and algal fuels, as well as renewable electricity based fuels, as highlighted in the recent directive COM(2018)2001 [10]. The water intensity of these advanced biofuels should however also be accounted for. As an example, algae show substantial unit WF amounts [59], which depend on factors such as technology (open pond, closed photobioreactors), water source used (freshwater, brackish, saline water), operation with and without recycling or algal species.

Green water is a scarce resource too, and thus there are limits to the human appropriation of green water resources [13]. We have shown that the WF of the EU energy sector is largely related to green water use, to produce energy from wood and biofuels. The green WF of energy from wood sources is for 94% located in the EU, but more than half on this internal WF is in member states that have less than 20% of sustainably available green water flows left to potentially allocate to biomass production [52]. Particularly in the Netherlands, Germany, Denmark, UK, Belgium, Greece, Czech Republic, and Portugal, practically all green water resources are already in use, occasionally at the cost of green water flows earmarked for nature [13]. Regarding biofuel crops, large green WFs are associated with rapeseed produced in the EU, Germany in particular, and palm oil imports from predominantly Indonesia and Malaysia. The large-scale conversion of previously set-aside grasslands to rapeseed fields [60], is an example of the competition over green water resources in Germany. In Indonesia and Malaysia, that competition displays through palm oil plantations invading forested lands with a large green water availability [61, 62].

This shows that the choice which renewables to promote, is essential to alleviate WS and maintain ecosystems and their services. Recent summer droughts and heatwaves, such as in 2003, 2006, 2015 and 2018, which will only become more frequent due to climate change [63], have already led to water being a limiting resource for energy production throughout the EU. Low water levels and high temperatures, experienced throughout many rivers in Europe like the Rhine or the Rhone, forced thermal power plants to reduce their output or shut down completely [64]. Reduced agricultural outputs can decrease biofuel production. Forest fires as experienced in Sweden in 2018 can decrease fuel wood yields. Policies on future energy investments therefore need to consider which renewables have low unit WF amounts.

Figure 8. Irrigated maize (a), (b) and soybeans (c), (d) contributing to and produced under blue WS in the USA, based upon different data sources [42, 54], showing (left) annual average (average of 12 monthly values) WS stress levels in locations where crops are irrigated (grid cells where >100 tonnes of irrigated crop per area) and (right) the cumulative production (million tonnes) of irrigated crop according to annual average WS conditions.
4.3. Comparison with other studies

A limited amount of WF studies related to the energy sector in the EU have been conducted. Most notably, Mekonnen et al [19] quantified for Europe (not the EU), a WF of energy production of 84 km$^3$ yr$^{-1}$ (green and blue WF), whereas we calculate 198 km$^3$ yr$^{-1}$. For solids we compute 1.9 km$^3$ yr$^{-1}$, Mekonnen et al 3.2 km$^3$ yr$^{-1}$. For nuclear the values are 1.3 km$^3$ yr$^{-1}$ respectively 2.9 km$^3$ yr$^{-1}$; for gas 0.2 km$^3$ yr$^{-1}$ respectively 2.1 km$^3$ yr$^{-1}$ and for oil 0.2 km$^3$ yr$^{-1}$ respectively 0.3 km$^3$ yr$^{-1}$. Our assessment is based upon much more detailed energy and water statistics, new databases and new spatially distributed assessments. For wood we used the spatially distributed assessment of Schyns et al of 2017 [20] whereas Mekonnen et al [19] used much older, spatially coarse assessments such as van Oel and Hoekstra of 2011 [65]. We also use detailed wood for energy statistics for EU countries. This results in our assessment in a WF for energy wood production of 147 km$^3$ yr$^{-1}$, whereas Mekonnen et al compute 33 km$^3$ yr$^{-1}$. For hydropower, we also use the newest spatially distributed analysis of Hogeboom et al [40] published in 2018, whereas Mekonnen et al use much older assessments. We compute a WF of reservoir hydropower production of 7 km$^3$ yr$^{-1}$ for the EU, whereas Mekonnen et al compute 42 km$^3$ for Europe. We account for evaporation related to other reservoir uses, Mekonnen et al do not. We account for 1st generation biofuels, Mekonnen et al do not. We calculate the WF of energy consumption, accounting for energy imports and exports. Mekonnen et al do not.

Another study that touches on the WF of the EU energy sector is Serrano et al [66], who quantify the green, blue, and grey WF of the EU27. These authors use an environmentally extended MRIO analysis, whereas we use a bottom-up approach. In their analysis they provide WF quantities for different sectors, but this does not include the energy sector as such. Later is not identified between different sectors in their database. Nor do they provide results per energy source. Also, Serrano et al [66] use national average WF unit values, opposed to the detailed spatial assessment which is the basis for our analysis.

4.4. Uncertainties

The estimated WF of various energy sources in this study have associated uncertainty, but their magnitude and relative proportions seem credible compared to a previous, coarser global assessment by Mekonnen et al [19].

In absolute terms, uncertainty in the total WF of the EU energy sector is mostly governed by uncertainties in the data on energy production and consumption per source (EU energy reference scenario, refs), and the unit WF (m$^3$ TJ$^{-1}$) of the sources contributing the largest share to this total: wood and biofuels. The data from the EU energy reference scenario are the outcomes of a model framework, calibrated by EUROSTAT data. Although each modelling effort is inherent to uncertainties, the outcomes of the EU energy reference scenario have been crosschecked and validated by EU member states. Unit WF amounts also have uncertainties, but as we use detailed geographically explicit databases, with particular information on characteristics, uncertainty will be smaller than e.g. Mekonnen et al [19].

Uncertainties in the unit WF of wood can be significant and are mainly related to the fraction of total forest water use that is allocated to wood production versus other ecosystem services (based on efforts to valuate ecosystem services [56]), and geographically-explicit data on the forest area used for wood production (for details see [20, 52]). The unit WF estimates for biofuels find their roots in the WF per unit of crop as estimated by Mekonnen and Hoekstra [41, 42], for which uncertainties can be up to ±20% [41].

WS amounts as used in this study are obtained from Mekonnen and Hoekstra [34], a modelling study which itself uses different input data. One important uncertainty factor is the choice of definition of environmental flows [37], set at 80% of the natural runoff. A choice of different environmental flows can result in substantially different WS amounts.

4.5. Future work

In our study, we addressed water quantity in the form of water consumption, not water abstraction [57]. We did not address water quality. The energy system has however an important impact on water quality, especially on the temperature of receiving water bodies. In addition, the production of certain energy sources also contributes to water pollution, such as nutrient pollution for 1st generation biofuels. A detailed geographical assessment of the influence of the EU energy system on water pollution requires further research. The grey WF [67] could also be used for this, although some authors explicitly choose not to work with this indicator [68].

5. Conclusions

The European Union, a global player, currently does not explicitly account for water resource use in its energy related policies. We therefore conduct a first-time, comprehensive and spatially distributed analysis of the WF of production as well as consumption of the EU energy sector. We use new databases with detailed spatial information.

Our analysis shows that the unit WF per produced energy amount for the renewables wood, 1st generation biofuels and reservoir hydropower is very high, whereas the amount for the renewables wind, solar, geothermal and run-of-river hydropower is low.

We quantify the absolute WF amounts for the energy produced and consumed in the EU, and
compare these with the water security and food sectors. Energy production has a WF of 1068 litres per person per day (l/cap/d), energy consumption a WF of 1301 l/cap/d. By far the largest part of these amounts is accountable to green water and a smaller part to blue water. Reservoir hydropower, wood and 1st generation biodiesel and bioethanol, with their very large unit WF amounts, are responsible for the largest fraction in the total WF of production and consumption of the EU energy sector. Solar, wind, geothermal and run-of-river hydropower, with their small unit WF amounts, are responsible for a small fraction in the total WF of production and consumption of the EU energy sector.

For the three sectors combined, the WF of consumption of an average EU citizen is 5011 l/cap/d. Municipal water supply accounts for less than 1% of this amount, energy consumption for 26%. In other words, it requires much more water to produce the energy EU citizens consume, compared to the water they use at home.

We show that WF amounts for each energy resource are spatially distributed in a heterogeneous way over the 281 NUTS2 regions of the EU. We also show that different energy sources are produced under blue WS and green water scarcity, both within the EU and outside the EU, in regions where the EU imports from. The fraction of energy quantities produced under WS differs whether computing average annual WS or monthly WS, with summer months accounting for the highest fractions. Policies that promote further externalisation of energy sources through imported biofuels or wood, could result in higher energy insecurity as they are often produced under water scarcity conditions. We recommend for introducing water-related criteria such as the water footprint, in long-term energy policies, to allow for a proper trade-off between decarbonisation goals and water sustainability, which relate to different SDGs.

We believe it is essential that researchers, stakeholders and policy makers working on climate change in the EU become aware of the results of our analysis, which provides the first comprehensive WF assessment to a level of detail required to inform EU policy making.

Data availability

Selected data that support the findings of this study are included within the supplementary material of this article. Additional data that support the findings of this study are available from the corresponding author upon reasonable request. Some data related to certain databases (such as Rystad Energy UCube) are not publicly available for legal reasons.

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