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Water-energy nexus input spreadsheet for calculator model

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Short Description

This report describes how the reciprocal dependencies between water and energy, i.e. the water-energy nexus, are implemented within the European Calculator. The data used to account for the water-energy nexus is also provided.

Quality check

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This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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List of abbreviations

CF – Capacity Factors

EEA – European Environmental Agency

EU – European Union

EU-28 – The 28 EU Member States as of 1 July 2013

EU28+1 - The 28 EU Member States as of 1 July 2013, plus Switzerland

FAO – Food and Agriculture Organization

IEA – International Energy Agency

Glossary

Cooling water: Water used to regulate the temperature of a process.

Fresh water: Water with low concentration of salts.

Local water availability: Refers to internal renewable water resources, excluding upstream inflows from neighbouring countries.

Water consumption: Water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment (Vickers, 1999).

Water demand: The total volume of water delivered to a system over a certain period of time, usually a year.[1]

Water footprint: Indicator that assesses the contribution of the system under study to water impact on the environment.

Water footprint (blue): Used and defined by the Water Footprint Network (WFN). It can be defined as water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time (Hoekstra, 2011). Irrigated agriculture, industry and domestic water use can each have a blue water footprint.

Water footprint (green): Used and defined by the Water Footprint Network (WFN). This is the water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants (Hoekstra, 2011). The green water is particularly relevant for agricultural, horticultural and forestry products.

Water footprint (grey): Used and defined by the Water Footprint Network (WFN). This is the amount of fresh water required to assimilate pollutants to meet specific water quality standards (Hoekstra, 2011).

Water resources: Water from natural resources that can potentially be used and are either renewable or non-renewable. Renewable water resources represent the long-term average annual flow of rivers and groundwater, while non-renewable water resources are groundwater bodies that have a negligible rate of recharge at the human time-scale (FAO)[2]. This term often directly refers to renewable water resources, which are either internal (generated from endogenous precipitation) or external (upstream inflow from neighbouring countries).

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[1] https://www.newportoregon.gov/dept/pwk/documents/Section06.pdf

[2] http://www.fao.org/3/Y4473E/y4473e06.htm

Water scarcity: refers to long-term water imbalances, combining low water availability with a level of water demand exceeding the supply capacity of the natural system.

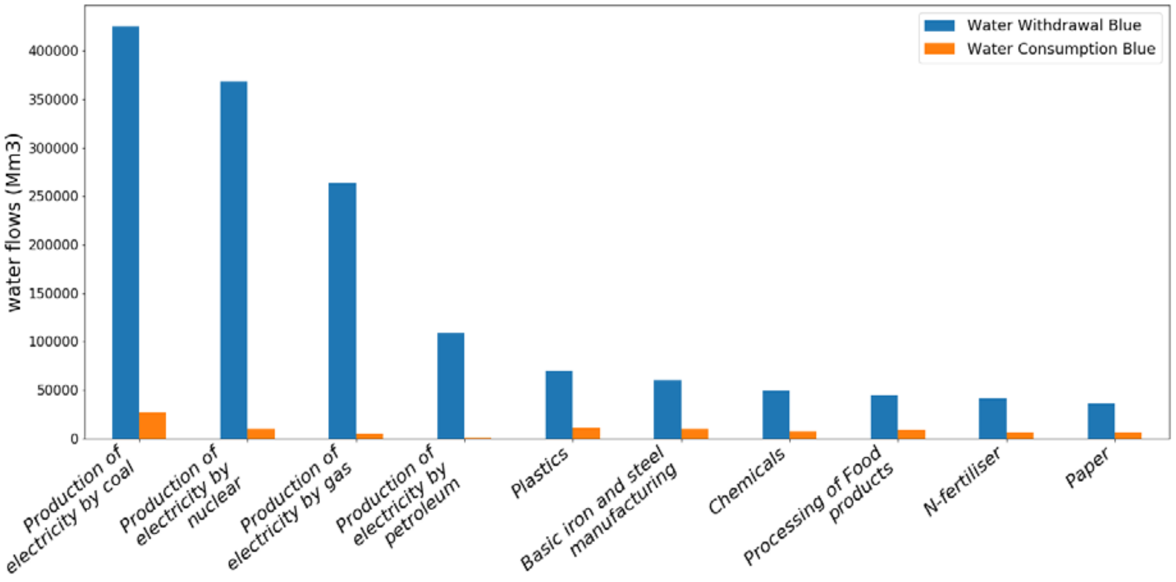
Water stress: occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of fresh water resources in terms of quantity (aquifer over-exploitation, dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.). Usually the Water Exploitation Index (WEI) is used to refer to water stress.

Water use: generic term used to describe an anthropogenic activity that involves water resources.

Water withdrawal: Water diverted or withdrawn from a surface water or groundwater source (Vickers, 1999).

1 Introduction

Recent studies have shown that water resources are increasingly stressed by population growth and climate change, thus contributing to higher scarcity risks (Gosling et al., 2016). Water scarcity arises in case of low water availability combined with water demand levels exceeding the supply capacity of the natural system. These changes in water availability can have an impact not only on food security (Rijsberman, 2006) but also on power generation cooling capacities (Tobin et al., 2018). The European Environmental Agency (EEA) estimated that in 2015, the largest water withdrawals came from agriculture (with around 40% of all withdrawals), followed by electricity production (28%), mining and manufacturing (18%) and households domestic use (11%) (EEA, 2018). At a more detailed level, the activities with the most substantial water withdrawals are the electricity productions from coal, nuclear, gas and petroleum, which abstract water for cooling purposes (see Figure 1).



*"Blue" water refers to the source of supply. It is equivalent to the natural resources (see Glossary for more details)

Figure 1 – Water flows from the most water withdrawing activities in EU over the period 1990-2011 (based on EXIOBASE data[3])

These observations show the extent to which water and energy are interdependent. Indeed, if water is used in mining for energy resources, biofuel production, hydropower generation and thermoelectric plant cooling, energy is conversely used for water extraction, water transport, water end-use and waste water treatment. This interlinkage is called the water-energy nexus (IEA, 2016).

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[3] Exiobase data download: https://www.exiobase.eu/index.php/data-download/exiobase3mon

This report aims specifically at describing the reciprocal dependencies of water and energy within the European Calculator (EUCalc). An excel file with all relevant data is attached to this document, as well as a metadata file describing the data.

2 The water-energy nexus in EUCalc: an overview

In EUCalc, the water-energy nexus is portrayed through the interactions between mainly four modules: Climate, Electricity supply, Agriculture and Water. Figure 2 illustrates the relations between these modules, and in particular the dependency of electricity supply and agriculture sectors on climate and water.

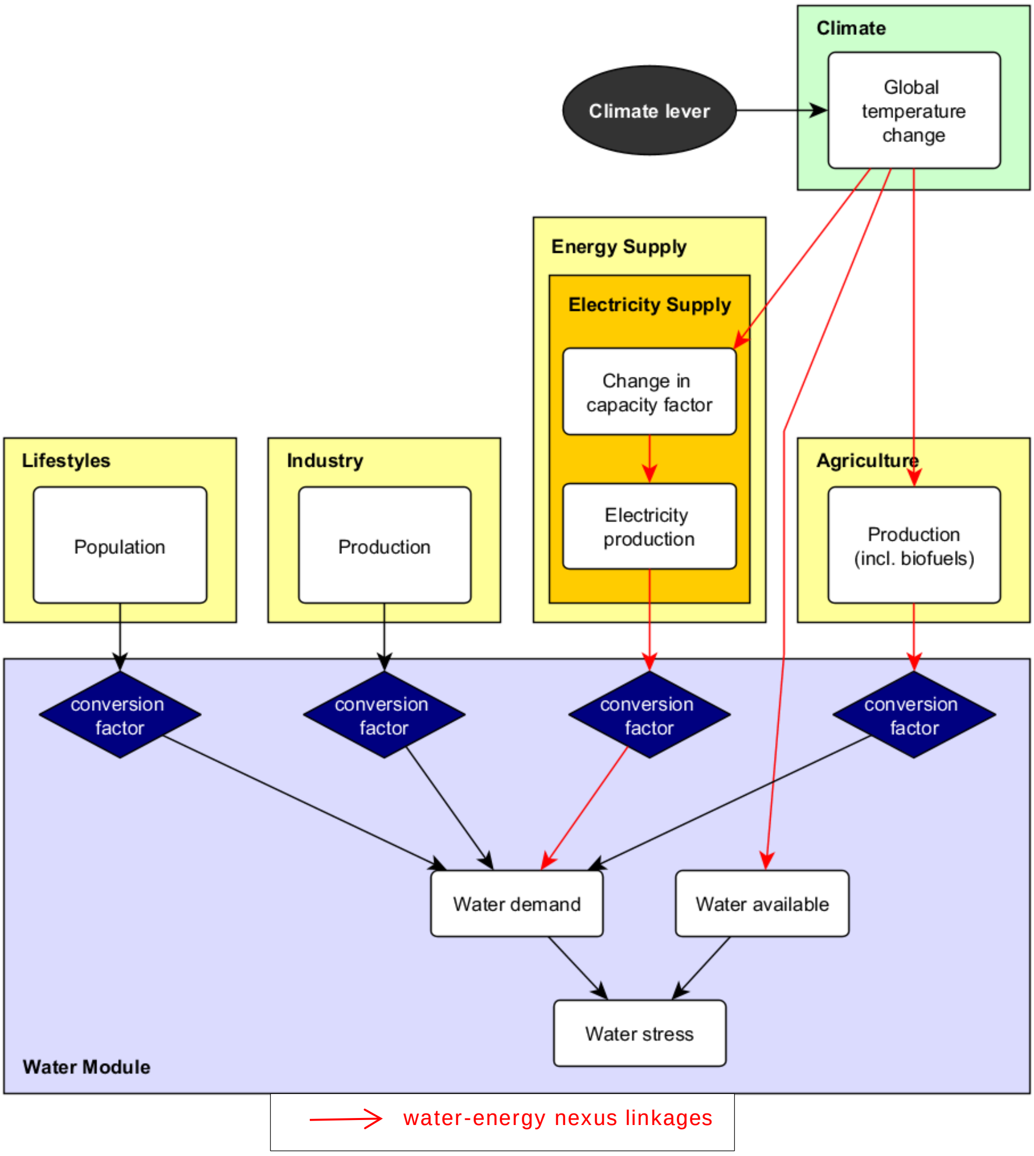

Figure 2 – The water-energy nexus in EUCalc

As shown in Figure 2, a climate lever controls the climate ambitions of the world and thus the variations in global temperature. This temperature change, in turn, impacts water availability. Data for water availability corresponding to the different climate scenarios considered in the model is provided by JRC and compiled in an excel file that can be downloaded with the following link: https://cloud.pik-potsdam.de/index.php/s/qkZyyDxteY8Vn7C (password: wtr_euc_09).

These variations in temperature are used as a proxy in the Electricity supply module to account for the reduction of production capacities of electricity generation systems, which is not only due to a temperature change but also to a shrinkage in water availability (see Section 3.1).

Likewise, the temperature – and water availability – variations affect the crop yields using FAO projections (FAO, 2018). The crop yields are used in the Agriculture module to compute the crops production which are meant to satisfy the demand of crops, including crops for biofuels. For a full description of the calculation logic and assumptions used in the Agriculture module, please refer to Deliverable 8.4 (Baudry et al., 2019).

The electricity and crop productions are then sent to the Water module and converted into water demands (see Section 3.2). The Water module quantifies various impacts of water demands on the local water resources in different user scenarios for the EU28 countries and Switzerland. Different types of water impacts are considered: water withdrawal, water consumption and water stress (see Glossary). Based on (i) the total water consumption derived from the water demand from all sectors and (ii) the local water availability driven by the climate lever, the Water module assesses a water stress at the country level and issues a warning to the users regarding the need to either improve water resource management or curb water demand. For a full description of the calculation logic and assumptions used in the Water module, please refer to Deliverable 8.4 (Baudry et al., 2019).

The following sections describe in more details the water-energy nexus interlinkages included in EUCalc, as well as the flows not modelled.

3 Water for energy systems

Water is a key resource for the following energy-related activities: cooling of thermal generation plants, hydropower generation, biofuel production, mining and production of fossil fuels (coal, oil, gas and nuclear). This section focuses on the water needs for electricity generation technologies by (1) describing how climate and water constrain electricity generation; (2) detailing how water demand is derived from electricity production within the Water module. The interlinkages between water and biofuel production were briefly explained above and follow the same logic. More details are available in Deliverable 8.4 (Baudry et al., 2019), which describes the Agriculture and Water modules. Finally, the water demand for the extraction and refining of fossil fuels is not yet implemented in the model but is considered for future improvement.

3.1 Climate constraint on electricity generation

Climate change can impact the electricity sector by reducing electricity generation capacities. Indeed, reductions in river flows combined with water temperature increases can affect the potential for cooling thermoelectric power plants, but also alter hydropower production due to decreases in precipitation and increases in evapotranspiration (Tobin et al., 2018). In EUCalc, the climate scenarios, as defined by the climate lever, influence the water available for hydropower plants and thermoelectric power plant cooling. More precisely, variations in temperature modify the capacity factors (CF) for hydropower and thermoelectric power generation, thus curtailing the energy production and its associated water demand.

As described in Deliverable 5.1 (Gyalai-Korpos et al., 2019), the CF expresses the ratio of actual production with respect to the full capacity production during a period, usually a year. It is computed as follows:

$$CF\,\% = \text{actual production in a year (kWh)} / (\text{capacity x } 365{,}25 \text{ x } 24 \text{ (kWh)})$$

Each electricity supply technology considered has a different CF depending on its characteristics. Tobin et al. (2018) recently assessed the impacts of climate change on these CF. They adopted an approach combining climate simulations, hydrological and energy modelling with a detailed spatial resolution to assess the impacts of climate change on hydropower and thermoelectric power generation (among others) in Europe for different global warming scenarios: +1.5 °C, +2 °C and +3 °C.

Based on the climate change scenario selected by the user, i.e. either +1.5 °C, +2 °C or +3.2°C change in global temperature by the end of the century, the CF of hydropower and thermoelectric power generation are adjusted in the Electricity supply module using data derived from Tobin et al. (see Figure 3). As the climate module provides the year when the global temperature change is reached, a linear interpolation is applied between the reference year and this target year to obtain yearly values of change in CF. If the source did not include values for specific countries, no changes are assumed. The changes in CF eventually affect electricity production, thus inducing changes in water demand from hydropower and thermoelectric power plants.

Data for changes in CF are compiled in an excel file available online.[4] The first two spreadsheets contain calculations intended to adapt the values from Tobin et al. to the climate scenarios used in EUCalc. Then, each following spreadsheet corresponds to the computed values for one electricity production technology, namely solar photovoltaics, wind, hydroelectric and thermoelectric.

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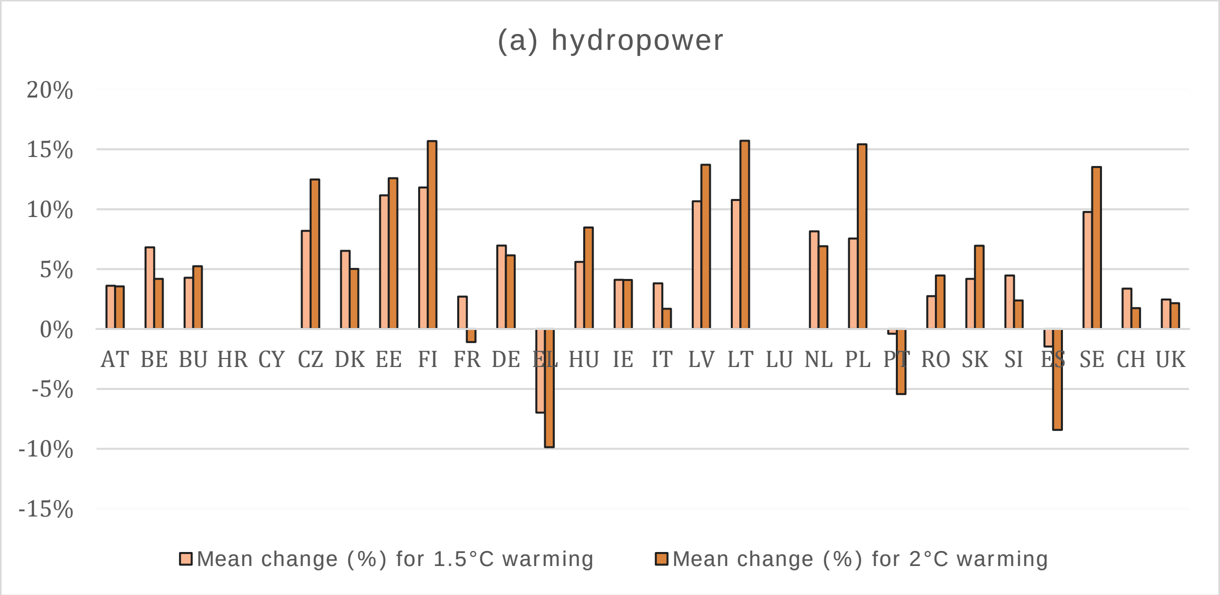
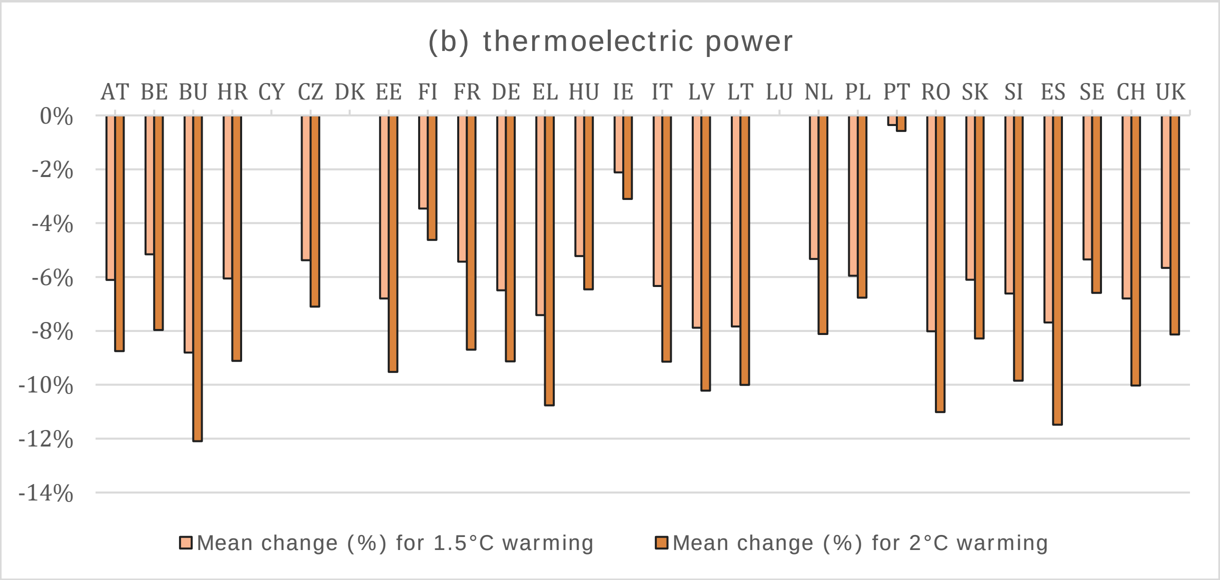
[4] link: https://cloud.pik-potsdam.de/index.php/s/qkZyyDxteY8Vn7C / password: wtr_euc_09





(a) % change in hydropower production relative to the reference period 1970-2000
(b) % change in thermoelectric power production relative to the reference period 1970-2000

Figure 3 - Future changes in national hydropower and thermal power productions under +1.5°C and +2°C global warming (adapted from Tobin et al., 2018)

3.2 Water demand for electricity generation

The water demand for electricity generation, i.e. the water required for hydropower plants and for cooling of thermoelectric power plants, is computed in the Water module. The calculation logic is illustrated in Figure 4.

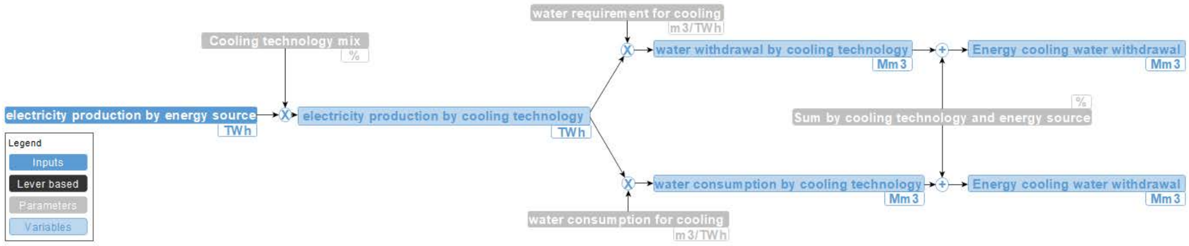


Figure 4 – Calculation logic for electricity generation water demand and flows in the Water module

The electricity generation from each power technology is converted into consumption and withdrawal water flows to account for the cooling needs or for the water evaporation resulting from the dammed water in reservoirs of hydroelectric facilities (Macknick, 2012). Table 1 summarizes the water footprints used in the model by electricity generation technology and cooling system type.

Table 1 – Water withdrawal and consumption factors per electricity generation technology and cooling system type

Technology type	Electricity generation technology	Cooling system	Water withdrawal values (m3/GWh)	Water consumption values (m3/GWh)	Source
Fossil	Coal	Once-thru	138’000	1’000	Davies et al., 2013
		Wet tower	3’800	2’600	
	Oil	Once-thru	132’000	900	Davies et al., 2013
		Wet tower	4’600	3’100	
	Gas	Once-thru	132’000	900	Davies et al., 2013
		Wet tower	4’600	3’100	
	Nuclear	Once-thru	168’000	1’000	Davies et al., 2013
		Wet tower	4’200	2’500	
	Biomass	Once-thru	132’000	1’100	Davies et al., 2013
		Wet tower	3’300	2’100	
Renewable	Solar PV		114	20	Adapted from Fricko el al., 2016
	Solar CSP		3’300	3’300	
	Wind onshore		2,47	2,47	Adapted from Fricko el al., 2016
	Wind offshore		2,47	2,47	
	Marine		0	0	
	Hydroelectric		0	17’000	Davies et al., 2016
	Geothermal		30	30	Adapted from Fricko el al., 2016

Table 1 shows that fossil technologies usually withdraw and consume much more water than renewable technologies. For fossil technologies, water flows are related to cooling needs from power plants. In the “once-through” technology, water is extracted from a river/reservoir, heated and directly discharged back into the water body, which leads to high withdrawals but low consumption. In the “wet tower” systems, water is either fully (in closed circuit) or partially (once-through with cooling towers) evaporated, which leads to higher consumption but lower withdrawals (Payet-Burin et al., 2018). Regarding renewable technologies, solar panels and wind systems require little water, mainly for cleaning. Geothermal technologies use relatively very small amounts of water for operational purposes. Finally, while marine (hydrokinetic) technologies do not extract water from the environment, hydroelectric technology induces high evaporative losses due to the dammed water (Macknick et al., 2012).

Water flows generated by the electricity generation sector are not only influenced directly by the energy technology mix but also indirectly by the demand of electricity from sectors such as transport or buildings. This suggests that the energy dependence on water can be mitigated in EUCalc through lever settings by switching to more renewable technologies (“power” levers), or by acting on the demand side, for instance by reducing the number of appliances used in households and buildings (“appliances owned” lever) or by turning to more efficient appliances (“appliance use” lever).

4 Energy for water systems

After assessing the water needs for energy production, we analyse in this section the dependence on energy of the water supply chain. Energy is used for the extraction from freshwater resources or through desalination, conveyance and distribution, end-use, and wastewater collection and treatment. According to the International Energy Agency, the water sector accounted for less than 4% of the total electricity consumption in the EU in 2014 (IEA, 2016).

The end-use, and more precisely heating for domestic hot water, is the most energy-intensive process (Plappally, 2012). For instance, Gerbens-Leenes (2016) found that heating water represents 92% of the energy needs to supply water in the Netherlands. In EUCalc, the energy demand for domestic hot water in buildings, which falls into the “end-use” step of water provision, is computed in the Building module. This energy consumption can be managed in EUCalc by adjusting the “Heating, cooling & hot water use” lever.

The energy consumption of on-farm irrigation systems, such as pressurized application systems (drip or sprinkler) and ground water abstraction from deep aquifers, is included in the Agriculture module, which computes the total energy demand to produce crops (for food, animal feed, bioenergy), vegetables and fruits, and livestock. The AGRiculture & Energy Efficiency (AGREE) project analysed the energy consumption of several agricultural processes in European countries. They found that the share of irrigation depends on the geographical location (and related climate), and on the intensity of the production systems. For instance, diesel used for field operations is the main direct energy input for wheat and sunflower production while irrigation represents a small share of the energy demand for these processes. On the other hand, irrigation represents about 70% of the direct energy input for cotton production (Gołaszewski et al., 2012). In EUCalc, the first version of the Agriculture module used to dissociate the irrigation energy demand from the other consumption (e.g., field operations, drying, storage) using the FAOSTAT database[5]. However, due to the need to use a common database across the modules concerning energy demand and supply for consistency and calibration sake, JRC IDEES[6] have been used to track the energy consumption of each sector and modules. As a drawback, IDEES does not dissociate energy-use for irrigation, which induce a limitation of the module regarding this specific issue.

Finally, the energy needed to extract water (from freshwater resources or through desalination), to treat and distribute it, and to collect and treat wastewater, is not modelled in EUCalc. Indeed, the Water module focuses on water quantity instead of quality. Water quality issues are outside the scope of this calculator because of limited data availability and the fair complexity of modelling processes such as nutrient pollution. Moreover, there does not exist a commonly accepted definition of water quality (Sutadian et al., 2016), thus hampering the design of reliable water quality indicators. Last but not least, modelling water treatment and reuse or desalination would create feedback loops (in particular with the energy supply module) thwarting the objective of real-time computation. Nonetheless, these aspects might be introduced in future developments of the calculator. Figure 5 illustrates a complete schematic view of the Water module, with the modelized and non-modelized elements.

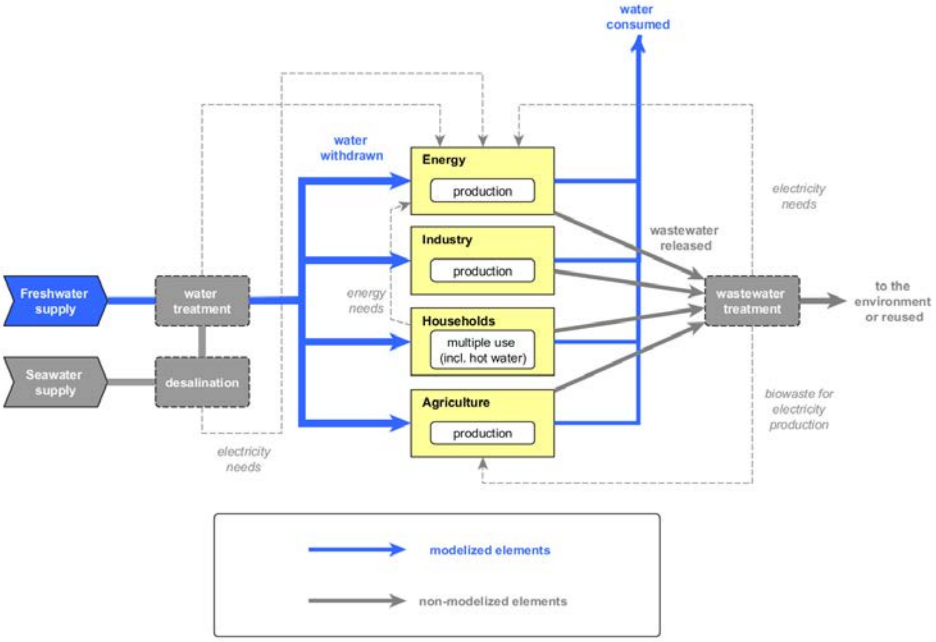


Figure 5 – Modelized and non-modelized water flows in the water module

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[5] Food and Agriculture Organization (FAO), FAOSTAT, Energy-use – Energy for power irrigation. Direct link: http://www.fao.org/faostat/en/#data/GN

[6] The JRC "Integrated Database of the European Energy System" (JRC-IDEES). Direct-link: https://ec.europa.eu/jrc/en/potencia/jrc-idees

5 Conclusion and lessons learned

Modelling the water-energy nexus requires an integrated approach. However, focusing only on energy and water resources is not enough to properly manage them. Indeed, such an approach would miss the potential competition for water resources with other use, such as food production. For this reason, the water-energy nexus is not a distinct feature in EUCalc. It is rather portrayed via the interlinkages between several modules such as Climate, Energy supply, Agriculture, Buildings and Water.

Although the EUCalc modular approach allows to implement the main water-energy nexus flows, the model also has several limitations. First, the space and time granularity (country and year) is not enough to properly model the impacts of water scarcity on food production or electricity generation. Indeed, these impacts generally occur in localized areas and during short period of time. A compromise was achieved in the Water module by increasing the granularity to include several regions inside large countries and two semesters. Second, as mentioned above, the calculator adopts an oriented-tree approach which prevents – in the current version – feedback loops to save computation time. On the other hand, to depict a complete picture of the water-energy nexus would require closing the loop, i.e. integrating the energy demand to supply and treat water.

References

Baudry, G., Raffray, M., Bouchet, A., Price, J., Forstenhaeusler, N. Onesmus Mwabonje, O., and Woods, J. (2019). Deliverable 8.4: Integration of the resource's modules "Land allocation, biodiversity impact & forestry", "Water scarcity" and "minerals" modules. Public Deliverable of the EUCalc project.

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L. and De Roo, A., Impact of a changing climate, land use, and water usage on Europe's water resources, EUR 29130 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-80287-4, doi:10.2760/847068, JRC110927.

Davies, E. G., Kyle, P., & Edmonds, J. A. (2013). An integrated assessment of global and regional water demands for electricity generation to 2095. Advances in Water Resources, 52, 296-313.

European Environment Agency (2018). Water use in Europe — Quantity and quality face big challenges. Link: https://www.eea.europa.eu/signals/signals-2018-content-list/articles/water-use-in-europe-2014

FAO (2018). The future of food and agriculture, Alternative pathways to 2050. FAO, Rome.

Fricko, O., Parkinson, S. C., Johnson, N., Strubegger, M., van Vliet, M. T., & Riahi, K. (2016). Energy sector water use implications of a 2 C climate policy. Environmental Research Letters, 11(3), 034011.

Gołaszewski et al. (2012). State of the Art on Energy Efficiency in Agriculture - Country data on energy consumption in different agroproduction sectors in the European countries. Project deliverable 2.1 of the AGRiculture & Energy Efficiency (AGREE) project. Report available here: https://edepot.wur.nl/278550

IEA (2016), World Energy Outlook 2016, IEA, Paris, https://doi.org/10.1787/weo-2016-en.

Gerbens-Leenes, P. W. (2016). Energy for freshwater supply, use and disposal in the Netherlands: a case study of Dutch households. International journal of water resources development, 32(3), 398-411.

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. Climatic Change, 134(3), 371-385.

Gyalai-Korpos, M., Hegyfalvi, C., and Zsiborács H. (2019). Deliverable 5.1: Energy supply module documentation. Public Deliverable of the EUCalc project.

Hoekstra, A.Y. (2011). The Water Footprint Assessment Manual, Water Footprint Network – WFN.

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters, 7(4), 045802.

Payet-Burin, R., Bertoni, F., Davidsen, C., & Bauer-Gottwein, P. (2018). Optimization of regional water-power systems under cooling constraints and climate change. Energy, 155, 484-494.

Plappally, A. K. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. Renewable and Sustainable Energy Reviews, 16(7), 4818-4848.

Rijsberman, F. R. (2006). Water scarcity: fact or fiction?. Agricultural water management, 80(1-3), 5-22.

Sutadian, A. D., Muttil, N., Yilmaz, A. G., & Perera, B. J. C. (2016). Development of river water quality indices—a review. Environmental monitoring and assessment, 188(1), 58.

Tobin, I., Greuell, W., Jerez, S., Ludwig, F., Vautard, R., Van Vliet, M. T. H., & Breón, F. M. (2018). Vulnerabilities and resilience of European power generation to 1.5 C, 2 C and 3 C warming. Environmental Research Letters, 13(4), 044024.

Vickers, A.L. (1999). “Handbook of water use and conservation”. United States.