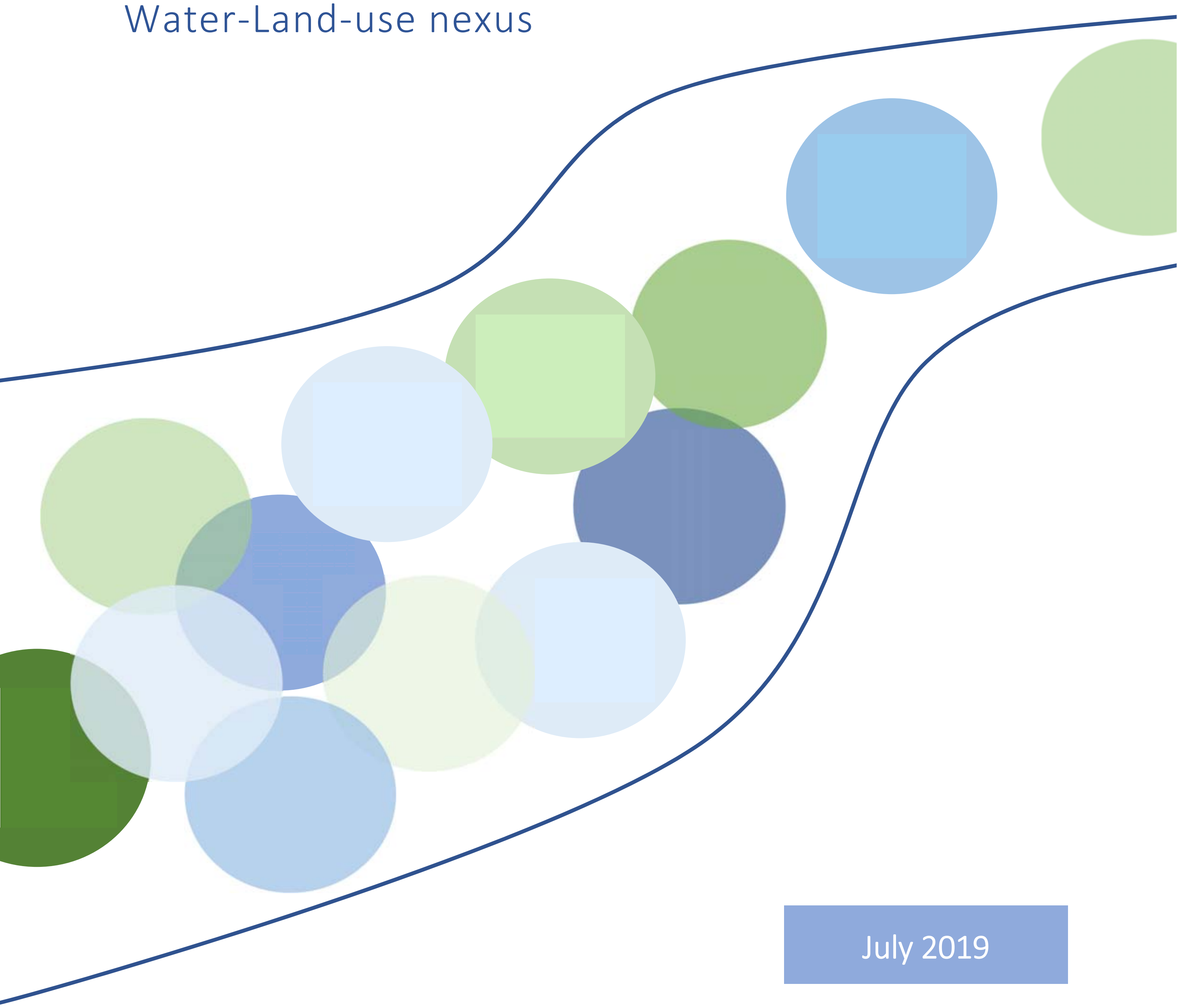
Deliverable 5.1

Focus Report on climate impacts on the Energy-Water-Land-use nexus



July 2019

About this report

This report has been undertaken under WP5 of the REEEM project 'Environment, Health and Resources', and constitutes Deliverable 5.1 'Focus Report on climate impacts on the Energy-Water-Land-use nexus'.

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About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

The REEEM project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691739.

Contents

Summary

This report analyses impact of climate change on the Energy-Water-Land-use nexus through focused studies presented in an article format. The studies are grouped and presented in the 3 sections outlined below.

1) Part I – Water Use for Electricity Generation, consist of 3 studies and focuses on water use for electricity generation.
2) Part II – Future Heating and Cooling Needs, consist of 1 study and focuses on changes in heating and cooling demand in Europe due to climate change.
3) Part III - Water Usage and Land-Use-Change Emissions from Biomass, consists of 1 study and focuses on projected water usage and emissions from land-use-change for biomass for energy production.

One of the findings of Part I – Water Use for Electricity Generation is that there is a substantial gap in the availability, access and quality of proper regional and global data in order to facilitate detailed quantitative analyses within the water-energy nexus. There is a great need for improving the current quality and availability of historical water use data (withdrawals and consumption) for virtually all major sectors and sub-sectors related to the water-energy nexus, including at matching spatio-temporal scales relevant for linking water and energy systems. In addition, there is also an urgent need for improved standardization of formats and data collection methodologies across different uses of the data, which in most cases presently are incompatible. Advances in this regard would immensely aid not just the validation of methods and models but would also contribute to an improved confidence in nexus assessments in support of management procedures and policy goals related both to current and future conditions. On top of the above, the standardization should also encompass future projections and scenarios for highest possible consistency similar to those of other multidisciplinary studies.

Additionally the extent to which estimates of an ensemble of factor sets representing volumes of water use per unit of electricity produced by different energy sources, in conjunction with a comprehensive review of the individual cooling technologies and water sources for individual electricity plants, provide an adequate predictor of water withdrawal and consumption levels generation by energy production was investigated. Based on validation data, the factor set estimates are found to generate a skilful reproduction of reported withdrawals on the coarse scales that were assessed, which, on a yearly basis, include historical levels for EU28 (1980-2015) and individual country levels (2015). The country-level information was extracted from a number of databases, some of which were found to be ambiguous, inadequate and/or contradictory. To support quantitative studies of the water-energy nexus at different levels and thus facilitate the improved management of water resources, sustained and coordinated efforts are needed towards improving the availability of data linking observations and projections of energy and water systems at relevant spatio-temporal levels using common scenarios (including climate change) and assumptions.

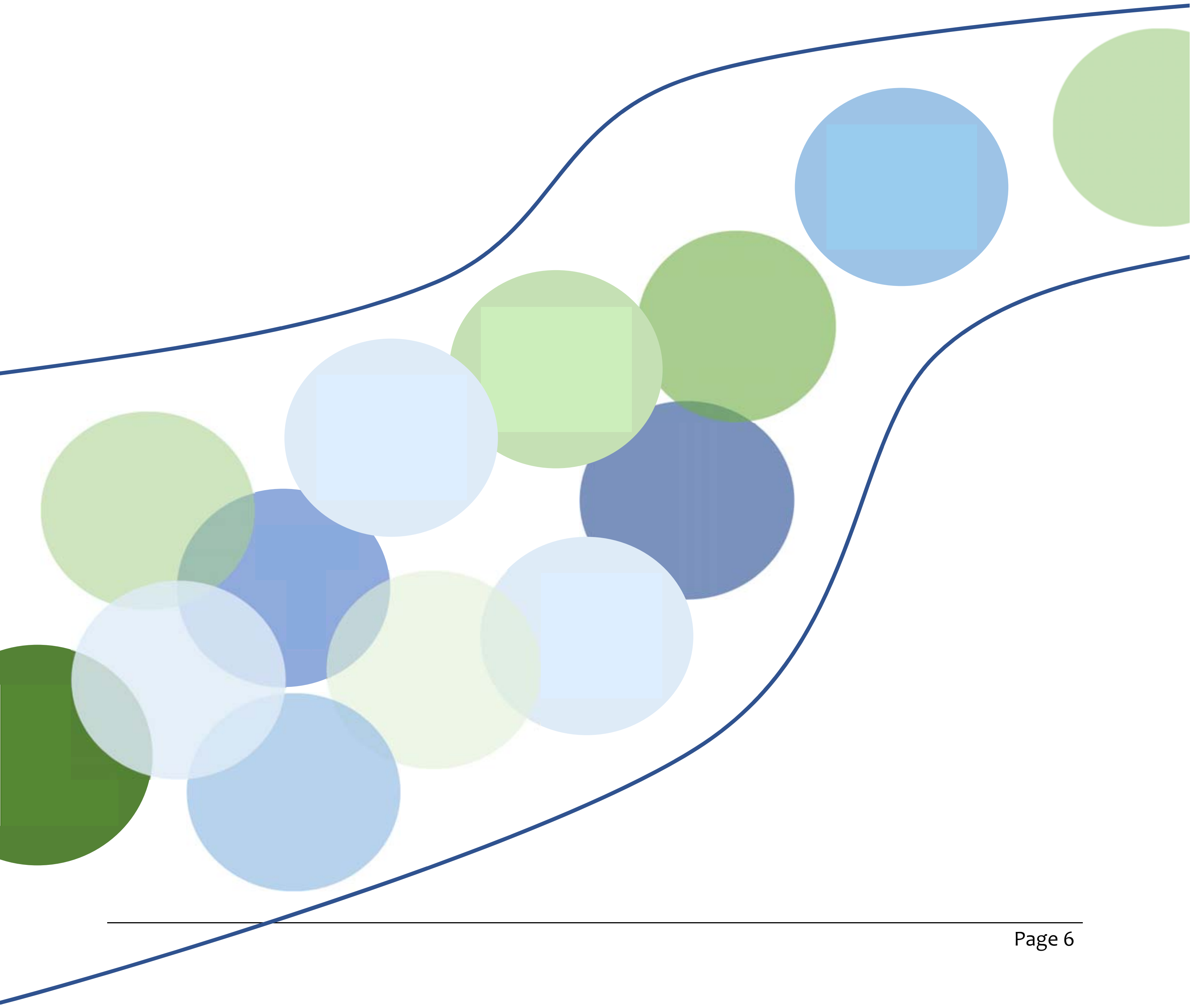
Assessment of REEEM Pathways with regard to water use for electricity generation shows that on a country level, the change in water consumption from 2015 towards 2050 is mainly affected by reduced levels of fossil fuel thermal plants, there among coal, and the introduction of geothermal energy acting as a counterbalance to these reductions. Six countries show increasing levels of water consumption regardless of the pathway whereas seven to ten countries show diverging sign of change depending on the scenario. The corresponding water availability shows a cross-model standard deviation corresponding to index levels of +/- 25-80% for individual countries.

Future Heating and Cooling Needs finds that, when analysing the mean temperatures, the annual anomalies show an increasing warming with the RCP forcing (RCP2.6 and RCP4.5) and distance into the future (2026-2035/2046-2055). The relative warming increases towards the north-eastern parts of Europe as well as for higher altitude areas such as the Alps, the Pyrenees, the Iberian Peninsula and the Carpathian Mountains. The occurrences per year > 22ºC of 100 days or more are seen in Southern and Eastern Europe. On a general level, following the warming trends represented by the RCP scenarios, the number of HDDs decreases throughout the European domain whereas the opposite is the case for CDDs. It is also evident that the temperature change in areas with high demands is the main driver for the change of national heating and cooling demands. Almost all countries in northern and western Europe have a higher decrease in HDD for RCP4.5 (>10% decrease) than for RCP2.6 (5-10% decrease). All countries in Europe are projected to experience a moderate reduction of heating demands between 5% and 10%, with the exception of Cyprus and Malta. The largest increase in cooling demands is seen for RCP4.5 especially for the Northern parts of Europe including UK, Germany and the Baltic countries (>100%). The main share of countries affected by cooling demands in both the base year and projection year experience increased relative cooling demands in the range of 25-75%.

Finally, Water Usage and Land-Use-Change Emissions from Biomass emphasizes the importance of recognizing the need for “downscaling” EU strategies to the national level and further to the regional and local levels, where overall targets are confronted by “reality” in the form of land and water resources as well as competition from other socio-economic sectors. Capacities and resources vary amongst regions. Hence, water availability, which is a critical factor for biomass productivity, may loom as a barrier for expanding the share of bioenergy production in some countries, in particular, Southern Europe. This is further likely to be exacerbated by climate change. To some extent, this can be circumvented by smart, informed choices on management practices and the types of biomass to pursue. Oil crops like rapeseed, are highly energy efficient, but also associated with high emissions and a high water usage compared to other kinds of biomass. Thus it must be carefully considered, whether this kind of crop is the optimal focus for a potentially water stressed country such as France even for a transitional period.

Part I

Water Use for Electricity Generation



Challenges of Data Availability: Analysing the Water-Energy Nexus in Electricity Generation

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Submitted to Energy Strategy Reviews.

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Keywords: Water-energy nexus, water-energy data, energy systems, integrated management, sustainable development, natural resources.

Abstract

Water is paramount for the operation of energy systems as well as securing food supply, industries, and municipalities and demands across sectors can negatively affect water scarce regions by e.g. power plants shutdowns, poor agricultural yields, and lack of potable water. Future economic and population growth as well as climate change is likely to exacerbate these patterns. However, models used for energy system management and planning in general do not properly include water availability which can lead to improper representations of water-energy interlinkages.

The paper initially highlights the water usage rates for current technologies within electricity generation and technologies with a potential to reduce water usage, electricity consumption or GHG emissions. Secondly, the paper presents currently available data on current and future projected water resources as well as data on energy statistics relevant to water-energy nexus studies. Thirdly, implementation cases are presented showing potential water-energy nexus uses for the data presented. Finally, the paper highlights main challenges in studying the linkage between water and energy. We find a substantial gap in the availability and quality of regional and global data for detailed quantitative analyses, despite existing data for some regions, and also identify a need for standardization of formats and data collection methodologies across data and disciplines. An effort towards a coordinated, and sustained open-access data framework with energy sector water usage at fine spatio-temporal scales alongside hydro-climatic observation and model data using common forcings and scenarios for future projections is therefore recommended for future water-energy nexus studies.

1. Introduction

Resolving the highly interlinked and interdependent nexus of water, energy and food systems presents a formidable challenge for sustainable development [1]. The importance of taking a nexus approach in policy and planning is highlighted globally in the UN 2030 agenda and its 17 Sustainable Development Goals (SDGs) [2,3] and regionally in the EU Water Framework Directive [4]. To properly analyse the coherence and competing demands of this nexus, not only at different temporal and spatial scales but also across sectors and climatic conditions, calls for integrated, systematic approaches and tools [5,6].

Water, as a part of the nexus, is an integral part of resource extraction, production, distribution, and use of energy. However, according to [1] 90% of the world's electricity and fuel production relies on non-sustainable water sources with regards to either quantity or quality, and overall electricity and fuel production accounts for about 15% of global water withdrawals. Conversely, the extraction, treatment, transport, and cleaning of water and waste water requires notable amounts of energy on their own amounting to, e.g., 4% of the total energy usage (transport and treatment alone) and 5% of total greenhouse gas (GHG) emissions in the US [7].

The demand for water, energy, and food is increasing, driven by a growth in population and economies, migration and consumer behaviour [8]. Global water withdrawal demands are expected to increase by 55% in 2050 [1] and 48% for global energy consumption by 2014 [9]. Moreover, in many places these increasing demands will induce intensified pressures on natural recourses and ecosystems, which are also exacerbated by climate change [10,11]. The human impact on global water resources has been shown to greatly surpass the impacts of climate change for irrigated river basins [12–14]. The latter finds 62-76% of the global river basin areas to experience increased water stress by 2050 (depending on scenario) and the main cause is attributed to income growth (more so than population growth). Along with changes in the distribution and demand-supply of water resources, land use patterns are also likely to change significantly due to population growth and the associated increased demand for natural recourses, commodities, and food, including increased agricultural, industrial, and urban areas [15]. Changes to the energy mix also affect the land use by introduction of new and expansion of existing energy technologies such as wind power, solar photovoltaic system (solar PV), hydropower and biofuels.

Projected future increases in energy demand are currently expected to be driven, in particular, by developing countries having the highest rates of economic and population growth combined with a low share of renewable energy technologies [1,16]. Increased global deployment of renewable energy technologies of which many are less water intensive than, e.g., existing thermal power generation from fossil sources has the potential to decrease water stresses and GHG emissions. However, the intermittent nature of renewable electricity generation such as solar PV, wind, and runoff/river hydro can result in a mismatch between energy supply and energy demand and thus entails a need for energy storage. Advances within plant efficiencies, decreased costs of electricity and fuel production, clean technologies (such as solar, wind, hydropower, carbon capture, recycling, biofuels), and storage/utilization is likely to aid in meeting future energy demands [17,18].

In general water and energy systems are managed and monitored at most scales, and therefore the availability of proper data sources in support of sustainable management of the water-energy part of the combined nexus should in principle be ensured. However, while adequate data exist on water recourses and electricity generation respectively, data on, e.g., water usages related to electricity generation remain much more limited. The same applies to information on the cooling technologies used in electricity generation, which may influence estimates of water use as much as the generation technology itself. Not to mention that for hydropower and bioenergy the relation of water use to electricity and fuel production is unclear. In this context reviews by [19–21] have previously addressed the operational water consumption and withdrawals (volume of water use pr. unit of electricity or fuel produced). Other studies have linked geographically distributed electricity generation and water resources globally [22,23] and regionally [24]. The availability of consistent data sets presents a significant challenge. Detailed analyses along the water-energy nexus require spatio-temporal information on the water usage and electricity generation technologies. But the nature of these data is multiplex and no coherent database exists holding this information at a level of detail adequate for supporting potential analyses of, e.g., achievable electricity generation pathways for water sustainability and future GHG reduction scenarios as also addressed by [25]. Further, currently available data coming from a range of sources, research communities and institutes lack a shared format, can be software specific [26], are non-accessible [27] or might include too vast a number of assumptions, and quality issues making them unsuited without proper experience.

Optimally, specific knowledge on the amount of water withdrawn and consumed should be employed. For reasons such as lack of control and bookkeeping [28], commercial interests [7,29], imprecision in registered values [30] or even expensive paywalls [31] these water usage levels are rarely comprehensive and assumptions and estimations therefore have to be made. One approach is to assess the specific technologies in question for the plants and facilities (without directly available data) and estimate water usages based on comparable plants operating under similar conditions although with a loss of detail as a result, as e.g. seen in [32]. Depending on the application, knowledge on water usages can be combined with plant- and facility locations ranging from sub-basin-level scales including information on source (aquifer/extraction depth/river etc.) up to country-level scales as typically used in larger scale studies. Finally, temporal scales could range from sub-daily data to account for market and pricing influences production up to yearly summarized data for larger scale studies.

In this paper we highlight some of the critical interlinkages mentioned above, including requirements and data availability for specifically analysing the nexus between water and electricity generation. For comparative purposes and to highlight technologies which are emerging and have the potential to shift the generation of electricity in a more sustainable direction further aspects have been included (e.g. biomass, CO_2 capture/storage, and energy storage). Initially, I) we address current estimates (ranges as well median values) of operational water usage in electricity and fuel production (consumption and withdrawals) and resource extraction for different energy technologies. Secondly, II) we summarize relevant examples of available data on large scale water resources (current and future) as well as energy statistics data relevant to water-energy nexus studies at different spatial scales. We then, III) present three implementation examples using some of the presented data to reflect potential uses in assessing the nexus between electricity generation and water (and climate conditions). Finally, IV) we discuss some of the present limitations, uncertainties and associated implications in linking water resources in terms of quantity (availability), quality and variability with ongoing efforts in energy system modelling and resulting policy recommendations along the water-energy nexus in a projected future of further carbon- and water constraints.

2. Water use in energy production and resource extraction

In the following, the term water is denoted as freshwater. Thus, the usage of sea water for, e.g., power plant cooling is not addressed. Water withdrawal is defined as the total extracted and diverted water including the share reinjected into the supply source whereas water consumption is the net balance, including only evapotranspirated water and water stored in crops and/or other products. Water consumption therefore becomes a subset of water withdrawals and differences between withdrawals and consumption can be substantial. Jointly, water withdrawals and consumption are referred to as water usage.

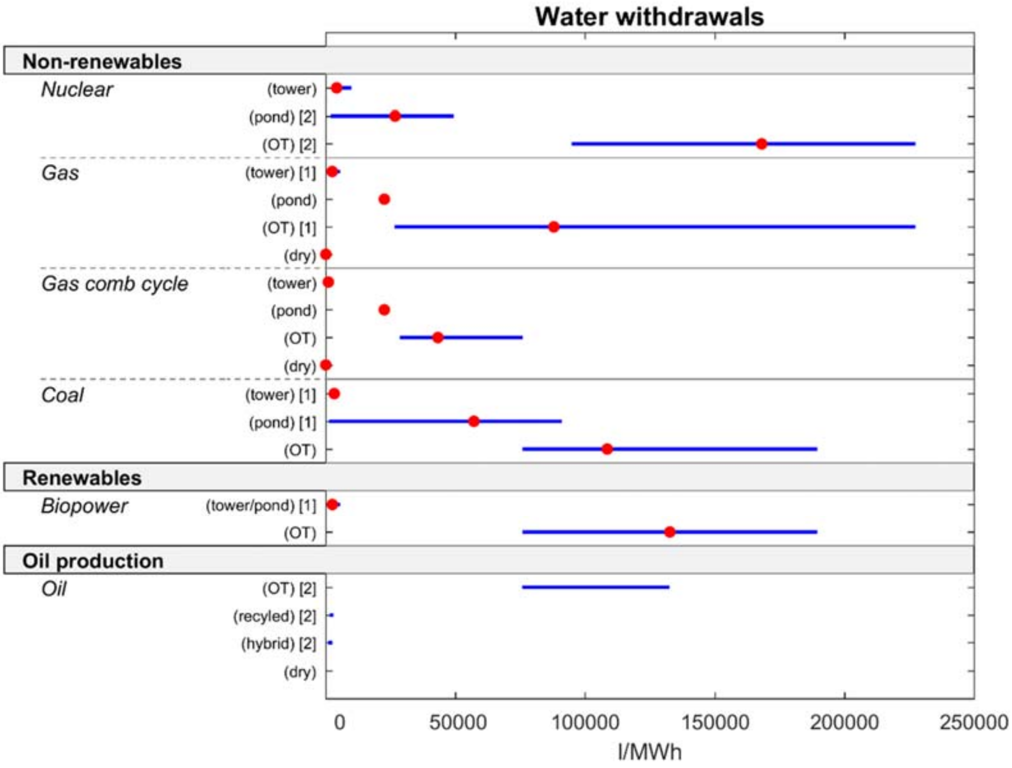


Figure 1. Operational water withdrawal ranges (median (where available), min and max) from common or prospected future energy technologies based on a review of both peer-reviewed and grey literature. The references for figure 1 and 2 include: [1,19,36–44,20–22,26,32–35].

Other than being dependent on energy source, type of plant/generation technology and cooling technology, the water availability, and therefore water usage, in electricity generation is highly dependent on the geographical location and thereby the hydro-climatic conditions in question. Geographical differences in water usages have not been included here, but it is worth noting that estimates of water use from the US, and to some extent EU, dominate the picture as corresponding estimates from other regions of the world are in general not easily obtainable. Environmental concerns, jurisdiction, policies and end-user water-energy interactions are also outside the scope of this paper. Due to limitations in addressing water quantity issues in the water-energy nexus, remote sensing/satellite data are also not taken into account here despite obvious large scale benefits.

Figures 1 and 2 collate the water withdrawal and consumption associated with currently common or prospected future energy technologies based on a comprehensive literature study of previous publications including both peer-reviewed and grey literature.

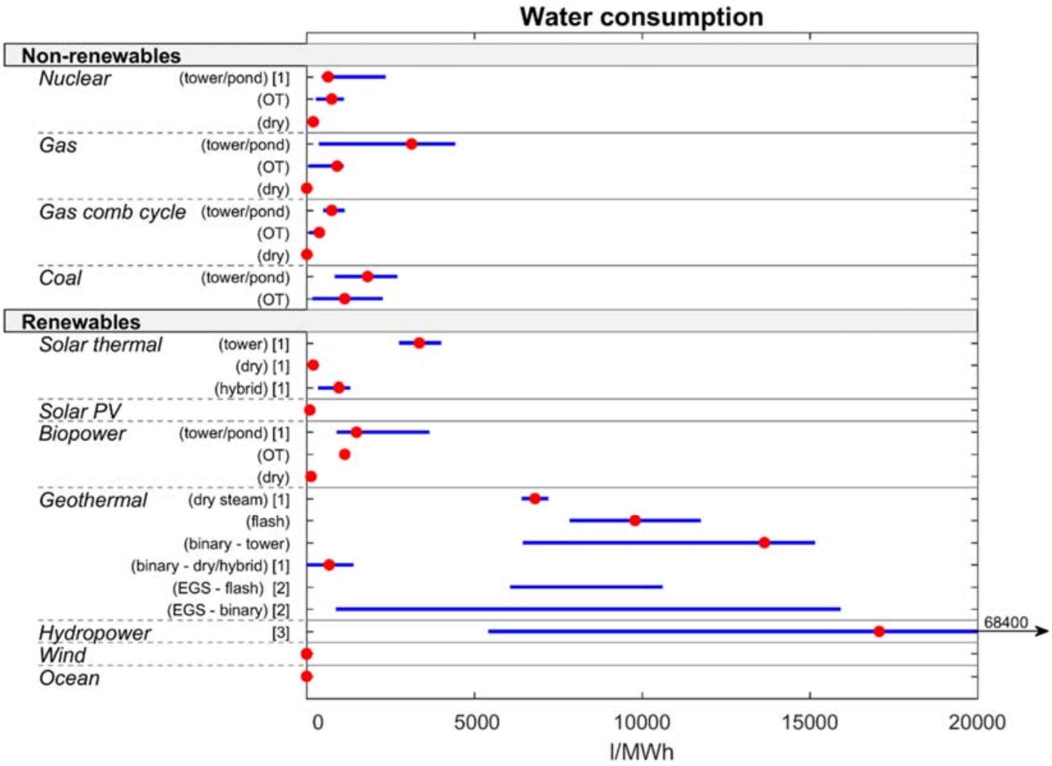


Figure 2. As for figure 1, but for operational water consumption.

2.1 Non-renewable sources

2.1.1 Thermal power plants

Thermal power plants currently make up approx. 80% of the global electricity generation [1] and share many characteristics, including the processes related to water usage, independent of their power source (coal, nuclear and, to some degree, gas). For these plants, cooling accounts for the bulk share of total water usage. For thermal power plant turbine cooling the closed water loop driving the turbine requires only limited amounts of make-up water. Cooling of the closed loop on the other hand is very water intensive but also highly variable. In general the cooling of thermal power plant may be divided into three categories (figure 3): I) Once-Through cooling (OT), II) Recirculation/tower/pond cooling (REC) and III) Dry cooling (DRY). The relative share of the different technologies is distinctly related to the availability of water resources and associated legislations. For example in the US the relative share of these different cooling technologies amounts to 43%, 56% (thereof 15% using cooling ponds) and 1% respectively [45]. OT plants generally employ water from adjacent sources such as rivers, groundwater, lakes (or the sea) and returns cooling water to its source (in a warmer state). Correspondingly, the withdrawal rate is immense for all energy sources (25,000-225,000 L/MWh) (figure 1) whereas the consumption rate is considerably less (50-2,300 L/MWh) (figure 2). Newer plants rarely employ OT cooling. REC based plants where water is reused in a loop, and where cooling is employed by evaporation have considerably lower withdrawal rates of 550-10,000 L/MWh for tower based plants and 1,100-91,000 L/MWh for pond based plants.

Consumption rates on the other hand are found to be slightly higher than for OT based plants for all energy sources and towers/ponds combined due to the evaporation loss (360-3,300 L/MWh). DRY based plants constitute a negligible share of the current global electricity generation (although on the rise with implementation examples from USA and South Africa) and use no water for cooling purposes, which is counterbalanced by lowered efficiencies (2-5%) and higher costs (3-8%) depending on the local climate. Hybrid plants, combining cooling technologies, consume only about 20-80% of water volumes required by REC plants [26] and are seen as fundamental for reducing plant water consumption within currently available methods. Nuclear plants in general have lower efficiencies and therefore have the highest consumption and withdrawal rates for thermal plants but are also more flexible in the choice of location due to the higher energy density in the fuel and can therefore more often use sea water cooling. Secondary water usages vary between thermal plants and include, e.g., pollution/dust control, cleaning and staff usage. In general, coal plants have the highest secondary usage levels (approx. 350 L/MWh) [26].

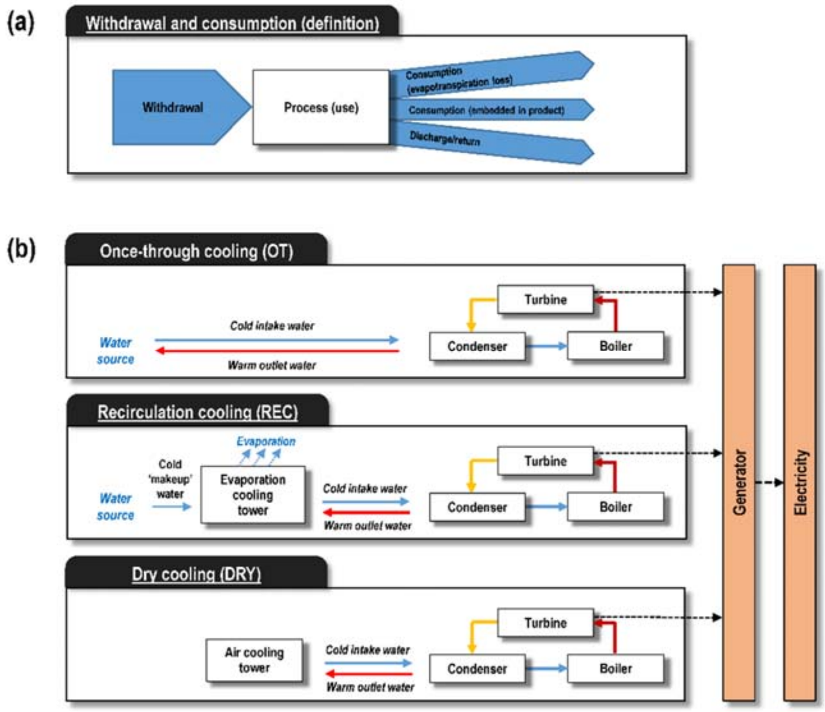


Figure 3. Water withdrawal and consumption definition (a) and cooling technologies in thermal power plants (b).

2.1.2 Water consumption in Oil, gas and coal extraction

The water consumption in oil, gas and coal extraction vary in relation to mainly geology, type of recovery and state of the reservoir. The main consumption share relates to secondary and tertiary oil recovery. For secondary recovery, water is injected below the surface to boost the extraction rate and the level of depletion. For tertiary recovery (often called EOR), various techniques are employed to enhance extraction by reduced oil viscosities by, e.g., steam injection from a co-generation power plant. Secondary extraction (80% of oil production in the

US) consume 802 L/MWh, whereas tertiary extraction (almost the remaining 20% of oil production in the US) consumes 505-1215 L/MWh [33]. Oil extractions in shallow oil sands generate consumption rates of 180-425 L/MWh (both mining and upgrading) [33]. Deeper deposits involve on-site upgrading with consumption rates of 25-210 L/MWh and is dependent on oil product and local geology. Water consumption from conventional natural gas extraction is negligible. Shale gas hydraulic fracturing has a limited water use of 17 L/MWh, but is applied very locally both spatially and temporally and is the subject of considerable environmental concerns [46]. Coal extraction involves consumption rates of 14-105 L/MWh for mining and washing and an added 43-90 L/MWh if transported by slurry pipeline [33].

2.2 Renewable sources

2.2.1 Biomass

Biomass used for liquid fuels in transportation and energy products is considered one of the key renewable energy sources aligned to reduce the use of fossil fuels [47] while requiring minimal changes to current infrastructure and vehicles [48]. The true net biomass carbon footprint is however debated and depend on the way it is implemented into the energy system [49]. An estimated 32 exajoules (10^{18} J) of biofuels will be required globally by 2050 (27% of the envisioned world transport fuel) to reach the global energy-related CO_2 target of 50% below current levels [48]. A substantial amount of water is required in the cultivation of biomass, varying greatly with crop and region [50]. As an example, there is a 90:1 volume ratio between water and produced ethanol from sugarcane in Brazil, whereas the corresponding ratio is 3500:1 in India [51]. The water use can however vary substantially depending mainly on irrigation demands and corresponding evapotranspiration [52]. The water consumption in biofuel production is typically small compared to the consumption used for cultivation. More recently, second generation biofuels have been introduced, utilizing biomass otherwise not well-suited for food or feed or biomass from (upgraded) residues and/or waste. Second generation biofuels therefore support rather than compete with potential scarce future resources and food supplies and accordingly do not include equally high water usage levels, i.e. by diminished needs for irrigation.

2.2.2 Geothermal electricity generation

Geothermal water consumption varies greatly with the type of facility. In general, there are three types of geothermal designs for steam resource locations at depths in a typical range of 50-3000 m [42,53]. I) The operation of dry steam plants employs hydrothermal fluids primarily in the form of steam directly connected to a turbine omitting only excess steam. II) Flash steam plants, which are more common, operate by ejecting hot (>180^{o}C) and pressurized steam into the turbine, sometimes followed by a second lower pressure turbine. These plants consume the largest amounts of water. Since the exploited water contains non-potable minerals, and there is a typical abundance of water in these regions, it can be debated whether the water consumption can be compared one-to-one with other electricity generation technologies. III) Binary cycle geothermal plants are of newer origin and operate by letting lower temperature water (below 200^{o}C) pass through a heat exchanger holding a fluid with a much lower boiling point (Organic Rankine Cycle). Here the geothermal water is reinjected, thus resulting in a much lower water consumption. For well depths of 3-10 km enhanced geothermal systems (EGS) are capable of exploiting the energy in some regions where hot water does not reach the ground surface. EGS operate by ejecting hot water at great depths, returning to the surface as steam powering turbines of either flash or binary type. For flash EGS, cooling water consumption is comparable to other flash usages. For binary

EGS, the water temperature affects the water consumption as lower temperatures require higher flow rates, which is the reason for larger spread in consumption rates for binary EGS (figure 2). Other types of thermal exploitation include co-produced electricity generation (or direct heating indirectly facilitating energy savings) from oil and gas wells and lower-temperature thermal energy. For these technologies, the use of binary techniques will contribute to lower water consumption rates.

2.2.3 Hydropower, wind, marine technologies (wave/tidal), solar PV, and concentrating solar power (CSP)

Water usage in hydropower electricity generation varies immensely and is highly dependent on the local climate, as the consumption is directly related to evaporation from the water reservoir storage and potentially net seepage, as opposed to direct turbine usage (5.400-68.000 L/MWh). The higher end of this range decisively constitutes the highest levels for all electricity generation technologies. Some studies [37] argue for neglecting the water consumption from hydropower due to the additional societal purposes of reservoirs such as flood control, leisure, irrigation and water supply. Wind, marine technologies, and solar PV have little or no direct water consumption related to electricity generation. They constitute a negligible fraction of the total water use compared to other energy sources, especially with regards to wind energy and ocean based technologies, which accounted for just 0.05% of renewable energy in the EU in 2013 [54]. Solar PV electricity generation incurs a small water consumption used primarily for the cleaning of surfaces and panels (0-125 L/MWh). For comparison concentrating solar power (CSP) technologies with cooling has a substantial consumption (2800-4000 L/MWh), whereas dry cooling CSP consume much less (100-300 L/MWh). Hybrid CSP plants fall here in between. For water cooled CSP, a disagreement between high incoming solar radiation (typically desert locations) and water availability is often seen. Further, CSP water is used for reflection mirror cleaning (75-150 L/MWh). However, global CSP installations are currently negligible.

2.2.4 CO2 capture, storage, and utilisation

CO2 capture, storage, and utilization technologies in combination with, e.g. conventional fossil electricity generation, represents a more recent development towards climate change mitigation in order to reduce the emission rates of GHG, where the main sources include electricity and heat generation, agriculture, industry, and transportation [16]. In general terms, the extraction of carbon emissions from electricity generation, the industry etc., is separable in two categories of either Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) - in combined terms referred to as CCSU. Considerable development is still needed for these technologies to be readily applicable [55]. With regards to water consumption, CCSU involves a range of processes and technologies where the capture share (as opposed to storage and utilisation) accounts for approx. 80% of the total CCSU water consumption [56]. Also, adding CCS increases cooling demands of approx. 25-140% per plant [38].

2.2.5 Water recycling and waste water treatment

Employing recycling and waste treatment within water usages can offer savings in both water extractions and financially due to decreased pumping and distribution demands, although not directly linked to electricity generation. In general, the added energy required for waste water reuse is considerably smaller compared to the added energy related to extracting the same amount of water from other sources [57]. The extent and nature of water treatment depends on the proposed water usages. As an example, irrigation water could require lower mineral and biochemical standards than drinking water. Examples of water recycling include electricity generation cooling, irrigation (agriculture and landscape), processing water in the industry, toilet flushing, construction, etc. Greywater has been mentioned as a potential source for recycling applicable for purposes of irrigation, indoor applications (toilet flushing), and heat reclamation (through household heat exchangers). Savings are very site- and application specific. A quantitative example include predicted energy savings of 0.8-1.3 kWh per m^3 saved water and water savings of 220,000 m^3 annually per plant (soft drink production in North America and Europe) after integrating recycling loops [57]. Desalination has been reported financially competitive in some regions, and can become increasingly relevant with increasing water prices [58].

2.2.6 Emerging technologies and storage solutions

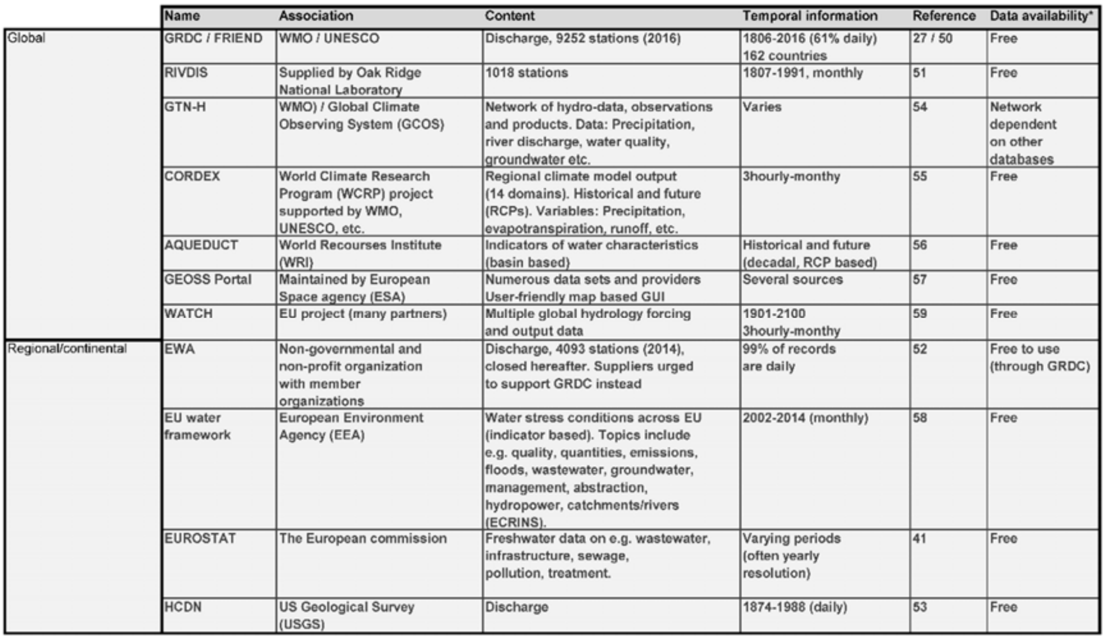
Potential advances in larger-scale energy storage technologies, potentially offering water use savings by improved electricity distribution in time, include: I) Chemical energy storage of hydrogen and methane from excess wind and solar electricity generation, adding to a more efficient use of non-water consuming energy technologies (albeit using water for energy conversion). II) Compressed air energy storage (CAES) in e.g. salt caverns (sealing cracks and fissures) to produce turbine generated electricity in periods of high demands likewise adding to the energy system flexibility [59]. III) Pumped hydropower, involving pumping (using e.g. wind and solar energy in locations of abundant supply) of water to higher altitude reservoirs and utilizing a reverse release through turbines on demand [60]. IV) Thermal energy storage (TES) potentials are currently counterbalanced by high costs, material property and utilization research but are regarded promising by implementation in CSP plants through molten salt and industrial waste heat [61].

3. Water resource data for water-energy nexus studies

Examples of freely available water recourse data relevant for global and regional scale energy nexus studies is described below and summarized in table 1.

Several data sets on river discharges exist on a global level. The **Global Runoff Data Centre (GRDC)** [27] holds data on river discharge on a global scale from an approximate 9000 stations dating back to 1806 down to daily resolution. **FRIEND** is another river flow database operated by UNESCO [62] consisting currently of 162 countries divided into eight regional sub-sections such as “EURO FRIEND”. In FRIEND, a certain overlap of data with GRDC and EWA (addressed below) is seen. **RivDis** is a global and long-term (1807-1991) river discharge database worth mentioning however with no continuous updating [63]. The **European Water Archive (EWA)** on river flow and catchment characteristics exemplifies a regional/continental scale data set, which has now been fully implemented into GRDC [64]. Another example, the **HCDN** data set, holds information on US streamflow from 1659 sites for the years 1874-1988 [65]. The **GTN-H** initiative aims at linking existing networks and data centres providing data and information on hydrology on a global level [66]. This includes for example hydrological data from the GRDC. **CORDEX** (The Coordinated regional climate downscaling experiment) offers access to regional climate model data output on a global level, based on 14 sub-domains, for historical and future periods [67]. CORDEX data resolutions are 12.5-50 km, in time steps down to 3-hourly. Relevant data for water-energy nexus studies include basic water balance variables such as precipitation, evaporation/ transpiration, runoff components as well as wind, temperature etc. CORDEX application examples are shown in figure 4. The **Aqueduct** dataset (currently in V.2.1) holds 12 global indicators of water quantity, water variability, water quality, public awareness of water issues, access to water, and ecosystem vulnerability as well as grouped risks and scores based on these [68]. The data are based on basins (as opposed to e.g. gridded data) and holds 25010 basins and sub-basins in its current database (shape-file). The **GEOSS Portal** is an initiative with data from multiple provider institutions and affiliations on a global level maintained by the European Space Agency with the aim of a user-friendly map-based GUI and data portal [69].

Table 1. Examples of larger scale water resource data.



	Name	Association	Content	Temporal information	Reference	Data availability*
Global	GRDC / FRIEND	WMO / UNESCO	Discharge, 9252 stations (2016)	1806-2016 (61% daily) 162 countries	27 / 50	Free
	RIVDIS	Supplied by Oak Ridge National Laboratory	1018 stations	1807-1991, monthly	51	Free
	GTN-H	WMO) / Global Climate Observing System (GCOS)	Network of hydro-data, observations and products. Data: Precipitation, river discharge, water quality, groundwater etc.	Varies	54	Network dependent on other databases
	CORDEX	World Climate Research Program (WCRP) project supported by WMO, UNESCO, etc.	Regional climate model output (14 domains). Historical and future (RCPs). Variables: Precipitation, evapotranspiration, runoff, etc.	3hourly-monthy	55	Free
	AQUEDUCT	World Recourses Institute (WRI)	Indicators of water characteristics (basin based)	Historical and future (decadal, RCP based)	56	Free
	GEOSS Portal	Maintained by European Space agency (ESA)	Numerous data sets and providers User-friendly map based GUI	Several sources	57	Free
	WATCH	EU project (many partners)	Multiple global hydrology forcing and output data	1901-2100 3hourly-monthy	59	Free
Regional/continental	EWA	Non-governmental and non-profit organization with member organizations	Discharge, 4093 stations (2014), closed hereafter. Suppliers urged to support GRDC instead	99% of records are daily	52	Free to use (through GRDC)
	EU water framework	European Environment Agency (EEA)	Water stress conditions across EU (indicator based). Topics include e.g. quality, quantities, emissions, floods, wastewater, groundwater, management, abstraction, hydropower, catchments/rivers (ECRINS).	2002-2014 (monthly)	58	Free
	EUROSTAT	The European commission	Freshwater data on e.g. wastewater, infrastructure, sewage, pollution, treatment.	Varying periods (often yearly resolution)	41	Free
	HCDN	US Geological Survey (USGS)	Discharge	1874-1988 (daily)	53	Free

On a European level, the **European Environment agency (EEA)** provide open data on a range of water resource related variables and indicators [70], there among on the use of freshwater recourses (previously; the water exploitation index) accounting for both the level of renewability and exploitation on a monthly basis since 2002. The EEA database also holds water related information on pollutants, quality, quantity, emissions (to surface waters), a flood archive, waste water, groundwater/aquifers, management plans, abstraction, hydropower, catchment and rivers (ECRINS) and ecology (regions). Also on a European level, the **EUROSTAT** database includes a combination of water and energy information [54]. For the former these include water resources, (per year, long-term average), abstractions by origin (fresh surface water & groundwater, other sources) and purpose, water use by supply scheme and by economic activity group, connection rates to wastewater treatment by type and level of treatment, wastewater treatment infrastructure, sewage sludge and aquatic pollution by source and discharge by type of treatment.

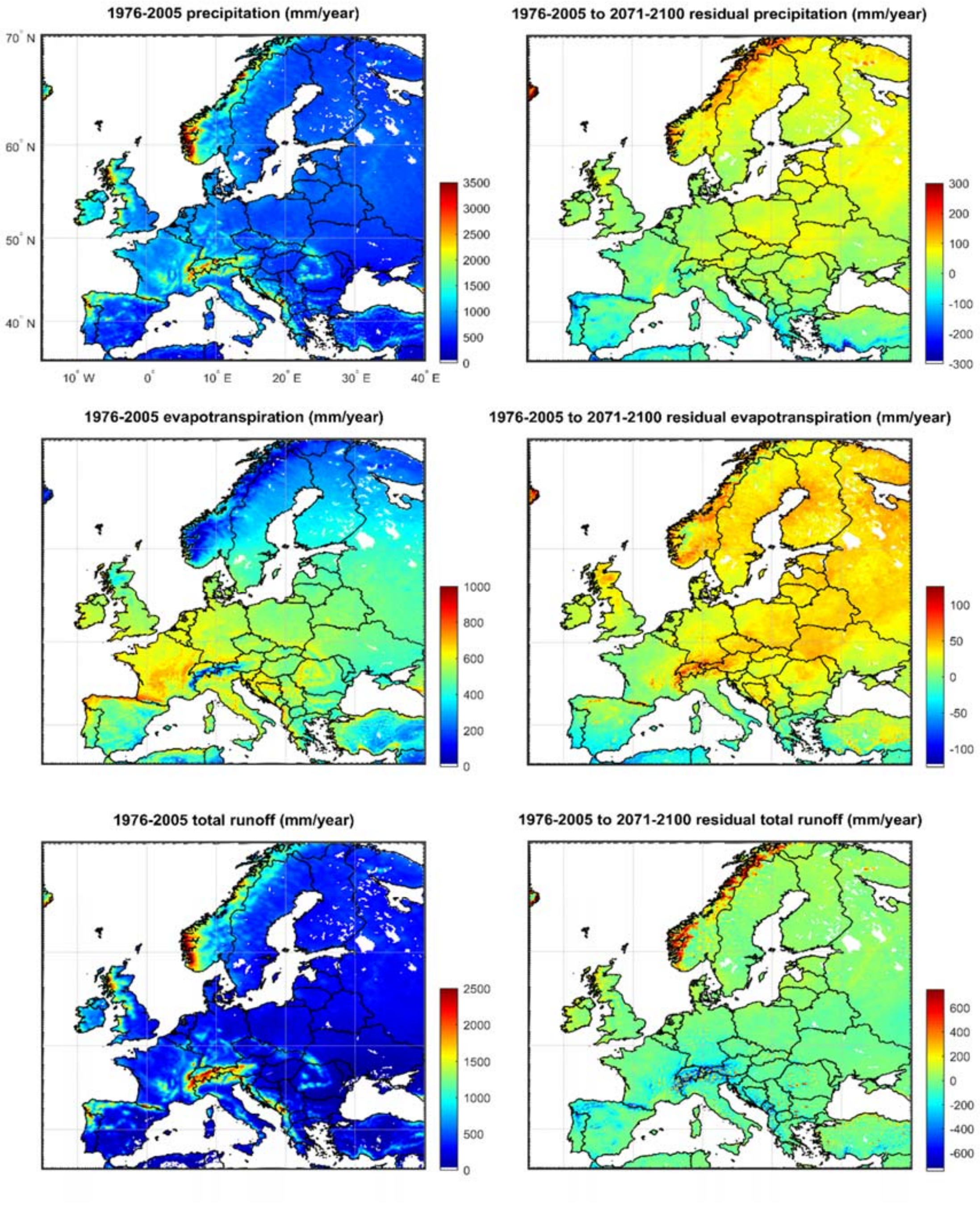


Figure 4. Historical and projected future water (and climate) data from the CORDEX database [67]. See the Application section for description.

In addition to the abovementioned (longer lived) initiatives and data centres the collection, creation, and distribution of water resource data have also been a core part of several research projects like the **WATCH** project [71]. WATCH comprises a relevant water resource database to be employed in water-energy nexus studies under climate change conditions as the data include both meteorological forcing data for hydrological model applications as well as model output. The forcing data include both a 20th century data set (ERA-40 reanalysis forcing, [72]), a 1979-2012 data set (ERA-Interim forcing, [73] and a projected 21st century data set based on three global climate models (GCMs) and the IPCC climate scenarios B1 and A2. The model output data include 20th century hydrology model/land surface model output for nine models and nine variables and 21st century output where each hydrology model is driven by future scenarios. Further, finer scale test river basins have been employed.

4. Electricity and energy statistics for water-energy nexus studies

Data from the energy domain that are relevant for water-energy nexus studies at a global or regional level is listed below and summarized in table 2. As indicated, most data sources are freely available.

International Energy Statistics published by **USEIA** (U.S. Energy Information Administration) [74] has a global coverage with a detailed division of electricity generation technologies. The data includes export, import, domestic consumption and losses, the temporal aggregation is yearly (from 1980) while the smallest geographical entity is country level. The Renewable Energy Source of Information (Resource) platform [75] published and maintained by **IRENA** (International Renewable Energy Agency) provides global annual electricity generation from renewable sources (from 1980) aggregated into 6 technological types (hydro, bioenergy, geothermal, marine, solar, wind). The data can be aggregated into regions (continents, Eurasia, Middle East and Central America and the Caribbean). **DataBank** [76] published and maintained by the World Bank is an analysis and visualization tool containing compilations of time series data on a variety of topics there among electricity generation data based on the World Development Indicators database. The data are a national level, in yearly resolution (from 1967), and aggregated according to input fuel (hydro, natural gas, nuclear, oil, coal and renewables without hydro). Countries can be aggregated according to geography, income, size, etc. The **International Energy Agency's** (IEA) Monthly Electricity Statistics [77] holds electricity generation and trade data for member countries of OECD aiming to report up-to-date and consistent information from recent months. It also provides annual data (from 1973) for previous years and year-to-date indicators at a country level as well as in organizational and regional groupings. **OECD Data** [78] published and maintained by OECD contains annual electricity generation for OECD countries. The only differentiation is between nuclear and not-nuclear technologies. The historical values start in 1973. **Global Energy Statistical Yearbook** by energy consulting company Enerdata [79] is a free online application, holding annual electricity generation, consumption, trade and share of renewables in electricity generation for 186 countries (2000-2015) however with no information on electricity generation technologies.

A few databases have a global coverage of detailed geographical and techno-economic data on specific power plants. An example includes the **World Electric Power Plants Database** by Platts [80] providing detailed technical boiler type, generator type, temperature at the turbine, and geographical coordinates of plant locations etc. Another example is the **Power Plant Tracker** by Enerdata [81] containing annual performance indicators such as electricity generation and efficiency. Both of these databases require membership. **Power Plants registered at Enipedia** [82] represents an open-source version of a global power plant register containing location and technical data on individual plants such as capacity, fuel used, cooling method, efficiency although data are often missing or incomplete.

Table 2. Examples on major energy statistics databases organized according to geographical coverage, geographical aggregation, temporal aggregation, and/or fuel/technology aggregation.

	Name	Association	Content	Temporal information	Reference	Data availability*	Link to water
Global	International Energy Statistics	U.S. Energy Information Administration (US EIA)	Electricity generation per technology type and fuel and power plant data	Annual (1980-2015)	[62]	Free to use	Electricity generation from thermal and hydropower plants
	Resource (Renewable Energy Source of Information)	IRENA	Electricity generation per technology type	Annual	[63]	Free to use	Electricity generation from thermal and hydropower plants
	DataBank	World Bank	Electricity generation by fuel	Annual (from 1967)	[64]	Free to use	Electricity generation from thermal and hydropower plants
	International Energy Agency (IEA)	Monthly Electricity Statistics	Electricity generation by fuel	Monthly (from 2006)	[65]	Free to use	Electricity generation from thermal and hydropower plants
	OECD Data	OECD	Electricity generation divided into nuclear and non-nuclear	Annual	[66]	Free to use	Electricity generation from nuclear plants
	Global Energy Statistical Yearbook	Enerdata	Gross annual electricity generation	Annual	[67]	Free to use	No
	The World Electric Power Plant Database	PLATTS	Technical data and geographical coordinates for specific production units	Updated quarterly	[68]	Paid subscription	Technical data
	Power Plant Tracker	Enerdata	Technical data and geographical coordinates for specific production units	Annual	[69]	Paid subscription	Technical and economic data and annual electricity generation
	Power Plants register	Enipedia	Annual electricity generation and geographical coordinates for specific production units	Annual	[70]	Free to use	Technical and annual electricity generation
	Energydata.info	World Bank Group and partners	Primarily geographical data on transmission grid expansion, power plant location, renewable energy potential and population demographics	Varying Hourly to annual	[89]	Free to use	Varying
	Global power watch	World Resources Institute (WRI) and partners	Under development data platform with georeferenced powerplant specific data	Likely annual	[90]	Free to use	Geo-referenced electricity generation that can enable linking to cooling water bodies and similar
	Global Energy Observatory	Open community, lead by Los Alamos National Laboratory	Annual electricity generation by plant, country and fuel type. Covers 40–95% of installed EU capacity	Annual	[79]	Free to use	Water withdrawals and consumption possible to fill in, but are often left blank.
Regional	Environmental Statistics and Indicators	Economic Commission for Latin America and the Caribbean's (ECLAC)	Water use for electricity generation and total electricity generation per country	Annual	[71]	Free to use	Hydroelectricity generation
	ENTSO-E	ENTSO-E Transparency Platform	Electricity generation and hydro reservoir inflow on country, control area and bidding zone levels	Hourly/weekly	[72]	Registration required	Electricity generation aggregated into 20 technology types and hydro reservoir inflow
	Renewables.ninja	Renewables.ninja web tool	Solar and wind capacity factors	hourly	[73]	Free to use	Only if cooling of PVs is considered
	EUROSTAT	The European Commission	Energy supply, transformation, consumption, imports/exports, market/prices etc.	Monthly	[41]	Free to use	Electricity generation pr. fuel source
	EMHIRES	EC JRC	Solar and wind capacity factors	hourly	[74]	Free to use	Only if cooling of PVs is considered
	Open Power Dystem Data	Several partners and original data sources	Conventional and renewable power plants, generation capacities and pricing	From 15min	[75]	Free to use	Indirectly only (by technology based assumptions)
Country level (examples)	Energy data	Energinet.dk	Electricity generation by plant type	Hourly	[76]	Free to use	Electricity generation from thermal and hydropower plants
	Production statistics	Svenska kraftnät	Electricity generation by plant type	Hourly	[77]	Free to use	Electricity generation from thermal and hydropower plants
	Nordic power balance	Stattnet	Electricity generation by plant type	Hourly	[78]	Free to use	Electricity generation from thermal and hydropower plants

An example of regional level energy data includes the **Environmental Statistics and Indicators database** [83] by the Economic Commission for Latin American and the Caribbean holding annual primary and secondary energy (separating electricity and hydropower) for the 29 countries of the region (1970 and 2014). At smaller geographical scales data are often available with finer geographical and temporal aggregation. For example, the **ENTSO-E** Transparency Platform (European Network of Transmission System Operators for Electricity) [84] holds data on e.g. hydropower reservoir filling rates, hydro plants, aggregated hourly production rates, and hourly generation for specific units (country, control area, and bidding zone level for EU and 13 neighboring countries from 2014). Similarly, the "**Renewables.ninja**" web tool [85] provides hourly PV and wind capacity factors for EU-28, Norway and Switzerland for the period 1985-2014. **EUROSTAT** offers data on e.g. energy supply, transformation, consumption, imports/exports, market/prices on a monthly basis [54]. The **EMHIRES** (European Meteorological HIgh resolution RES time series) dataset published by the Joint Research Centre [86] contains solar PV and wind data for EU-28, Norway, Switzerland and the non EU countries of the Western Balkans. The time series cover: I) hourly solar power capacity factors at country level, bidding zone level, NUTS 1 and NUTS 2 level, II) onshore and offshore wind power capacity factors at country level and III) wind power capacity factors at bidding zone, NUTS 1 level and NUTS 2 level without aggregation into onshore/offshore (all 1986-2015). **Open Power System data** is an effort towards collecting, processing and holding free energy data from multiple sources dissimilar nature onto a shared database structure [87]. The data include power plant information, generation capacities, pricing, house hold data etc. at the EU level. At the country level, e.g., energy statistics is generally provided by the national energy authorities. For example in Denmark, Danish transmission system operator, **Energinet.dk**, publishes hourly electricity generation profiles by type of plant [88]. Swedish transmission system operator, **Svenska kraftnät**, publishes hourly electricity generation profiles by type of plant [89], while Norwegian power system operator, **Stattnet**, publishes hourly electricity generation profiles by type of plant for four Nordic (Denmark, Norway, Sweden,) and three Baltic (Estonia, Latvia, Lithuania) countries [90].

5. Application

This section presents three examples of how the data presented here can be applied to nexus studies.

5.1 Large-scale hydro-climatological application

This example exhibits the extraction of three main variables from the water balance from a mini-ensemble of regional climate models (RCM) from the CORDEX database [67] over Europe in 12.5 km resolution (figure 4). The variables include precipitation, evapotranspiration and total runoff and are plotted as yearly mean levels for the historical period of 1976-2005 and as residuals between the historical period and 2071-2100 based on the RCP4.5 scenario. The models are driven by global climate models (GCM) at the domain boundary and include the MPI-ESM-LR/CCLM4, EC-Earth/RCA4 and EC-Earth/RACMO22 models. This type of data is relevant to larger-scale water-energy nexus studies by providing a robust realisation of future trends for hydrological and meteorological variables with a high influence to the energy system. At the scales shown, a projection on the direction of trends, their magnitude and timing can be estimated. For more local predictions on e.g. stream flow, groundwater levels or water temperatures, smaller scales hydrological models need to be applied.

5.2 Water use by electricity generation plants

For this example, the electricity generated in EU28 is extracted per energy source from [54] (figure 5, left). Then, by using knowledge on the water withdrawal rates for each energy source, cooling technology (and their distribution), and the estimated freshwater/sea water shares on a EU28 level the corresponding freshwater withdrawals rates were then calculated (figure 5, right). This was particularly interesting since the reported freshwater abstractions were found available [54] acting as a validation of the method and showing highly similar results. The amount of gap filling needed for reported abstractions (using running means) increases for earlier data, and levels prior to 1995 is therefore now shown here (some countries have data from 1970). The data on the distribution of cooling technologies and freshwater/sea water usage were estimated from [82,91]. The same calculations could have been done for water consumption, as shown in figure 2, although a similar dataset of reported consumption rates (which likewise could act as validation data) was not found available in the process of conducting this study.

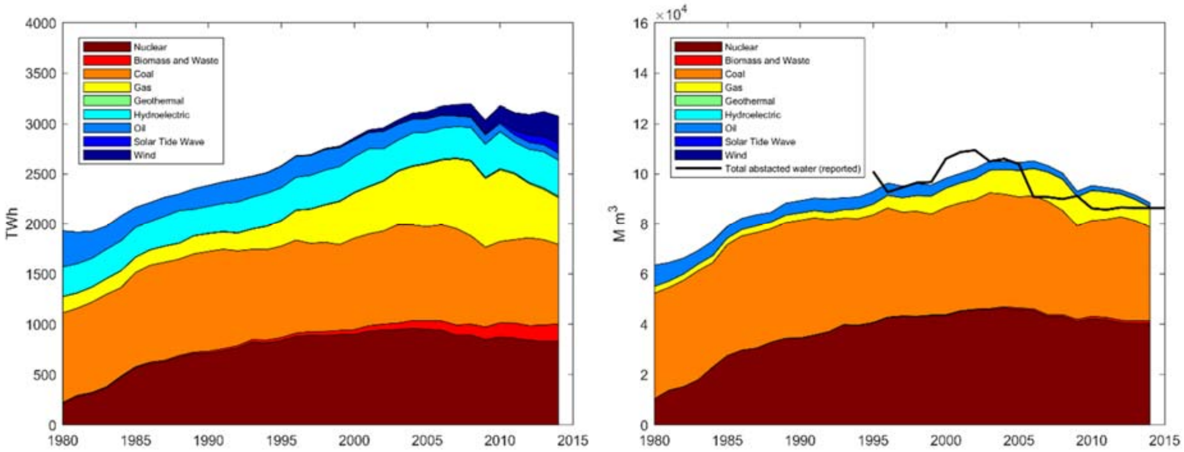


Figure 5. Left: The total generated electricity (TWh) for all EU28 countries for different fuel sources for 1980-2014 [54]. Right: The estimated water withdrawals rates per energy source calculated by using the generated electricity per energy (shown left) and literature estimates on median water withdrawal rates (figure 1) for each energy source and (cooling) sub-technology as well as the estimated freshwater/sea water shares. Also shown is the reported freshwater abstractions here acting as validation data. See the Application section above for a description of calculation steps.

5.3 Detailed water usage at plant level

At a very local scale, the final example highlights a step towards the level of detail in water-energy nexus data as urged by the authors of this study. Here more detailed monthly withdrawal and consumption rates for a range of selected US power plants are visualized (figure 6) for the 2014-2015 period as available from [74]. The plants have been selected to reflect a range of energy sources (coal, nuclear, gas, wood/waste/biomass, and municipal solid waste), and cooling types (OT/REC etc.). From the figure it can be seen that the plants in relation to their cooling technology exhibit a water use similar to the levels in figure 1 and 2, but also that there is a high temporal variation and seasonality and which therefore supports the argument of employing a high detail in the spatio-temporal linkages to water and meteorology data in nexus studies.

6. Discussion

In the preceding sections we present current estimates of operational water usage in electricity and fuel production, and we have summarized some of the key data sources that currently describe water resources and electricity and fuel production. What is evident is that the combined domains of water and energy, at least at the spatial scales we address above, are poorly covered by the data sources that are currently available for analyses of the water-energy nexus. This includes lack of detailed data sets describing, e.g., the water use by the energy sector in a spatio-temporal resolution adequate for linkages to water resource and energy system models. Thus, most energy data of high temporal resolution omit water use linkages entirely, whereas those that include information on water uses tend to be aggregated at annual scales and therefore do not capture spatio-temporal details, e.g. seasonal variations, which are important for managing most water/hydrology systems. Ideally, such details would encompass information at the plant level such as the intake/re-ejection amounts, time/space information, quality (temperature/chemistry), source (river name, location, and aquifer depth etc.). On the other hand, with the notable exception of the aggregated annual data collected by the EEA and EUROSTAT water uses by the energy sector are also not generally included in most of the readily available data on water resources (cf. table 1).

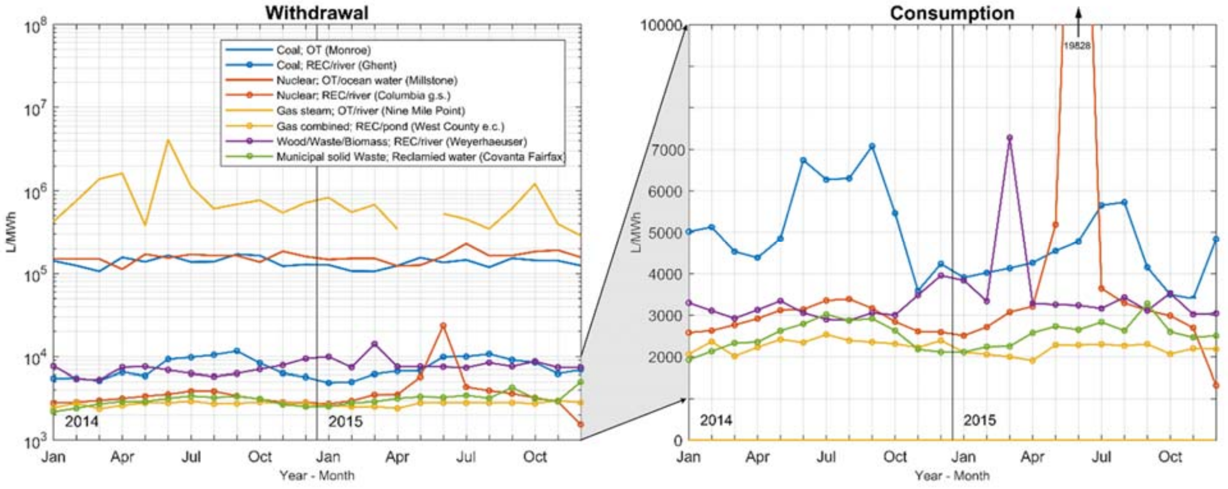


Figure 6. Withdrawal and consumption rates (L/MWh) for selected US power plants of varying fuel sources (coal, nuclear, gas, wood/waste/biomass and municipal solid waste) and cooling types (OT/REC etc.) for 2014-2015 [74].

Parallel to the need for more detailed water use-energy sector data, is the need for an updated and sustained hydro-climatic framework facilitating open access data from large-scale hydro- and climate models (separately and combined), where existing models are driven by the same forcings, historically and for future scenarios. The framework and available data may well be much along the lines of e.g. CORDEX [67] and WATCH [71] initiatives although with a more sustained effort than the latter and with more recent future scenarios. This would enable reasonable comparison grounds and hydro-climatic ensemble studies much along the lines of what is often seen in climate model research [92,93] thereby allowing for a range of research aspects within hydrological variability and extremes, and to obtain more trust in future projections.

The alternative to detailed in situ data on water usages in electricity and fuel production is to use values based on current estimates (see above) of operational water usages as a means to bridge the gap between water and energy systems. For quantitative nexus studies however, this approach is likely to introduce considerable uncertainties due to the large spans in, e.g., recorded water usages for individual power plants (see figures 1 and 2), as caused by not only variations in technology usages but also depend on regional hydro-climatic conditions, local regulations, plant optimization, incorrect/inconsistent reporting, etc. Likewise, data of adequate quality are found to be plentiful for some electricity generation technologies, whereas in other cases such data are scarce, there among for several technologies that are currently considered as part of shifting from more traditional fossil GHG emitting electricity generation technologies to other more sustainable forms [21].

Another challenge is seen in the conditions for the collection and availability of data on water use by the energy sector which differ immensely between countries and regions, which can constrain the applicability and comparability of estimated water uses. As an example, historical records from the US has significant gaps in terms of missing information related to critical energy technologies (e.g. nuclear and gas combined cycle) despite otherwise adequate data availability [21]. Historically, the lack of reliable water use data in reviewed sources could potentially have some level of linkage to the universal challenge of water being an undervalued resource [94].

On top of the spread in estimates of the water use in electricity and fuel production, as introduced by natural, geographical, technological and hydro-climatic variations, discrepancies in definitions and calculation/measurement methods can also constitute a significant challenge for data collection in the context of nexus studies. As mentioned above, assessments of water use in hydropower production can, depending on its definition, range from negligible to the exceedance of all other electricity generation technologies. This depends in part on how water evaporation is shared among multiple uses of a reservoir and also on how evaporation is calculated ranging from simply dividing the total reservoir evaporation with electricity generation to only accounting for net evaporation (substituting the water balance prior to reservoir construction) [95]. Across different fuel types the differences in water footprint definitions in general make reported estimates/water consumption rates even less comparable. This is particularly evident when comparing the generally reported water footprint of electricity generation with the footprint from the production of liquid biofuels. These are some of the most well studied fuels in the water-for-energy literature, yet they are typically not reported in a way, which is comparable and ready to be incorporated in an energy systems analysis. In summary, the development of methodologies for comparing different types of reported water use factors should be in high demand and is poorly covered by the existing scientific and technical literature.

So far we have only addressed the challenges of carrying out water-energy nexus from a general perspective of quality and representability. However, integrated assessments of the water-energy (and food) nexus, including connections to eco-systems, livelihood, security, etc. [96,97] range from pieces of policy discussion [10,98] to complex quantitative modelling of management and policy scenarios at different scales [5] using a variety of methodologies and tools as highlighted by [99]. This means that the data requirements for different kinds of assessments will of course also vary extensively. Thus, for many real-life applications the estimated water uses and data sources discussed above could be entirely adequate for mostly qualitative and/or semi-quantitative nexus assessments. For national policymaking, the values of taking an integrated approach has been demonstrated by e.g. [5], regional cases of stakeholder conflicts across the water-energy nexus has been addressed in [100] while [97] outline a methodology for stakeholder participation in assessments of transboundary nexus challenges.

Conversely, recent developments in integrated assessment type modelling [5] represent the entire water-energy nexus chain as a series of highly complex and interlinked numerical processes, prescribing information on human and natural systems and their interactions, which requires or even supersedes the level of detail and/or precision mentioned above. This is especially true at the regional and/or basin scale, which is often the natural focus of water and energy systems management, and consequently also in the center of deliberations towards ensuring the sustainable use of resources across the water-energy (and food) nexus. Modelling the dynamic linkages between water and energy at this scale evidently requires combining fully distributed spatio-temporal models of both water and energy systems, potentially addressing both present and future climatic and socio-economic conditions. For water alone, this would require modelling of water flows and storages in spatio-temporally distributed sub-components of both surface- and groundwater, involving aspects of vegetation from land surface models, forced by data from, e.g., atmospheric or ocean models or even dynamically coupled climate-hydrology models [101]. For energy, this would encompass integrated spatio-temporal modelling of production levels, technologies, markets, trade, and demand. Further, linkages to other sectors such as agriculture, food, industry, cities, etc. needs to accounted for. Presently, there are few if any models, which represent the water-energy nexus at the very high resolution and complexity suggested here. However, there is no doubt that ongoing research efforts within numerical modelling of both physical, economic, and social science dynamics, the increasing computational resources available and the demand for reliable simulation tools for testing management scenarios and policy initiatives will continue to advance the field of numerical water-energy nexus studies. Hence still more (complex) processes will be added to the model systems either through 'hard' or 'soft' linking to represent the different nexus systems and their broader context. Also, for this aim it is imperative that improved data sources are collected and shared. Already a decade ago [29] highlighted this importance and proposed efforts to facilitate such data sharing. As the need and value for such data, e.g. in terms of integrated planning and tool development has only increased since then, the need to overcome data sharing obstacles such as proprietary, business or security concerns is likely even more important today, and in itself present a major challenge in terms of studying the intricacies of the water-energy nexus in a changing world.

7. Conclusions and recommendations

In this paper we highlight some of the main challenges related to data availability when analyzing the water-energy nexus. For this aim we have assessed current estimates of operational water usage in electricity and fuel production for different energy technologies, and we have also considered the currently available data on the state of water resources (present and future) and electricity and fuel production at different scales. In general we find that there is a substantial gap in the availability, access and quality of proper regional and global data in order to facilitate detailed quantitative analyses within the water-energy nexus. Thus, there is a great need for improving the current quality and availability of historical water use data (withdrawals and consumption, or stocks and flows depending on terminology) for virtually all major sectors and sub-sectors related to the water-energy nexus, including at matching spatio-temporal scales relevant for linking water and energy systems. In addition there is also an urgent need for improved standardization of formats and data collection methodologies across different uses of the data (research, operations, planning, etc.), which in most cases presently are incompatible. Advances in this regard would immensely aid not just the validation of methods and models but would also contribute to an improved confidence in nexus assessments in support of management procedures and policy goals related both to current and future conditions. On top of the above, the standardization should also encompass future projections and scenarios for highest possible consistency similar to those of other multidisciplinary studies.

Acknowledgements

Parts of this work have been supported by the REEEM project (Role of technologies in an energy efficient economy – model-based analysis of policy measures and transformation pathways to a sustainable energy system) funded by the European Union Horizon 2020 research and innovation programme under grant agreement No 691739.

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Water Use in Electricity Generation for Water-Energy Nexus Analyses: The European Case

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Published in Science of the Total Environment: https://doi.org/10.1016/j.scitotenv.2018.10.045.

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Keywords water management, water withdrawal, water intensity factor, energy systems, Europe, large-scale water analysis

Highlights

- Electricity plant water withdrawals are estimated using a comprehensive analysis
- Estimates resemble reported levels on spatio-temporal scales of country/year
- The results support perspectives in larger scale water-energy nexus management
- More open source, freely available and detailed data are however urged

Abstract

With almost 40 percent of the global population suffering from water scarcity, the need to manage water resources is evidently urgent. While water and energy systems are intrinsically linked, the availability of comprehensive, integrated data sets across the domains of water and energy is generally lacking. As a result, estimated indicators representing volumes of water usage per unit of electricity or fuel produced are often required to analyse the water-energy nexus. In this paper, an “ensemble” of indicators is assembled representing water usage spanning different electricity-generation technologies based on previously published works in an attempt to depict the level or lack of detail in current large-scale energy-sector water-usage data. Based on these, the degree in which using such estimates is suitable for reproducing electricity-production water-usage at coarser spatio-temporal scales is assessed. The performance of the ensemble median/min/max as a predictor of water use is evaluated for the period from 1980 to 2015 using additional information about the constituents of the European energy system. Comparing with the reported values for 1980-2015, the median provides a skilful reproduction of historical yearly water use for the EU (EU28) as a

whole. A further analysis for 2015 indicates that reasonable agreement is also seen at the country level. Thus, the results suggest that an “ensemble-based approach” has the potential to provide sturdy estimates of yearly water use by energy systems for analyses at both the country and regional levels.

1. Introduction

Water and energy systems are inextricably interdependent. The water sector is a major consumer of energy for purposes such as water treatment, pumping and desalination. Similarly, water is essential for cooling power plants, electricity generation and bio-fuel production, as well as in the extraction, mining, processing, refining and disposal of fossil-fuel residues. 44% of total global water withdrawals are used for energy production, a dominant share of which is cooling water in thermoelectric electricity generation (Collins et al., 2009). Energy and water are both limited resources that are essential for the fundamental services, including food production, required by a rapidly growing global population that is projected to reach 9.7 billion in 2050 (United Nations, 2017). As a result, it is increasingly critical to manage the nexus between energy and water properly (Kurian, 2017) in the broader context of dependent socio-economic sectors, including the wider water–energy–food nexus (Griggs et al., 2013; Howells and Rogner, 2014; United Nations General Assembly, 2015). Moreover, proper water-energy management is especially crucial in light of the fact that electricity and fuel production relies on an estimated 90% of non-sustainable water sources (WWAP, 2014), as well as the increasing demands for water, energy and food driven by, among others, the growth in population and economies (Hoekstra et al., 2012).

Over the last decade or so, analyzing issues within or related to the water–energy nexus has become increasingly important for both the scientific and policy-making communities (Dai et al., 2018; Miralles-Wilhelm, 2016). Likewise, the capacity to assess water and energy interlinkages at an increasingly higher resolution has also improved accordingly. Analyses of the water–energy nexus span a broad range of spatial levels, from the local (e.g. plant or city) (Chen and Chen, 2016) to the regional or national (Kibaroglu and Gürsoy, 2015; Mayor et al., 2015). Meanwhile temporalities range from multi-decadal (including climate change)) (Mekonnen et al., 2016; Voisin et al., 2013) down to days or hours (or even lower) for operational applications (Castronuovo and Lopes, 2004).

A comprehensive review of methods and tools for macro-assessments of the water–energy nexus has recently been carried out by (Dai et al., 2018). From this analysis it is evident that, while a wide range of new methods and frameworks for comprehensively assessing interactions between water, energy and other elements have been developed, in general the availability of tools for nexus analyses that are at the same time integrative and multi-level is still poor(Daher and Mohtar, 2015; Howells et al., 2013). Instead, methodologies used for analyzing the water–energy nexus tend to be characterized by specific levels and data requirements (Liu et al., 2017), ranging from purely qualitative assessments to highly data-intensive model-based approaches (Granit et al., 2013). The review also found that none of the studies and methods considered provide a ‘singular framework’ for performing nexus studies.

The challenges of data availability at relevant spatio-temporal levels for analysing the water–energy nexus, for example, on water use by energy systems and vice versa, is well documented (Chini and Stillwell, 2017; IRENA, 2015; Larsen et al., 2016). While in general water and energy systems can be considered to be well-monitored and managed (developing countries excluded), the availability of integrated data sets covering both domains is often severely limited at the relevant levels of aggregation in relation to nexus calculations, that is, beyond the site-specific level. Further, such data may be incomplete and inconsistent due, for example, to differences in the inherent conditions for the collection of data on water use by the energy sector between countries and regions, which can constrain the applicability and comparability of estimated water uses. For example, records from the US, while otherwise of good quality, have significant gaps concerning water-intensive energy technologies like nuclear (Macknick et al., 2012). Conversely, dependencies between water and energy systems, that is, water consumption or withdrawals related to specific energy technologies, may be expressed in terms of representative volumes of water use per unit (e.g. L/MWh) of electricity or fuel produced (Basheer and Elagib, 2018; Gleick, 1994; Inhaber, 2004; Macknick et al., 2012). This approach introduces a significant source of uncertainty arising from the (lack of) accuracy, but it also enables quantitative nexus calculations to be made at different levels and is frequently used by integrated assessment models.

In light of the poor data on water usage within the energy sector, as highlighted above, this paper addresses the extent to which reported estimates of water usage in electricity production provide an accurate 'bridge' when modelling the interdependencies between water and energy systems. Thus, many initiatives, like the Platform for Regional Integrated Modeling and Analysis (PRIMA) (Kraucunas et al., 2015), as well as the ETSAP-TIAM community (Føyn et al., 2011), aim at developing flexible multi-scale tools for analyzing the water–energy nexus in order to satisfy users' increasing demands by linking existing model components with new ones that use such an approach. In this context, the present study may be seen as an attempt to identify and validate a suitable set of parameters. To estimate water usage, multiple literature estimates of water withdrawal and consumption rates for electricity production technologies are collected in conjunction with the distribution of individual power plants and their corresponding technologies in order to calculate the country-level EU28 yearly water usages for 1980-2015, followed by a validation against reported numbers (Eurostat, 2018).. The analysis is relevant because it highlights the best possible estimates of water usage within electricity production at coarser scales using freely available sources, albeit at coarse spatio-temporal resolutions (country/yearly). Thus, despite a certain resemblance between estimates and reported values, the paper also aims to show that the currently available data on energy-sector water usage is very inadequate, not least, in their detail and availability. Despite the current focus on providing open-access environmental data of increasing quality, data on the water–energy nexus are still limited in their availability. One aim of this paper is therefore to convey this information to users mainly in the academic community but also to politicians in light of the current tendency towards more open and available data.

2. Data and Methodology

In this study, withdrawals of water are defined as the total amount of water that is extracted or diverted from its groundwater or surface water source and used during electricity-generation operations (as opposed to, e.g., including the construction phase), including the return flow. Thus, the cooling water addressed in this paper is freshwater only. Water consumption is similarly defined as the net balance, including only evaporated and transpired water, as well as water stored in crops and/or other products. Both terms (withdrawals and consumption) are jointly referred to as 'water usage'. Using this definition water consumption becomes a subset of water withdrawals.

The term 'median', as used in this study, is the most commonly used term in the recent literature (Davies et al., 2013; Macknick et al., 2012). It can therefore to some extent be regarded as the standard metric. However, some literature uses the term 'average' (Mielke et al., 2010; NETL, 2010), whereas other, typically older literature sources simply give a representative value (Gleick, 1994; Inhaber, 2004). Furthermore, many studies build upon each other by re-issuing the findings of older studies. However, for any literature sources where the median estimate is based the middle value in between the reported minimum and maximum spans, this may introduce a certain bias towards underestimation, as argued by (Macknick et al., 2012). The span of the entire range is addressed by employing the minimum and maximum estimates. Correspondingly, the estimated mean and min/max ranges cannot be asserted to be 'robust' from a strictly statistical perspective (e.g., as quantified by t-procedures).

2.1 Data

The data used in this study can be grouped into three main categories depending on their nature and how they are used. I) The first category covers data on the water withdrawal and consumption rates of electricity production as a function of the energy source and cooling technology in question. The sources for these data are listed in Table 1. II) The second category covers data on individual electricity-generation plants which are used to estimate country-specific electricity generation per energy source, cooling technology and water source (fresh/saline). These data derive from (Enipedia, 2018; Global Energy Observatory, 2018; Shift Project Data Portal, 2018). These databases aim to include up-to-date information on individual power plants, although the present study necessitated substantial further online research to confirm whether or not, for example, plants were active or the type of cooling technology. III) The third category covers actual reported surface and groundwater withdrawals (both freshwater) used for cooling electricity generation plants, data being derived from (Eurostat, 2018). Annual data for the EU are available from 1970 to 2015. However, for earlier years there are an increasing number of data gaps on reported freshwater withdrawals. 1980 is therefore used as a starting point. For data gaps which are still present after 1980,linear interpolation has been used to fill the gaps, since this is the most conservative method and since a method aiming to reproduce patterns from neighbouring countries was considered too arbitrary for the short periods which needed gaps to be filled (a few years).

2.2 Estimated water use by energy source and technology

The estimated water usage related to specific energy technologies found, for example, in the scientific literature exhibit great local variations across natural, geographical, technological, hydro-climatic conditions and differences in definitions. Table 1 gives a list of previous studies within the categories of both peer-reviewed and 'grey' (report-style) literature as identified by the authors, who have estimated water usage by different energy technologies. While the list is comprehensive, it is by no means complete. Figures 1 and 2 give all individual withdrawal and consumption factor estimates (median, min and max levels) respectively from the listed studies (markers) as well as their average value (bars) and appendices A and B give the corresponding median values in table form. In general, the levels were found to be reasonably similar across literature sources, particularly for the median values, which also form the basis of the present study. The definitions in depicting water usage vary across literature, which is often not elaborated but instead visible from the numbers themselves or from the categories used. As an example, some sources group water usages across technologies, making the ranges appear exceptionally broad. All such cases are omitted in order to reflect only actual combinations of energy source and cooling technology. Another example includes pond cooling where the levels vary substantially which is believed to be related to definitions (using either the total withdrawn amount or only make-up water). In the present study, this is accounted for by dividing these definitions into two separate shares. It is further highlighted that data points in figures 1 and 2 may appear directly on top of each other having the same or corresponding values.

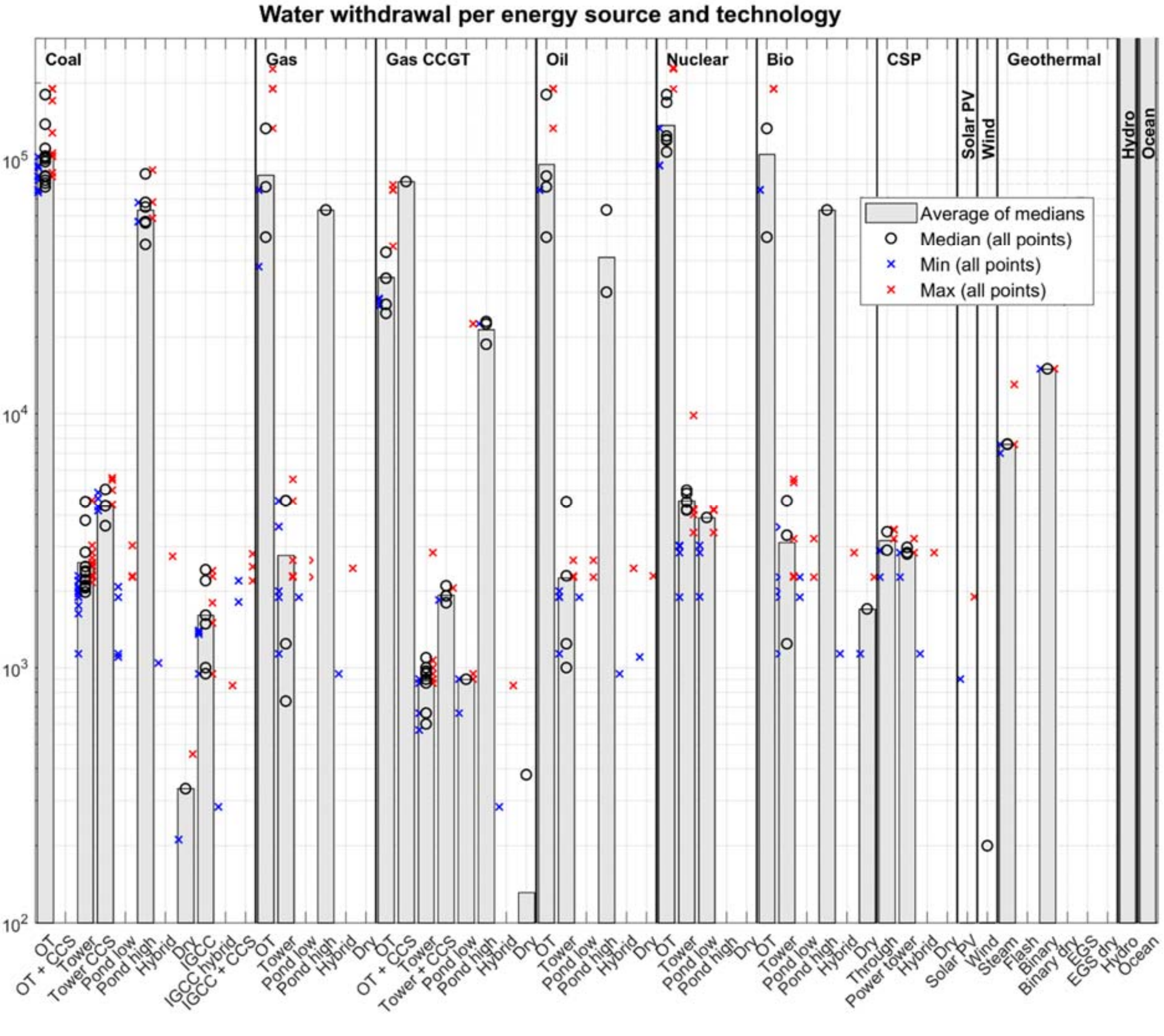


Fig. 1. *All median, min, max (markers) and average of medians (bars) water withdrawal rates (L/MWh) for each energy source and cooling technologies combination (as visible within the Y-axis limits). 'CCGT' denotes combined cycle gas plants, 'OT' denotes once-through, 'CSP' denotes concentrated solar power and "EGS" denotes Enhanced geothermal system.*

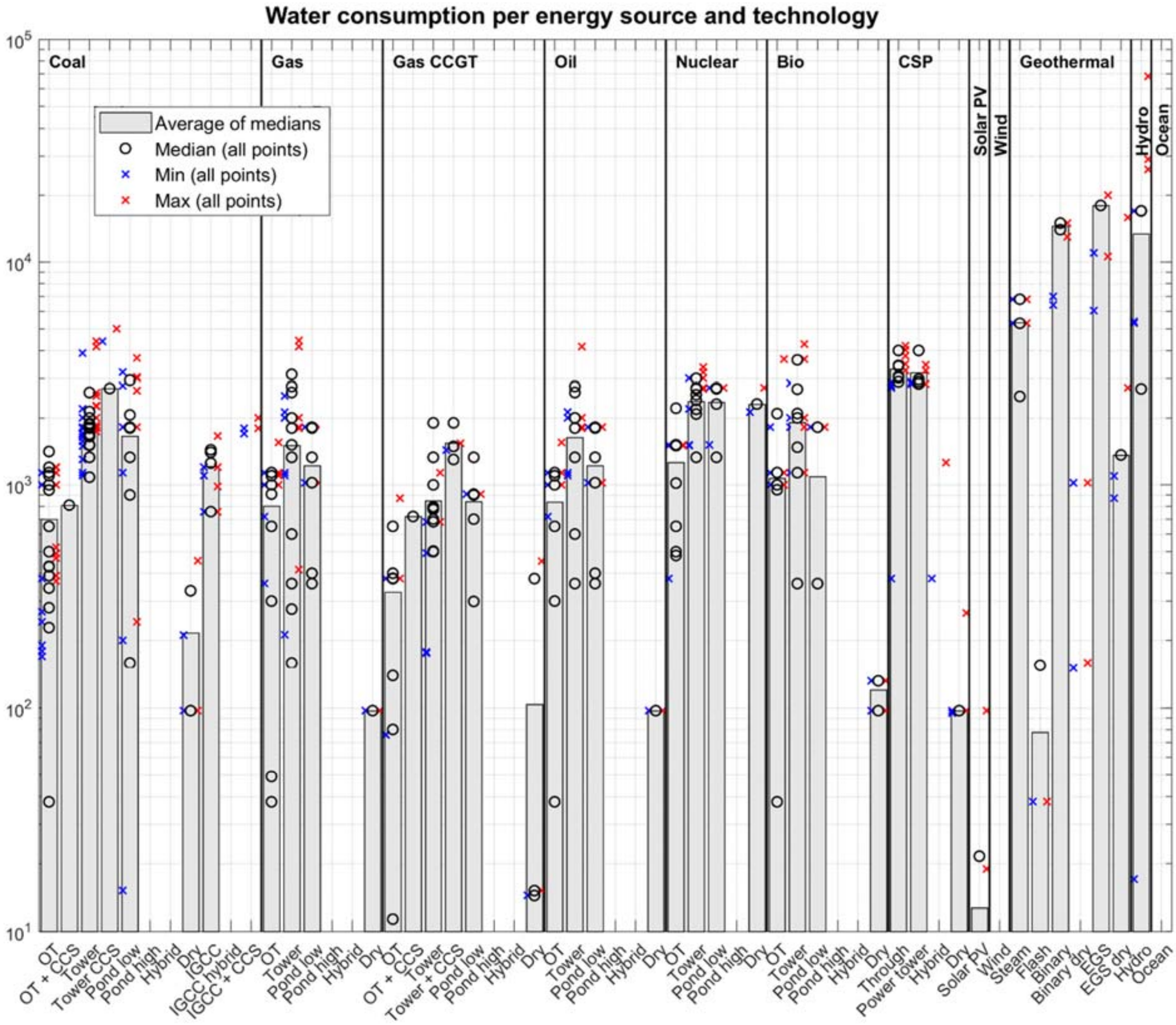
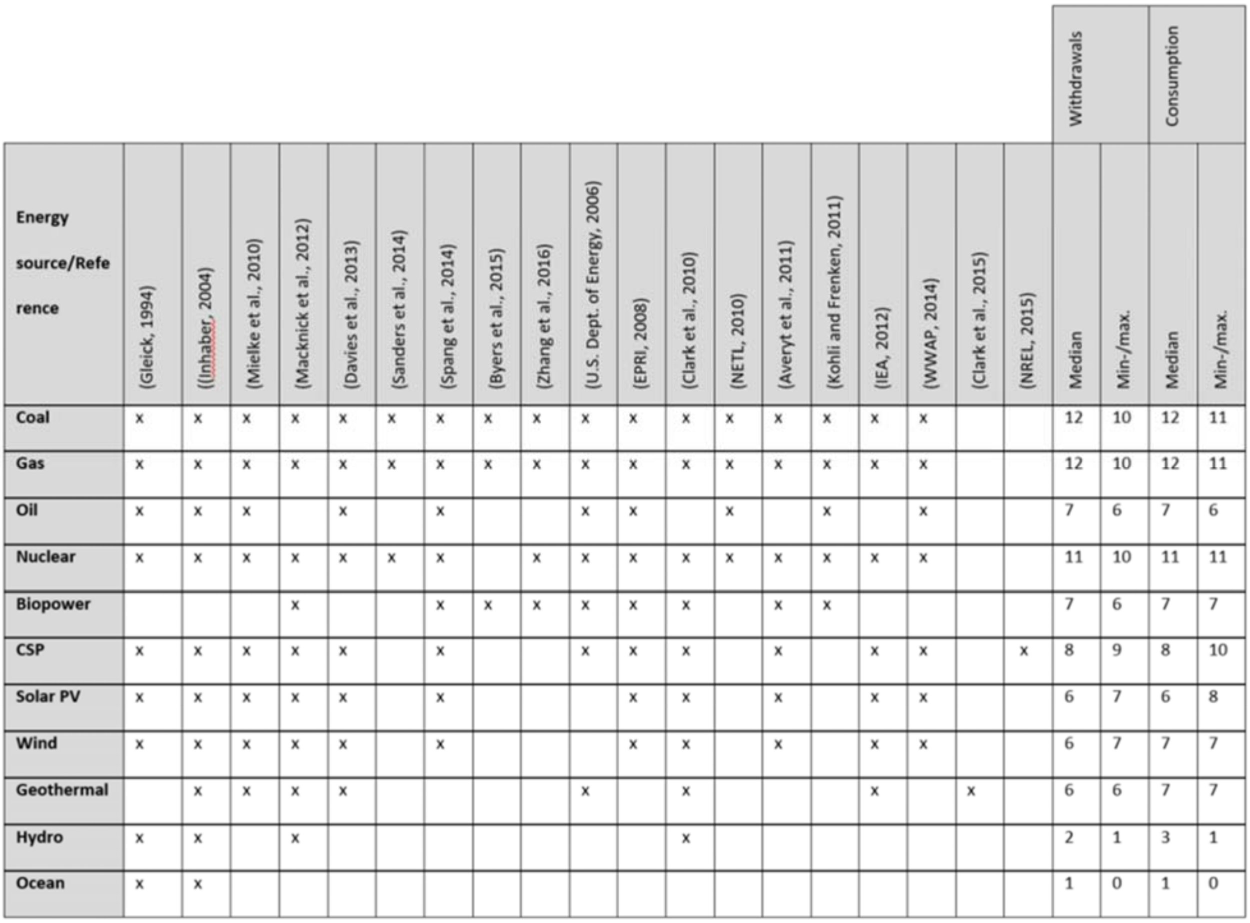


Fig. 2. *Similar to figure 1, except for depicting water consumption rates.*

2.3. Reconstruction of water use by energy plants in Europe

To evaluate the performance of water-usage levels derived from the literature review, the water used by European energy systems is estimated. To do this, information on the share of different (a) energy sources



																			Withdrawals		Consumption	
Energy source/Reference	(Gleick, 1994)	((Inhaber, 2004)	(Mielke et al., 2010)	(Macknick et al., 2012)	(Davies et al., 2013)	(Sanders et al., 2014)	(Spang et al., 2014)	(Byers et al., 2015)	(Zhang et al., 2016)	(U.S. Dept. of Energy, 2006)	(EPRI, 2008)	(Clark et al., 2010)	(NETL, 2010)	(Averyt et al., 2011)	(Kohli and Frenken, 2011)	(IEA, 2012)	(WWAP, 2014)	(Clark et al., 2015)	(NREL, 2015)	Median	Min-/max.	Median	Min-/max.
Coal	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			12	10	12	11
Gas	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			12	10	12	11
Oil	x	x	x		x		x			x	x		x		x		x			7	6	7	6
Nuclear	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x			11	10	11	11
Biopower				x			x	x	x	x	x	x		x	x					7	6	7	7
CSP	x	x	x	x	x		x			x	x	x		x		x	x		x	8	9	8	10
Solar PV	x	x	x	x	x		x				x	x		x		x	x			6	7	6	8
Wind	x	x	x	x	x		x				x	x		x		x	x			6	7	7	7
Geothermal		x	x	x	x					x		x				x		x		6	6	7	7
Hydro	x	x		x								x								2	1	3	1
Ocean	x	x																		1	0	1	0

Table 1. *Literature sources for the estimates of water usage per unit of energy produced, an indication of the available information per relevant energy source, and the number of total occurrences in the literature of the median/minimum/maximum levels for withdrawals and consumption. The literature is sorted chronologically within the categories of peer-reviewed and grey literature respectively. 'CSP' denotes concentrated solar power, and PV denotes photovoltaic solar technology.*

and (b) cooling technologies (national), (c) the source of the water body used in nexus calculations (i.e. sea- or freshwater), principal cooling technologies related to energy source and country, and the electricity generated for each of the EU28 countries is collected. Only open-source data were used (see below). Based on this information, the amount of electricity plant cooling water is estimated. Hereafter this estimate of electricity plant cooling water will be referred to as EW ('estimated withdrawals'). Finally, the results are compared with the actual reported freshwater withdrawals available through Eurostat. Hereafter, this dataset will be referred to as RW ('reported withdrawals'). As a part of the same literature review, the electricity plant cooling water consumption share (i.e. the net share excluding the return flow as defined above) is also estimated. Hereafter, this estimate is referred to as EC ('estimated consumption'). However, EC could not be validated against the reported levels, as data on reported consumption quantities could not be found (hence, the abbreviation 'RC' is not used here).

Estimates of electricity plant cooling water are divided into two separate analyses.

EW1980-2015: This analysis focuses on the temporal evolution of water use in electricity plants. It employs country-specific estimates of energy sources and cooling technologies, whereas data on the freshwater/sea-water shares are largely dependent on the plant-specific information, which is not generally available historically. The corresponding reported withdrawals are denoted 'RW1980-2015'.

EW2015: This analysis is based on the latest year for all data sources (2015). Unlike EW1980-2015, this assessment includes a comprehensive analysis of the level of a single electricity plant after (Enipedia, 2018; Global Energy Observatory, 2018), which allows country-specific water and energy sources to be taken into account, as well as cooling technologies (also feeding back into EW1980-2015). The corresponding reported withdrawals are denoted 'RW2015'.

As for EW, EC1980-2015 and EC2015 (estimated consumption) were calculated based on the same literature, methodology and years.

Steps in the analysis:

(a) Water usage. As described in section 2.2, this step in the analysis assessed the water withdrawal and consumption levels (volumes of water per energy unit – e.g. L/MWh) for each energy source and sub-technology within each of these. See Table 1 for a list of the literature used and figures 1 and 2 and appendices A and B for the resulting estimates of withdrawal and consumption levels.

(b) Energy source. The electricity generation per energy source (nine categories, see Fig. 3 and Fig. 4) was extracted for all EU28 countries in the available resolution (country-level/annual) from the Shift Project Data Portal (Shift Project Data Portal, 2018) (see Fig. 3 for EU28 aggregated values and corresponding use per technology). The energy source categories differ from those extracted from literature (figures 1 and 2) in that solar PV, solar CSP and ocean categories were grouped into one.

(c) Cooling technology. Each of the nine energy sources is further subdivided into subcategories depicting their respective cooling technologies, thus forming a total of 56 energy source/cooling technology combinations (see categories in Figures 1 and 2).

(d) Sea-/freshwater use. At this point, the analysis provides an estimate of the total water usage for electricity generation within EU28. To address freshwater usage only, as described above, the databases of (Enipedia, 2018; Global Energy Observatory, 2018) were assessed for a single plant within EU28. This was done to determine the cooling water source and cooling technology. In a few select cases this information was readily available, whereas for most plants it proved necessary to inspect the plant location visually using satellite imagery. This extra inspection revealed further shortcomings in the databases that substantially affects the results (in relative terms), and these were therefore corrected accordingly. For some countries and technologies, a significant number of electricity plants exist, necessitating a substantial work load if all were to be represented. In these few cases, a threshold was used such that only the largest electricity plants constituting a minimum of 75% of the country's electricity generation were assessed. The remaining plants were then assumed to have the same distribution of technology and water sources, although this assumption might not hold fully (see discussion). If the two databases differed, an online search was used to assess the (current) power-plant configuration. Plants with an estuary, fjord or river outlet location (most often UK and Benelux country plants) were assumed to use seawater, its usability for other sectors (e.g. irrigation) being poor or non-existent. The resulting freshwater percentages are shown in Table 2.

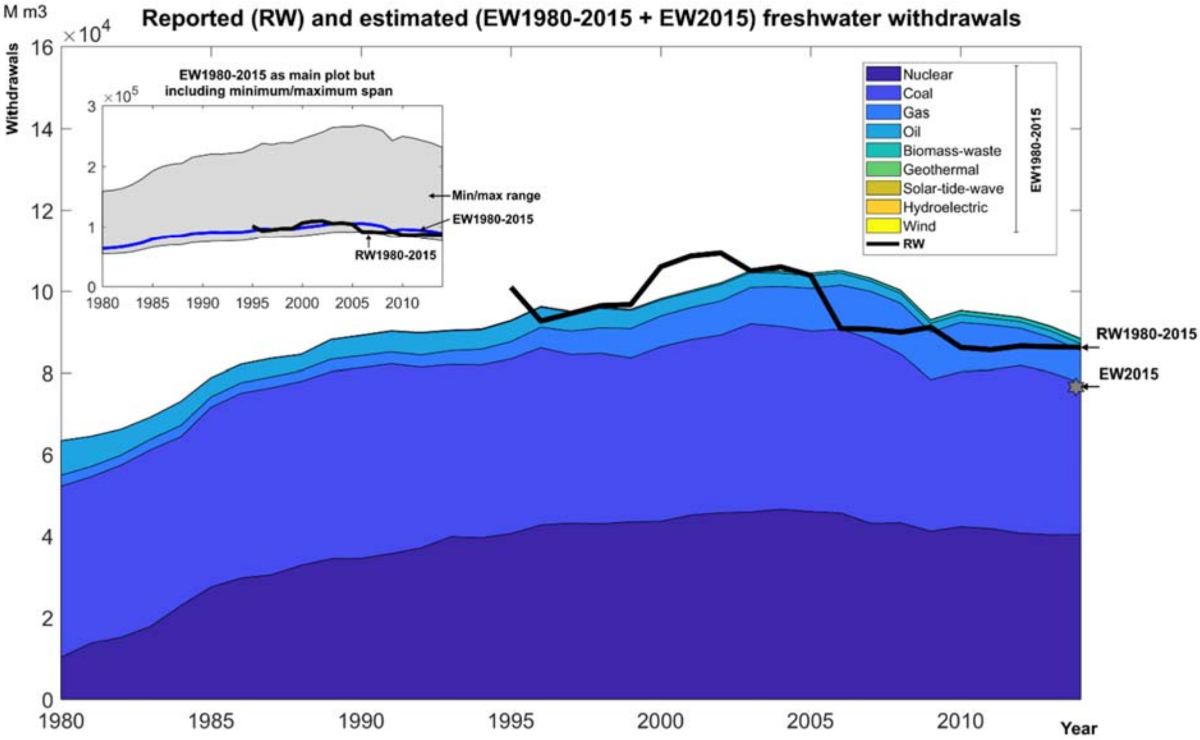


Fig. 3. *Main figure: reported (RW) and estimated freshwater withdrawals per energy source (EW1980-2015) (as well as the sum of estimated freshwater withdrawals per country (EW2015) (arrow)). Insert: EW1980-2015 calculated based on minimum and maximum water-usage levels for each energy source, cooling technology and RW.*

Below, the key energy source and country-specific methodology issues are addressed.

Geothermal. The distribution of geothermal technologies within Europe is based on (Bertani, 2015), as only a single Italian plant is listed within EU28 in (Global Energy Observatory, 2018), whereas Hungary, Ireland, Poland and UK also have geothermal electricity plants (Shift Project Data Portal, 2018).

Energy source/country	EU28	AT	BE	BG	CZ	DK	EE	FI	FR	DE	EL	HU	IT	LI	MT	NL	PL	PT	RO	SI	ES	SE	UK
Nuclear	59.23			100	100				71.4	89.5		100		100	0	100			100	100		0	0
Biomass and Waste	16.9							100				100			0								0
Coal	73.5	100	100	100	100	0				93	100		0		0	76.1	100			100	60		40
Gas	52.2	100	90		100	0				100	0.43	100	41.7	90	0	88		100			45	0	19.5
Geothermal	100														0								
Hydroelectric	0														0								
Oil	43.3					0	100				0				0								0
Solar Tide Wave	100														0								
Wind	0														0								

Table 2. *Freshwater share (%) in electricity plant cooling per EU28 country and energy source in cases of the plant inspection differs from EU28 levels (as shown in left-hand column; see analysis step 'd' above).*

Solar-tidal-wave. To calculate the water usages of the 95.15 TWh produced by means of solar, tidal and wave generation, it is necessary to know the share produced by concentrated solar power (CSP), since this is the only one of these technologies to use water for cooling. Installed capacities in 2014 include 90000 MW solar PV (SolarPower Europe, 2017), 2313 MW CSP (EurObserv'ER, 2017) and 5 MW of ocean energy (tidal and wave) (Magagna and Uihlein, 2015), corresponding to a solar CSP share of 2.5%. Here, the share of CSP technologies (parabolic trough, Fresnel or solar tower) is based on the list of CSP plants in (EurObserv'ER, 2017), and the specific water usages of these technologies are from (JISEA, 2015). whether or not wet/dry cooling is used is based on a manual assessment of CSP plants, concluding that all larger plants have a capacity in the order of 50 MW, and all use wet cooling (for plants where cooling type is listed – 30 out of 45). These 45 50-MW CSP plants are all located in Spain, constitute 97% of the total EU28 capacity, and all employ parabolic trough technology.

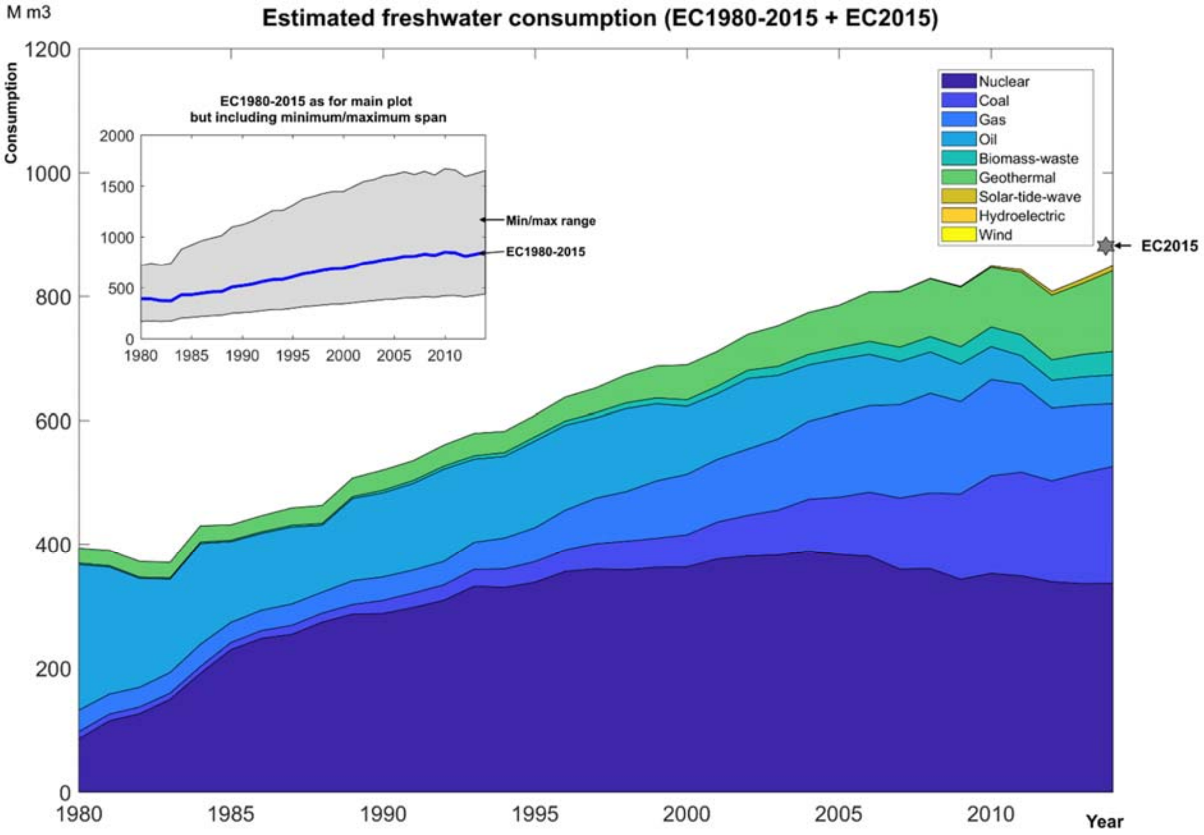


Fig. 4. *Main figure: estimated freshwater consumption (EC1980-2015) per energy source and the sum of estimated freshwater consumption per country (EC2015) (arrow). Energy sources correspond to legend in Fig. 3. Insert: EC1980-2015 calculated based on minimum and maximum water usage levels for each energy source and cooling technology.*

In the Baltic States a high level of mismatch between the databases was found, necessitating correction. One example is the absence of the gas-/oil-based Elektrenai power plant in Lithuania from the Enipedia database, even though it accounts for a dominant share of electricity generation in the country. Another example is the 84% use of coal declared for Estonian electricity generation at the Shift Project data portal, although no plants are listed either in Enipedia or by the Global Energy Observatory. Detailed data on the Czech Republic's electricity systems, including information on plants and cooling technology, were obtained from (Ansorge et al., 2016). For Greece, a lowered median water withdrawal rate of 2220 L/MWh was used compared to the 3238 L/MWh used for other countries (see references in Table 1 and values in Fig. 1 and Appendix A), as described in (Fernández-Blanco et al., 2017). For the Netherlands, the differences between RW and EW could be caused by differing definitions, since only 11 out of 32 gas plants (34% of generated electricity) are clearly located inland at river locations or by the sea, whereas for coal plants the corresponding level is 5 out of 8 (40% of generated electricity) (Global Energy Observatory, 2018). As the remaining parts are located close to the outlets of rivers or within estuaries, inconsistencies between the use of either the 'freshwater' or the 'sea' category could arise between databases. Similarly, the Borssele nuclear plant is located close to the Schelde River outlet but is listed as having freshwater cooling. Therefore, for the Netherlands, the estuary/downstream locations were defined as freshwater plants, since this was seen as the only plausible explanation for the high RW, although it is still not matched by EW using this definition. For Sweden, no coal power is listed by the Global Energy Observatory (Global Energy Observatory, 2018), whereas it is listed in Enipedia (Enipedia, 2018) and the Shift Project Data Portal (Shift Project Data Portal, 2018). This might be due to the interchangeable energy source for the Västerås power plant, the only coal-fired electricity plant in Sweden.

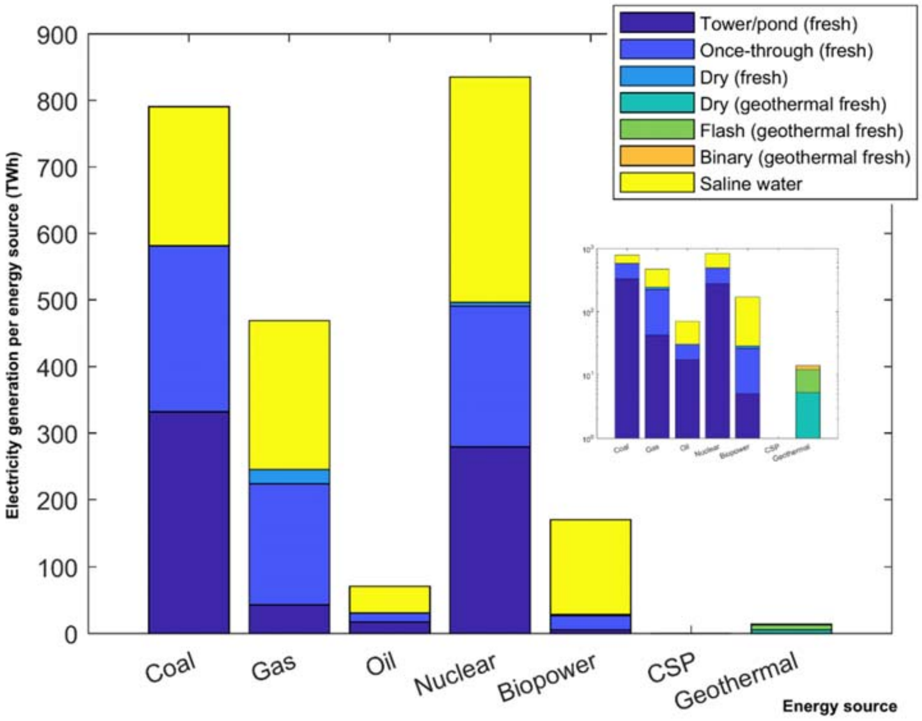


Fig. 5. Electricity generation per energy source (Eurostat, 2018), freshwater shares per energy source and corresponding cooling technologies for these freshwater shares. The 'insert' plot corresponds to the main plot but uses a log-scale y-axis for improved reproduction of low-generation energy sources such CSP.

3. Results

In the following the results of reconstructing levels of the withdrawal and consumption of freshwater from the energy sector in EU28 are compared with reported withdrawal data from Eurostat (Eurostat, 2018). As discussed above power plants and their associated energy production (in TWh) in Europe, based on the available EU28 level information for the period from 1980 to 2015, are initially characterized, followed by estimates of corresponding water usages using the median, minimum and maximum factors from figures 1 and 2 (EW1980-2015 and EC1980-2015). For 2015, for which more detailed information is available, an improved country-level analysis is carried out (EW2015 and EC2015).

Figures 1 and 2 depict all the 896 median, min and max data points on electricity production water withdrawal and consumption which have been extracted in literature as a basis for this study (although a few are not visible within the selected Y-axis limits). See also appendices A and B. A total of 56 technologies are listed based on eleven energy sources (gas is seperated between non-CCGT and CCGT for better visual overview). The span in levels from literature varies depending on energy source and technology but there is a tendency for the dominant combinations such as coal, gas and nuclear using tower and once-through cooling (see also figures 3 and 4) to have more consistent estimates. A tendency for the withdrawal estimates to be more similar than the corresponding consumption estimates is also seen. A reasonable level of agreement between RW and EW is seen (Fig. 3) using the median factors at the aggregated spatio-temporal levels used here. It is evident that conventional energy sources such as nuclear, coal and gas, which require excessive amounts of cooling water, clearly dominate the picture, whereas renewable (and less water-intensive) energy sources are essentially negligible. Results based on the more detailed country-level plant data from 2015 (indicated by a star), on the other hand, seems to slightly underestimate actual water use by the total European energy system. Furthermore, it is evident that the span between the minimum and maximum estimates is substantial (Fig. 3; insert).

In the case of EC (Fig. 4), select renewables such as geothermal and biomass are found to play a significant role here compared to RW/EW, and EC2015 is estimated at a higher level than EC1980-2015. As seen in the insert (Fig. 4), a large span is seen between the maximum and minimum values As compared to Fig. 3, in this case it is difficult to assert the validity of the median estimates since no figures are reported for validation in the literature.

Fig. 5 summarizes analysis step ‘d’ above by providing an overview of the estimated divison of cooling technologies within each energy source (sources with negligible water use are omitted) and the corresponding water source, that is, freshwater or saline water, for EU28. Despite a higher total level, the generation of electricity from nuclear sources (830 TWh) shows lower water-consumption figures than electricity generation from coal sources (791 TWh). This is related to the division of energy sources in between countries and their access to cooling water. For example, Germany produces a large share of its electricity based on coal as an energy source in inland locations. From the figure it is also clear that renewable technologies employ negligable amounts of water, though this omits biofuel production or evapotranspiration from hydropower reservoirs.

Fig. 6 compares country-level estimated withdrawals (EW2015, top right) and estimated consumption levels (EC2015, bottom right) respectively with the reported values (RW2015, top left) based on the more detailed country-level analysis for 2015. From RW2015 it is clear that energy systems in Central Europe, in particular in France and Germany, are particularly water-intensive with regard to total volumes of water compared to the rest of EU28. This pattern is less significant when correcting for the electricity produced (insert, top left), where instead Belgium, Bulgaria, Estonia, Finland, Hungary and the Netherlands stand out. Furthermore, it is seen that the estimated water withdrawals for Europe generate country-level ‘patterns’ that resemble those of RW (see also Fig. 7). In general, RW is found to exceed RW2015 for most countries (bottom left) with some notable exceptions like Germany, Lithuania and the United Kingdom, although the latter’s deviation is likely to be related to low absolute withdrawal levels due a high degree of seawater cooling. Slovenia also stands out (approx 100% overestimate). This is likely to be related to the single nuclear plant in Slovenia, which uses approximately 74% of all national cooling water according to the calculations (EW). Therefore the RW/EW difference may be related to differences between the median values, given the conditions of this single plant. In Finland, most of the larger electricity plants are located along the coastline while still having a freshwater use (RW) of approximately 5000 M m^3. While most biomass plants in Finland are located inland, adding to the country’s freshwater use, a high relative difference of approximately 50% is still seen. For Italy, little attention has been given to investigating the reasons for the large spread between RW and EW, since the latest RW reporting dates from 1980, rendering any attempts at validation futile (the 1980 level is used throughout the period).

Fig. 7 shows the water usage results for EW2015 (top panel) and EC2015 (bottom panel) for each country using the median, minimum and maximum levels. For EW2015, the results are shown in conjunction with RW2015 to enable their validation by country. Assuming this to be a first-order estimate of the ‘true’ associated uncertainty, the estimates (EC2015) approximate well to the corresponding reported values (RW2015), and all estimates are within the illustrated range associated with the country-level estimates except in the case of Malta, where information on local energy sources is lacking.

4. Discussion

As shown above, the estimates of water withdrawal rates compare reasonably well with the independent validation data from Eurostat and with the spatiotemporal scales assessed here, both in reproducing key aspects of the time series data from 1980 to 2015 and in representing the variability in water use for energy by country. Below the implications of the analysis presented here are discussed alongside recommendations for the direction of future data provision within the water–energy nexus.

To achieve the above-mentioned results an ‘ensemble’ of water-usage factors from a range of studies (cf. Table 1) was initially considered. While the authors by no means consider this factor set to be exhaustive, in each of the studies reviewed the estimated water uses (withdrawal and/or consumption) by different energy (cooling) technologies were inferred from local investigations. There was a tendency for them to originate in the USA in particular, possibly due to commercial interests resulting in data not being directly obtainable (Rothausen and Conway, 2011). One example of openly available data originating from the US is (Maupin et al., 2014), which contains very detailed information over time on, for example, water withdrawals per source (surface/groundwater) and per sector (industry, agriculture, housing), with numerous subcategories. As a result of the excessive data from the US, it might be expected that slight differences in local management practices and technology implementation between the US and Europe (and the rest of the world) might introduce a bias. A study by (Macknick et al., 2012), which also examines the water-usage data sources used in the present study, states that some median values are created based on the midpoint between the range endpoints, which may introduce an underestimation bias. Moreover, for some energy production and/or cooling technologies only a very few studies exist (cf. Table 1). In summary, these potential sources of uncertainty and biases imply a lack of complete statistical robustness with regard to the term ‘median’.

However, the median estimates in the studies considered here inherently agree well (results not shown), suggesting that the median factor seems to represent a fairly robust metric with which to represent yearly water usage on the larger European scale. Conversely, and not surprisingly, there is greater variability in the case of the minimum and maximum factor values (e.g. as illustrated by the inserts in Figs. 3 and 4), which are used here to represent the uncertainty associated with the factor estimates.

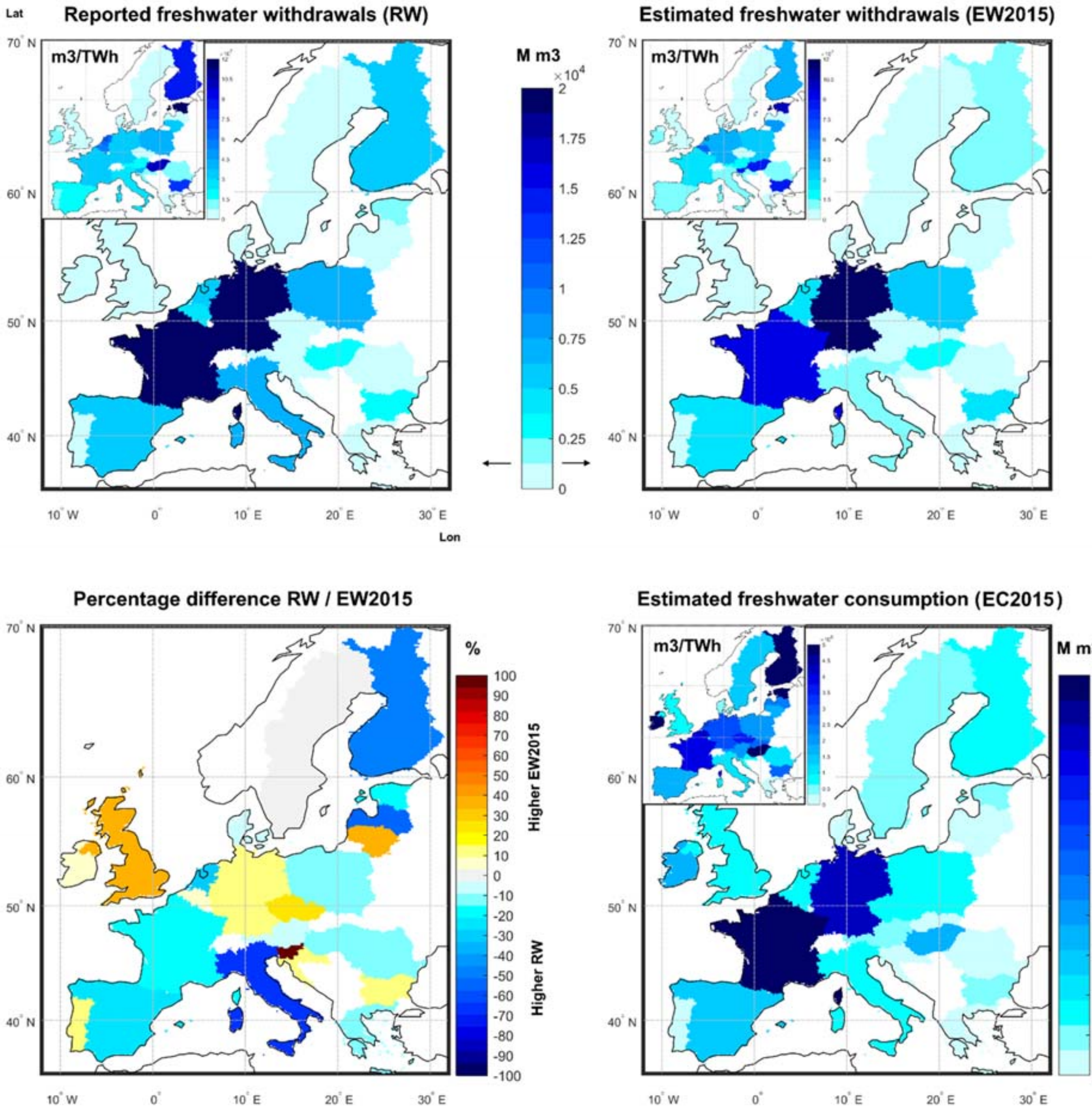


Fig. 6. *Freshwater withdrawals (EW and RW) and consumption (EC) for EU28 countries. Top left: reported freshwater withdrawals (RW2015). Top right: estimated freshwater withdrawals (EW2015). Bottom left: difference between RW2015 and EW2015 (%). Bottom right: estimated freshwater consumption (EC2015). Inserts show levels from the main plots but per generated electricity amounts. Cyprus, Luxembourg, Malta and Slovakia have no reported water withdrawals (white colour).*

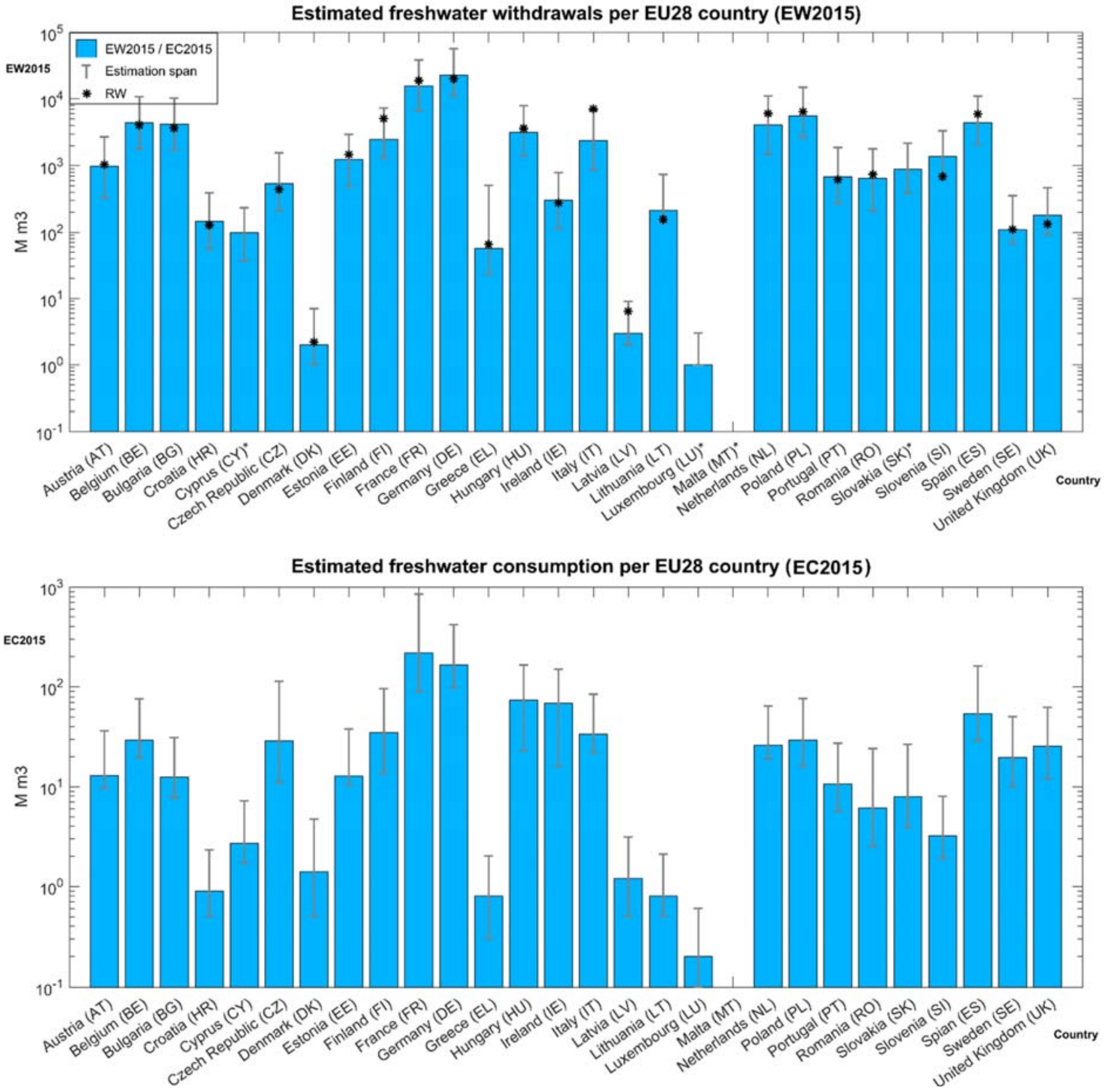


Fig. 7. *Estimated and reported freshwater withdrawals, as well as estimated freshwater consumption with ranges based on minimum and maximum water-usage levels for each energy source and cooling technology. Cyprus, Luxembourg, Malta and Slovakia have no reported water withdrawals (marked with asterisk).*

Another source of uncertainty is the assumption that the low-generation plants have the same technology/water source characteristics as the top 75% of electricity plants (calculated on the basis of electricity generation; see above). Smaller plants tend to have the oldest technologies (i.e. once-through cooling) using more water per unit of electricity generated (as seen in the databases listed above and in (U.S. Dept. of Energy, 2006)), which would imply a negative bias in respect of the estimates of water withdrawals. Here this bias is regarded as largely negligible for EU28 based on the low extent of countries and energy sources where not all plants were assessed.

Mapping European energy production convincingly represents another considerable source of uncertainty. In this study information from several sources is combined to represent energy production and dominant technologies across EU28, as well as to detect and account for obvious gaps or flaws in the underlying data sets. The availability of accurate information in this regard is clearly critical for the results, as this might otherwise lead to erroneous results and/or introduce significant biases in estimated water usages. That said, even for the relatively data-sparse case of modelling water use by energy sources for EU28 between 1980 and 2015, a decent level of agreement with the validation data was found (e.g. Figs. 3 and 7).

A key motivation for conducting the present study estimating water usage in electricity production is the lack of data available to analyse the water–energy nexus properly in quantitative terms, as also highlighted by (Chini and Stillwell, 2017; Larsen et al., 2016). Optimally, such data should be freely available, have wide (global) coverage, have a high temporal resolution, have detailed information on a single plant level, as well as with regard to water (source/sink), have shared and user-friendly formats, be collected using the same conventions, be forced by the same conditions (e.g. for future scenarios) and be congregated in a single database for easy acquisition. Taken together these suggestions are fundamentally out of reach for the near future for reasons of policy (Scott et al., 2011), coordination, financing and commercial interests (Goldstein et al., 2008). However, every step in this direction would improve the possibilities and range of the analytical steps and assumptions needed for most nexus analyses and, in essence, facilitate the emergence of firmer conditions for studying the implications of anthropogenic energy-related activities and water-management perspectives, as (Hussey and Pittock, 2012) also conclude.

By embedding the assembled median water-usage estimates within energy-system models such as TIMES (Simoes et al., 2013) or OSeMOSYS (Howells et al., 2011), the water-requirement impacts could be dynamically simulated and used to investigate a range of water management- and policy-related issues more reliably. In the context of the water–energy nexus, another potential issue to investigate is the impact of introducing more renewable energy technologies into the energy grid and/or add water shortages and related market demands.

5. Conclusions

This paper has investigated the extent to which estimates of an ensemble of factor sets representing volumes of water use per unit of electricity produced by different energy sources, in conjunction with a comprehensive review of the individual cooling technologies and water sources for individual electricity plants, provide an adequate predictor of water withdrawal and consumption levels generation by energy production. Based on validation data, the factor set estimates are found to generate a skilful reproduction of reported withdrawals on the coarse scales assessed here, which, on a yearly basis, include historical levels for EU28 (1980-2015) and individual country levels (2015). In the present demonstration, country-level information was extracted from a number of databases, some of which were found to be ambiguous, inadequate and/or contradictory. To support quantitative studies of the water-energy nexus at different levels and thus facilitate the improved management of water resources, the authors therefore recommend sustained and coordinated efforts towards improving the availability of data linking observations and projections of, for example, energy and water systems at relevant spatio-temporal levels using common scenarios (including climate change) and assumptions.

Acknowledgements

Parts of this work have been supported by the REEEM project (grant agreement no. 691739) funded by the Horizon 2020 (LCE) EU research programme.

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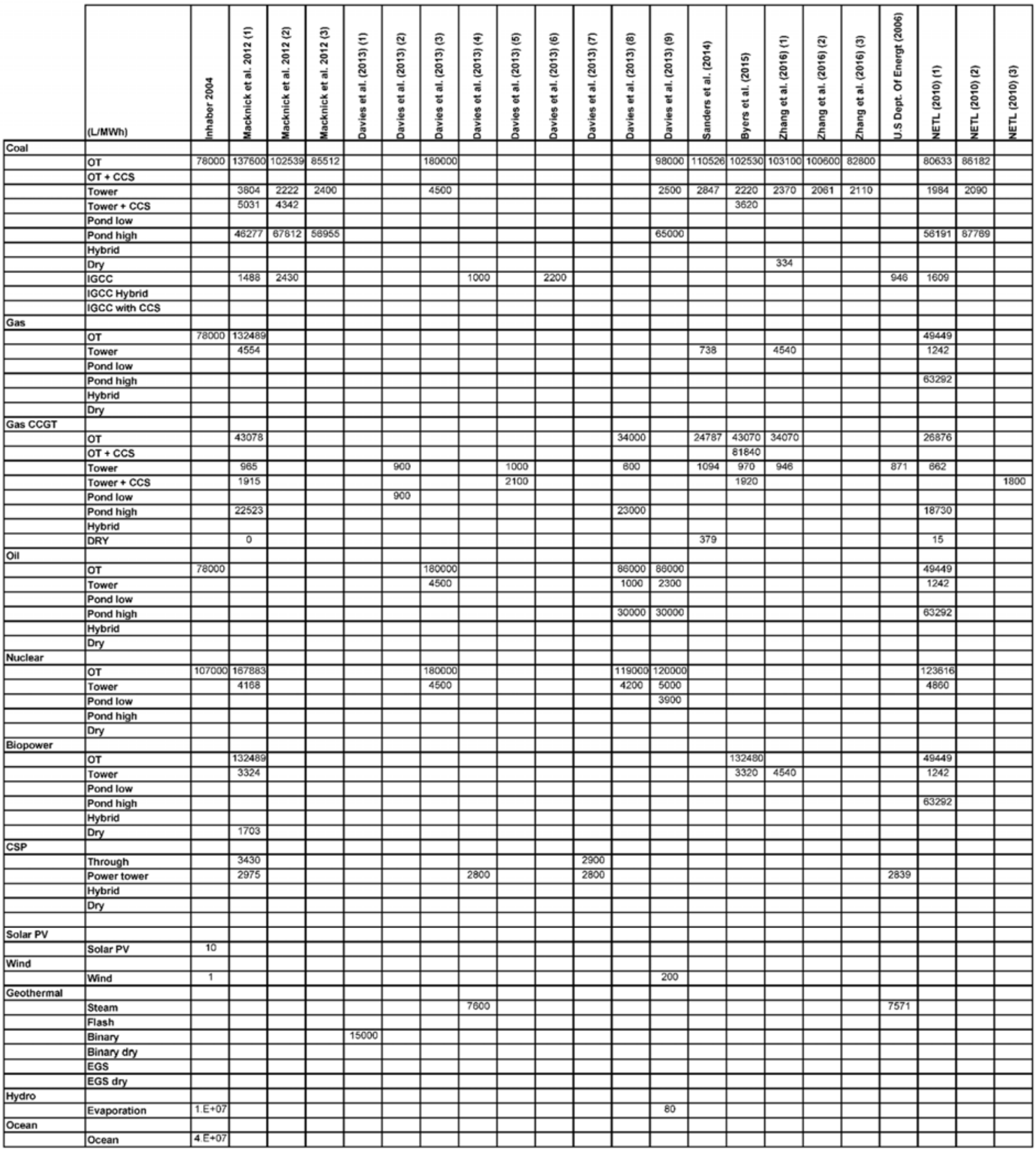
Appendix A

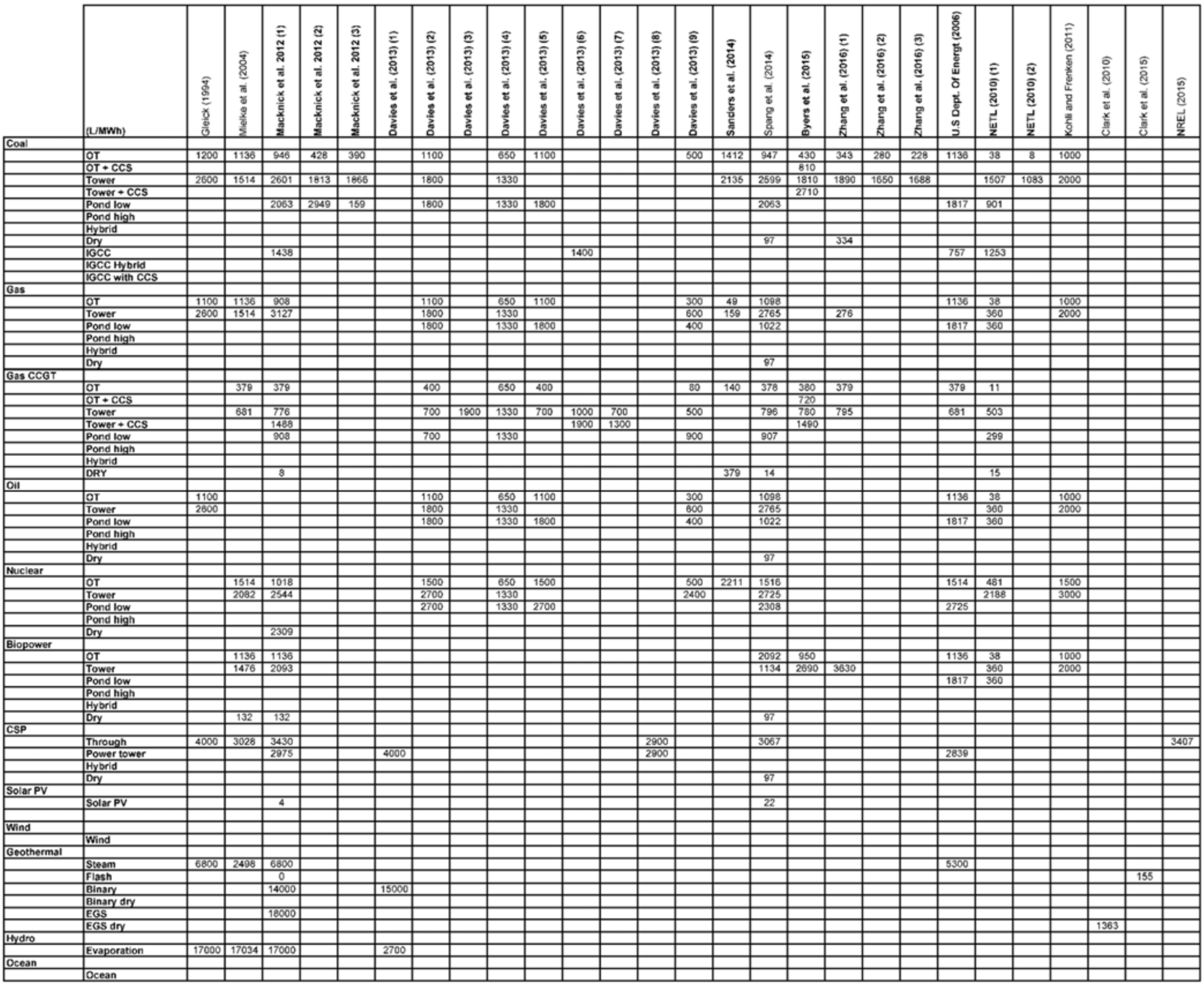
Median water withdrawals. Table form of median values in Fig 1. Literature sources with several values are numbered accordingly.



	(L/MWh)	Inhaber 2004	Macknick et al. 2012 (1)	Macknick et al. 2012 (2)	Macknick et al. 2012 (3)	Davies et al. (2013) (1)	Davies et al. (2013) (2)	Davies et al. (2013) (3)	Davies et al. (2013) (4)	Davies et al. (2013) (5)	Davies et al. (2013) (6)	Davies et al. (2013) (7)	Davies et al. (2013) (8)	Davies et al. (2013) (9)	Sanders et al. (2014)	Byers et al. (2015)	Zhang et al. (2016) (1)	Zhang et al. (2016) (2)	Zhang et al. (2016) (3)	U.S Dept. Of Energt (2006)	NETL (2010) (1)	NETL (2010) (2)	NETL (2010) (3)
Coal																							
	OT	78000	137600	102539	85512			180000						98000	110526	102530	103100	100600	82800		80633	86182	
	OT + CCS																						
	Tower		3804	2222	2400			4500						2500	2847	2220	2370	2061	2110		1984	2090	
	Tower + CCS		5031	4342												3620							
	Pond low																						
	Pond high		46277	67812	56955									65000							56191	87769	
	Hybrid																						
	Dry																334						
	IGCC		1488	2430					1000		2200									946	1609		
	IGCC Hybrid																						
	IGCC with CCS																						
Gas																							
	OT	78000	132489																		49449		
	Tower		4554												738		4540				1242		
	Pond low																						
	Pond high																				63292		
	Hybrid																						
	Dry																						
Gas CCGT																							
	OT		43078										34000		24787	43070	34070				26876		
	OT + CCS															81840							
	Tower		965				900			1000			600		1094	970	946			871	662		
	Tower + CCS		1915							2100						1920							1800
	Pond low						900																
	Pond high		22523										23000								18730		
	Hybrid																						
	DRY		0												379						15		
Oil																							
	OT	78000						180000					86000	86000							49449		
	Tower							4500					1000	2300							1242		
	Pond low																						
	Pond high												30000	30000							63292		
	Hybrid																						
	Dry																						
Nuclear																							
	OT	107000	167883					180000					119000	120000							123616		
	Tower		4168					4500					4200	5000							4860		
	Pond low													3900									
	Pond high																						
	Dry																						
Biopower																							
	OT		132489													132480					49449		
	Tower		3324													3320	4540				1242		
	Pond low																						
	Pond high																				63292		
	Hybrid																						
	Dry		1703																				
CSP																							
	Through		3430									2900											
	Power tower		2975						2800			2800								2839			
	Hybrid																						
	Dry																						
Solar PV																							
	Solar PV	10																					
Wind																							
	Wind	1												200									
Geothermal																							
	Steam								7600											7571			
	Flash																						
	Binary					15000																	
	Binary dry																						
	EGS																						
	EGS dry																						
Hydro																							
	Evaporation	1.E+07												80									
Ocean																							
	Ocean	4.E+07																					

Appendix B

Median water consumption. Table form of median values in Fig 2. Literature sources with several values are numbered accordingly.



	(L/MWh)	Gleick (1994)	Mielke et al. (2004)	Macknick et al. 2012 (1)	Macknick et al. 2012 (2)	Macknick et al. 2012 (3)	Davies et al. (2013) (1)	Davies et al. (2013) (2)	Davies et al. (2013) (3)	Davies et al. (2013) (4)	Davies et al. (2013) (5)	Davies et al. (2013) (6)	Davies et al. (2013) (7)	Davies et al. (2013) (8)	Davies et al. (2013) (9)	Sanders et al. (2014)	Spang et al. (2014)	Byers et al. (2015)	Zhang et al. (2016) (1)	Zhang et al. (2016) (2)	Zhang et al. (2016) (3)	U.S Dept. Of Energt (2006)	NETL (2010) (1)	NETL (2010) (2)	Kohli and Frenken (2011)	Clark et al. (2010)	Clark et al. (2015)	NREL (2015)
Coal																												
	OT	1200	1136	946	428	390		1100		650	1100				500	1412	947	430	343	280	228	1136	38	8	1000			
	OT + CCS																	810										
	Tower	2600	1514	2601	1813	1866		1800		1330						2135	2599	1810	1890	1650	1688		1507	1083	2000			
	Tower + CCS																	2710										
	Pond low			2063	2949	159		1800		1330	1800						2063					1817	901					
	Pond high																											
	Hybrid																											
	Dry																97		334									
	IGCC			1438								1400										757	1253					
	IGCC Hybrid																											
	IGCC with CCS																											
Gas																												
	OT	1100	1136	908				1100		650	1100				300	49	1098					1136	38		1000			
	Tower	2600	1514	3127				1800		1330					600	159	2765		276				360		2000			
	Pond low							1800		1330	1800				400		1022					1817	360					
	Pond high																											
	Hybrid																											
	Dry																97											
Gas CCGT																												
	OT		379	379				400		650	400				80	140	378	380	379			379	11					
	OT + CCS																	720										
	Tower		681	776				700	1900	1330	700	1000	700		500		796	780	795			681	503					
	Tower + CCS			1488								1900	1300					1490										
	Pond low			908				700		1330					900		907						299					
	Pond high																											
	Hybrid																											
	DRY			8												379	14						15					
Oil																												
	OT	1100						1100		650	1100				300		1098					1136	38		1000			
	Tower	2600						1800		1330					600		2765						360		2000			
	Pond low							1800		1330	1800				400		1022					1817	360					
	Pond high																											
	Hybrid																											
	Dry																97											
Nuclear																												
	OT		1514	1018				1500		650	1500				500	2211	1516					1514	481		1500			
	Tower		2082	2544				2700		1330					2400		2725						2188		3000			
	Pond low							2700		1330	2700						2308					2725						
	Pond high																											
	Dry			2309																								
Biopower																												
	OT		1136	1136													2092	950				1136	38		1000			
	Tower		1476	2093													1134	2690	3630				360		2000			
	Pond low																					1817	360					
	Pond high																											
	Hybrid																											
	Dry		132	132													97											
CSP																												
	Through	4000	3028	3430										2900			3067											3407
	Power tower			2975			4000							2900								2839						
	Hybrid																											
	Dry																97											
Solar PV																												
	Solar PV			4													22											
Wind																												
	Wind																											
Geothermal																												
	Steam	6800	2498	6800																		5300						
	Flash			0																							155	
	Binary			14000			15000																					
	Binary dry																											
	EGS			18000																								
	EGS dry																									1363		
Hydro																												
	Evaporation	17000	17034	17000			2700																					
Ocean																												
	Ocean																											

Projected European energy sector water usage, 2015-2050

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Abstract

In the future, the demand for freshwater is projected to increase for some regions and sectors globally, alongside still worsened freshwater resources with regard to availability, quality and sustainability. In this light, proper projections of the water usage per sector is needed to implement proper water management.

This study aims to project the future water use of electricity generation over the EU28 countries (+ Norway and Switzerland) alongside analyses on the trends of the projected future water availability.

The electricity generation water usage is calculated based factors, i.e. water use per electricity unit produced, per energy source and sub-technology and then multiplied by the specific projected electricity generation for these energy sources/technologies as produced within the H2020 REEEM project TIMES-PAN-EU energy modelling system. The energy model is optimization based and was forced based to produce pathways for three scenarios namely 'Base' (policy as is), 'Local solutions' (LS) (every country implements individual targets) and 'Paris agreement' (PA) (every country aims to follow the regulations of the Paris Agreement).

The projected water resources for the future (until 2050) is based on regional climate model simulations using the RCP2.6, RCP4.5 and RCP8.5 future scenarios extracted from the CORDEX data repository extracting the 'net precipitation (precipitation minus evapotranspiration, i.e. the available water).

The study shows geothermal energy to be the main water consumer in the shift towards more renewable energy sources. Also, some countries will experience decreasing water availability (here calculated on annual levels), especially regions in Southern Europe, which will also potentially affect the use of CSP technologies and potentially increase conflicts with other sectors.

1. Introduction

As a part of the REEEM project (Montenegro and Fahl 2017) the environmental footprint of future modelled energy systems scenarios were assessed. Due to the inherent connection between energy and the environment, for water often referred to as the Water-Energy-Nexus, the analysis of the transition of the energy system towards renewable energy sources and more modern technologies needs to be performed in conjunction with environmental analyses.

As the energy system is a major consumer of water as mostly used in the cooling of thermal power plants, but also other uses such as cleaning, energy system transitions will also influence water usage levels. This study aims to address the future water consumption from electricity generation with Europe up until 2050 for the three general pathways, which were developed within REEEM.

2. Methods

2.1 Future electricity generation water consumption

To project future water consumption levels from EU electricity generation, the yearly electricity generation (TWh) per country/fuel source was combined with water consumption factors (water usage per unit of electricity produced) from (Larsen and Drews 2019).

That study (Larsen and Drews 2019) reviews water consumption factors from electricity generation from a broader literature study on a historical timescale (1980-2015) and subsequently validates the results against estimated/reported levels per country as acquired at (Eurostat 2018) and concludes a general good agreement (on the relatively coarse spatio-temporal scales where data was available). The general methodology includes the assessment of water consumption factors from literature including median, minimum and maximum levels. The resulting factors are then estimated using the 'median of medians'. This is done for all water consuming energy sources and for each of the cooling sub-technologies (i.e. tower, pond, dry cooling), as most power plant water usage stems from thermal cooling of non-renewable fuels. Subsequently, all power plants are analyzed from a combination of sources including (Enipedia 2018; Global Energy Observatory 2018; Shift Project Data Portal 2018) as well as satellite imagery analyses to estimate both the cooling technology, since this vastly affects the water usage, as well as the water source as only freshwater resources are addressed in (Larsen and Drews 2019) as well as in the present study. The combination of these analyses is the used to estimate electricity generation water consumption. In the present study, the water factors from (Larsen and Drews 2019) are then used in conjunction with electricity generation levels from three future pathways as estimated by modelling efforts within the REEEM project (Montenegro and Fahl 2017) (see next section).

2.2 Modelled future electricity generation

The projected electricity generation levels are based on REEEM project (Montenegro and Fahl 2017) modelling efforts from the three pathways of "Base" conditions (Base), "Local Solutions" (LS) and "Paris Agreement" (PA) (Montenegro and Fahl 2017). The Base pathway narrates a future where energy carrier suppliers take on the highest burden in the decarbonisation of the EU energy system, while consumers observe it mostly passively or respond to policies as they come. The LS pathway narrates a future where consumers (especially households) engage in the transition towards a low-carbon energy system, by choices on end use appliances, energy efficiency measures and transportation technologies. The PA pathway narrates a future where the EU undertakes an ambitious decarbonisation effort, with a target of 95% reduction of CO2 emissions by 2050. This overshoots the Paris Agreement pledges. Both energy carrier suppliers and consumers engage in the challenge.

Following the development of these pathways, the TIMES-PAN-EU (Gotzens et al. 2018) European energy model has been forced by these projected pathways to produce energy systems characteristics and output there among power plant electricity generation levels across EU28 (+2) on a country level spatial scale for 2015-2050, in 5-year steps, and divided into fuel source and CHP/non-CHP implementation. Here, no distinction are made between CHP and non-CHP due to equal water usage levels (Larsen and Drews 2019) – these summed and used in conjunction. These electricity generation levels have been used in the present sub-study to further project the water consumption of electricity generation levels at a similar spatio-temporal aggregation.

2.3 Water projections

The reasoning for this study is the assessment of water resources within the water-energy nexus where the demand for water from different sectors such as agriculture, industry, private consumption, as well as of course energy, can potentially exceed the available supply. This scenario is especially likely in certain regions with increasingly for drier conditions (as well as increasing demand) and in certain periods as caused by natural variability from the hydro-climatic system. Therefore, in conjunction with the assessment of electricity generation water consumption within Europe from 2015-2050, the hydro-climate is also assessed to estimate the future water availability.

For this, the CORDEX regional climate model (RCM) output repository and database is used (Giorgi and Gutowski 2015). In CORDEX, the RCMs are generally available for historical periods as both 'evaluation' data (employing re-analysis data for domain boundary forcings) and 'historical' data (employing dynamical downscaling using GCM boundary forcings). For future projections, the IPCC RCP scenarios are used as forcing data. The CORDEX data was chosen as data source since a range of hydro-climatic variables are accessible over various regions, including Europe, historically as well as for the future as based on representative concentration pathways (RCP) (IPCC 2014) on spatiotemporal resolution matching the output from the energy systems modelling efforts in REEEM (Montenegro and Fahl 2017). Specifically, we here use the output from all available RCM models in CORDEX which holds simulations for the IPCC scenarios of RCP2.6, RCP4.5 and RCP8.5 (IPCC 2014) (see table 1) employing the RCM ensemble mean as the metric to calculate water consumption. This ensemble approach with equal weights between models is the standard approach for climate change modelling studies (Christensen et al. 2019; Matte et al. 2019).

For the present analysis, the CORDEX variable 'total runoff' was extracted (entitled 'mrro' in CORDEX terms). This variable represents the 'net precipitation' which is the actual evapotranspiration subtracted from precipitation. Thus, this variable was here regarded as the best proxy to summarize the water balance and estimate the water that is available for replenishing surface as well as sub-surface reservoirs, anthropogenic as well as natural and acquifer-based- wherefrom power plant cooling water is extracted. The data was extracted from the CORDEX data repository on a monthly resolution in 12.5 km grid cells. For the country-level analyses presented here, only cells with a +50% overlap with the country in question was employed.

Other than employing the RCM ensemble mean, the coefficient of variation (standard deviation normalized by the mean) between the models was calculated to depict the level of model agreement. This metric was used to account for the large differences between different regions of Europe allowing for better relative comparisons. Further, separate results were generated for Spain to highlight a region were droughts are predicted for the future. Here, the results of individual RCM grid cells were plotted in histogram format for all RCMs and RCPs to depict the changes in surface runoff as large differences occur within each country.

Table 1. RCM and GCM model combinations from the CORDEX data repository (Giorgi and Gutowski 2015) used in the study. For all model combinations, the scenarios of RCP2.6, RCP4.5 and RCP8.5 have been used.

RCM	GCM
RCA4	EC-EARTH
RACMO22	CNRM-CM5
CCLM4	EC-EARTH
REMO2009	MPI-ESM-LR

3 Results

On a EU28 (+2) level, the total water consumption from electricity generation is decreasing from 2015 towards 2050 for the Base pathway (figure 1) and to some extent the LS pathway (figure 2) whereas the PA pathway decreases towards 2035 where after an increase to approximately 2015 levels is seen in 2050 (figure 3). The main sources for the decreasing levels is seen for the traditional non-renewable energy sources such as coal, lignite, natural gas and to some extent nuclear. The main water consuming energy sources after the implementation of renewables is geothermal energy – for all pathways a vast increase in geothermal water consumption is seen, especially for LS. The main differences with regards to water future consumption between LS and PA is the significant increase in geothermal electricity in the LS (Figures 4-6). The higher water consumption for PA compared to LS, almost reaching 2015 levels in 2050, is due to the significant share of coal-fired electricity in 2050 (figure 6).

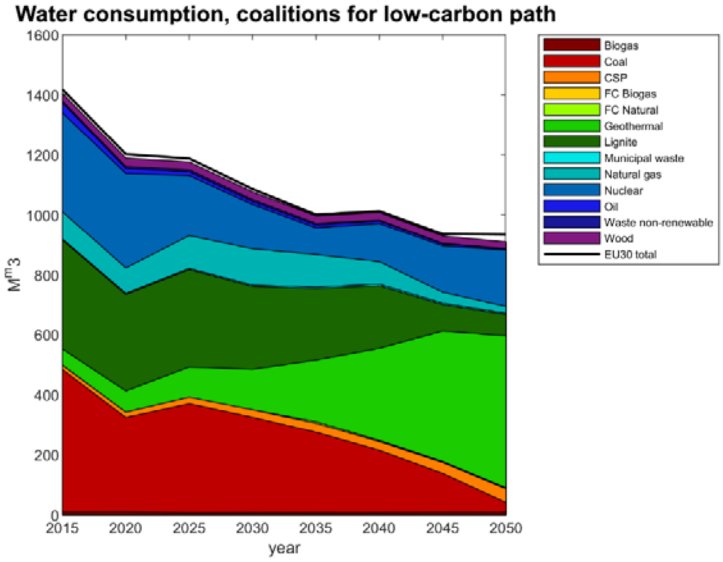


Figure 1. Water consumption for the Base (Base) pathway for EU28 (all energy sources) and EU28+2 (total).

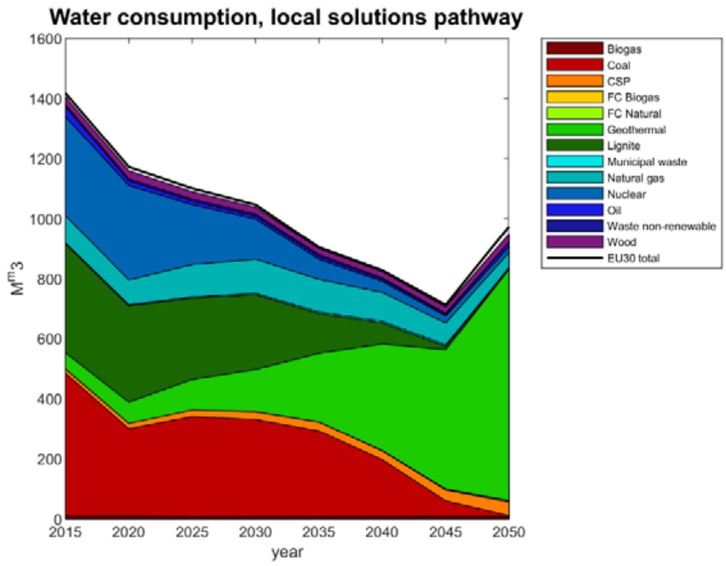


Figure 2. Water consumption for the Local Solutions (LS) pathway for EU28 (all energy sources) and EU28+2 (total).

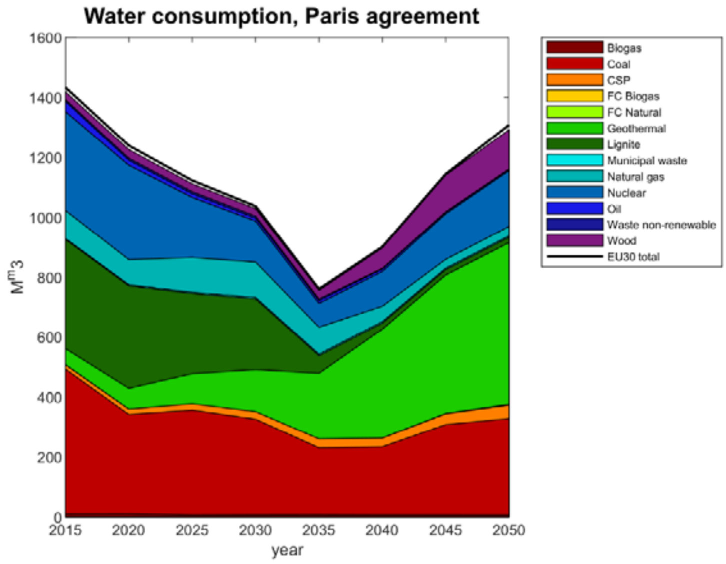


Figure 3. Water consumption for the Paris Agreement (PA) pathway for EU28 (all energy sources) and EU28+2 (total).

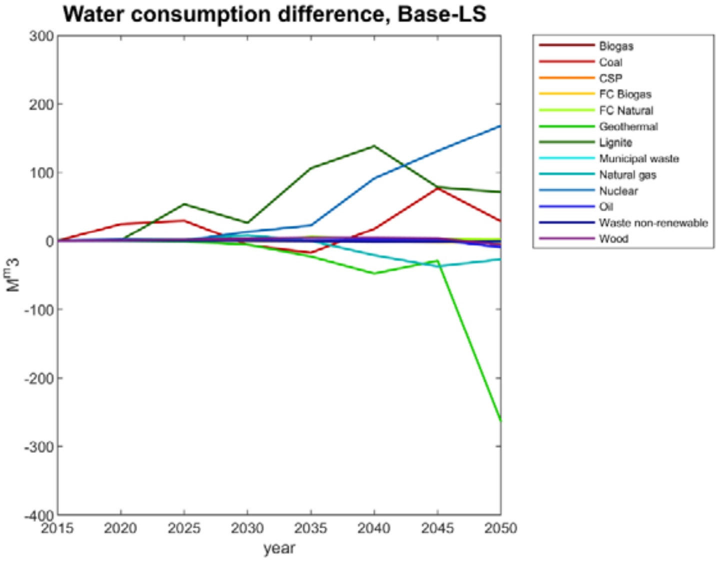


Figure 4. Water consumption difference between the Base and LS pathways for EU28 (LS subtracted from Base – hence; positive equals higher Base values).

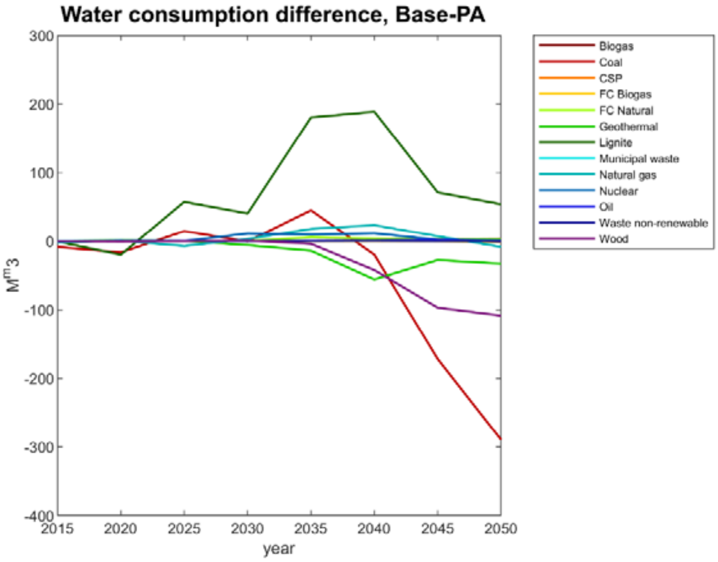


Figure 5. Water consumption difference between the Base and PA pathways for EU28 (PA subtracted from Base – hence; positive equals higher Base values).

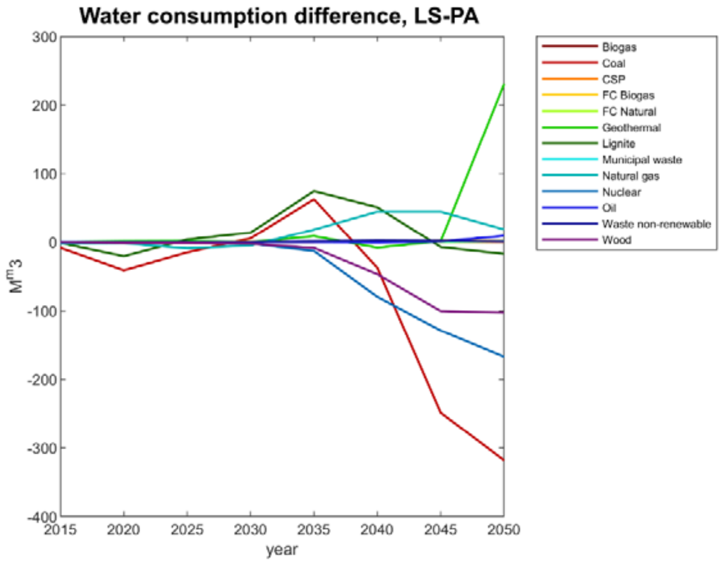


Figure 6. Water consumption difference between the LS and PA pathways for EU28 (PA subtracted from LS – hence; positive equals higher LS values).

The mean surface runoff across RCMs is seen for all three RCPs for the years 2015 and 2050 in figure 7 as well as the residual between those years. In general and unsurprisingly, the patterns follow those of precipitation: western UK, western Norway, the Alps, The Pyrenees, the Dinaric Alps and Galicia show the highest levels of surface runoff with more moderate levels over Sweden, central and eastern Europe. Some larger differences are seen between RCPs: UK and Sweden experiences increased water availability for RCPs 4.5 and 8.5 whereas RCP2.6 is more moderate. A decrease for northwestern Norway is seen for RCP4.5 only. The increase in central Europe is most profound for RCP4.5, whereas here the southern Alps are characterized by a general decrease as opposed to RCPs 2.6 and 8.5. The decrease for southern Europe is generally consistent throughout all RCPs.

The consistency between model predictions is depicted in figure 8 as the coefficient of variability (see the Methods section). In general, the highest levels of model disagreement are seen for the regions of southern Europe were dry conditions are seen in figure 7 although also profound over parts of Eastern Europe. Little consistency in the change of patterns is seen from 2015 onwards to 2050 between the RCP scenarios. In general however, RCP2.6 shows less model divergence for 2015 all throughout Europe (figure 8 upper right).

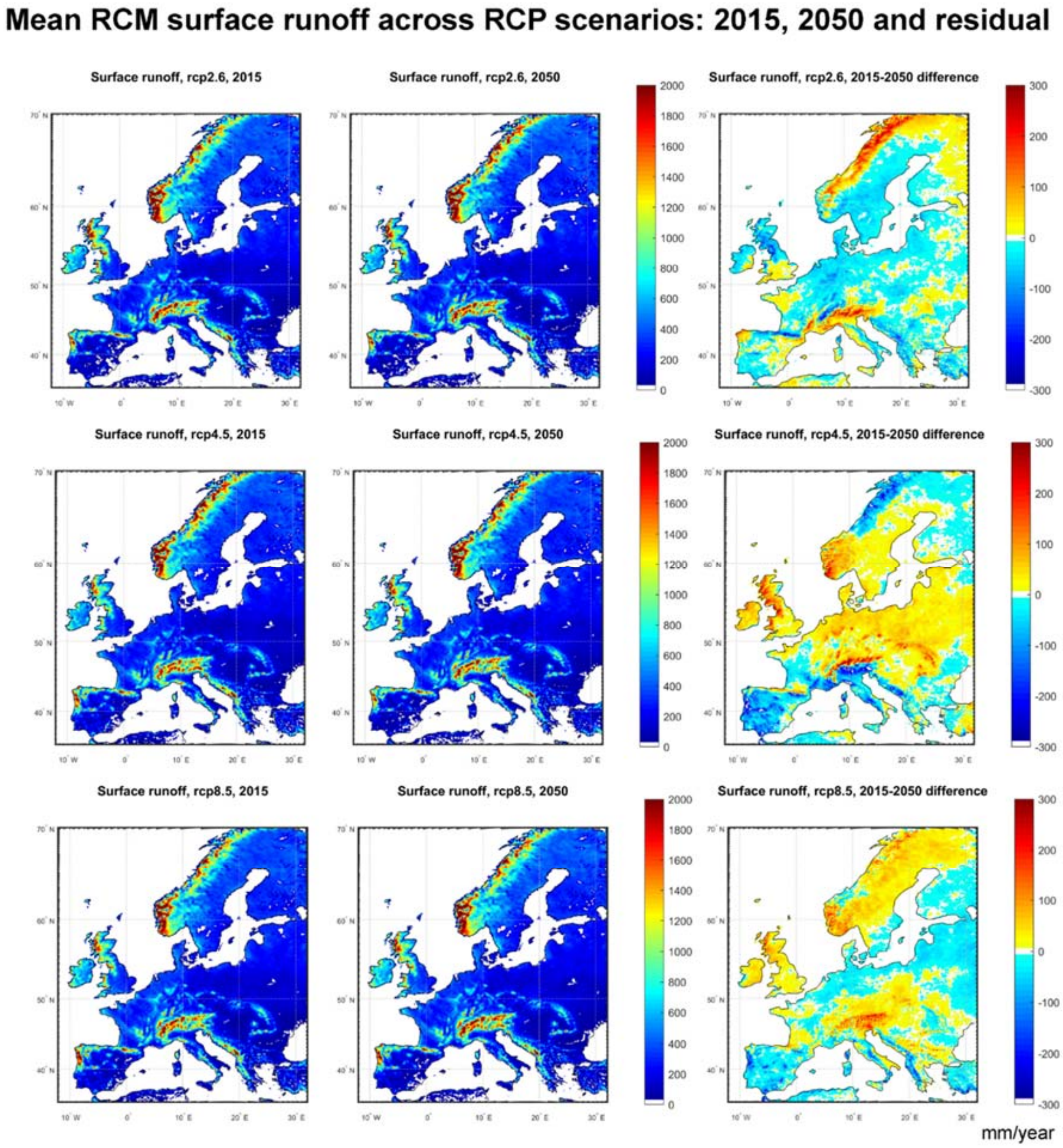


Figure 7. Mean surface runoff (mm/year) between the four RCMs for 2015, 2050 and the 2015-2050 difference (2015 subtracted from 2050 – hence; positive equals higher 2050 level) for the rcp2.6, rcp4.5 and rcp8.5 scenarios (extracted from the CORDEX data repository (Giorgi and Gutowski 2015)).

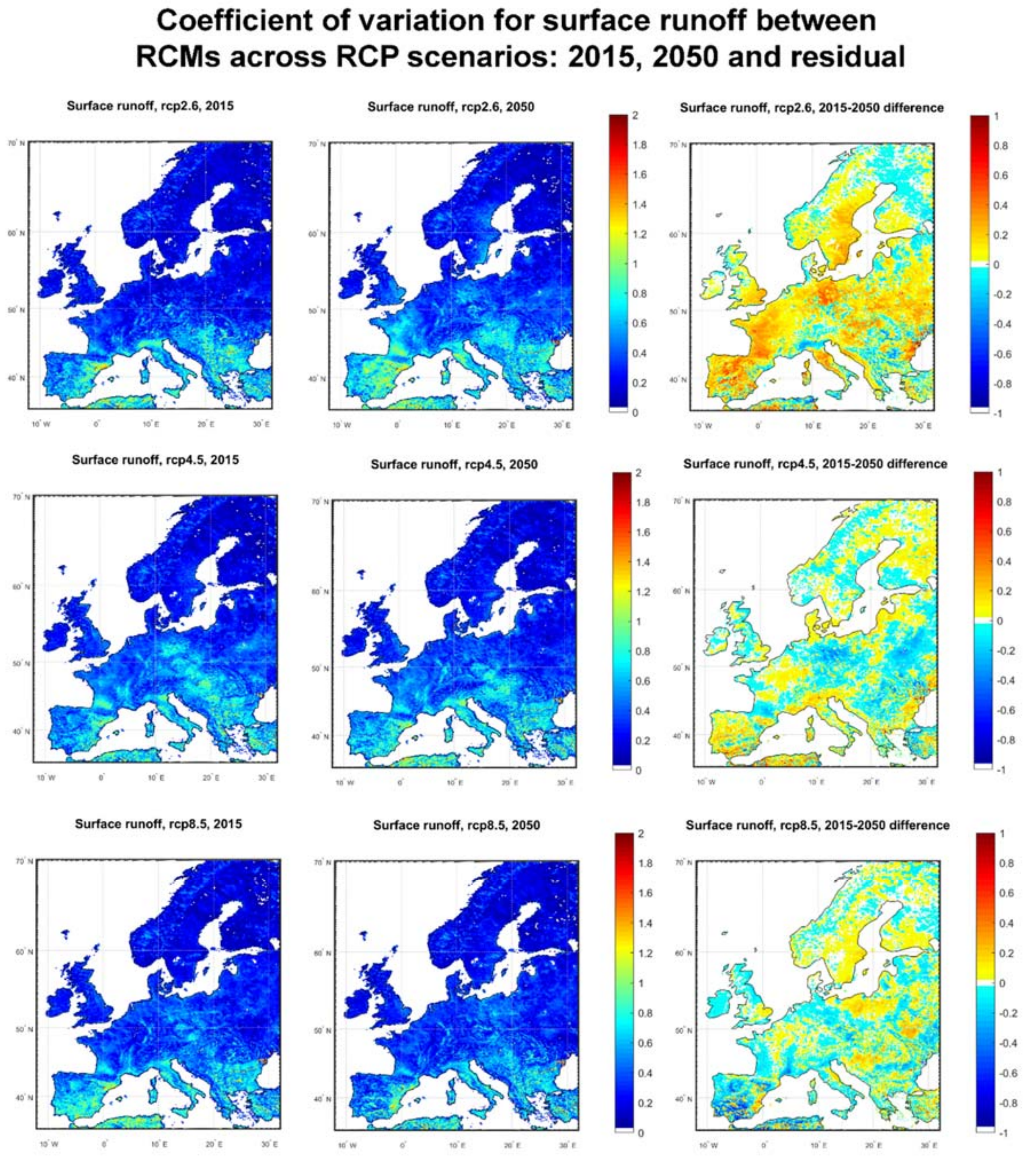


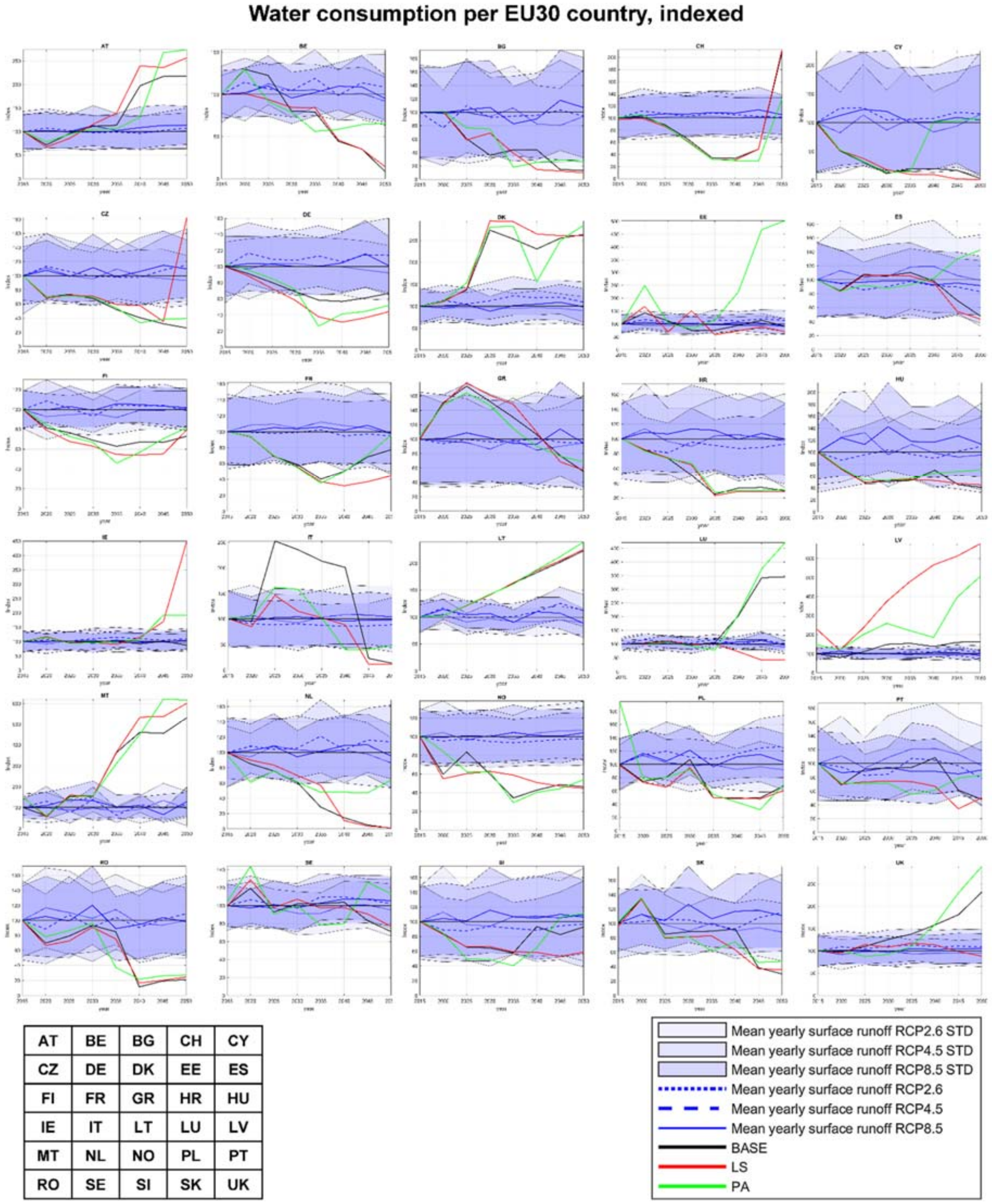
Figure 8. Coefficient of variation between the four RCMs for surface runoff (standard deviation normalized by the mean) for 2015, 2050 and the 2015-2050 difference (2015 subtracted from 2050 – hence; positive equals higher 2050 level) for the rcp2.6, rcp4.5 and rcp8.5 scenarios (extracted from the CORDEX data repository (Giorgi and Gutowski 2015)).

The water consumption per EU28 (+2) country in indexed levels relative to 2015 is seen in figure 9 as well as the corresponding surface runoff. In conjunction, the sign of change (+/-) of water consumption and surface runoff (equal to net precipitation), can be regarded as an indicator of potential critical conditions with regards to water supply and demand from the energy sector.

General increasing water consumptions levels can be seen from a number of countries such as AT, CH, DK, LT, LV and MT whereas some countries experience increasing levels for certain pathways only, here among: CY, CZ, EE, IE, LU, LV and UK (see appendix A for country abbreviations) (figures 9-10). These differences arise from different TIMES-PAN-EU energy system modelling responses to the forcings of the three pathways (Gotzens et al. 2018). Likewise, the levels vary between pathways as mostly decided by level of introduced geothermal energy.

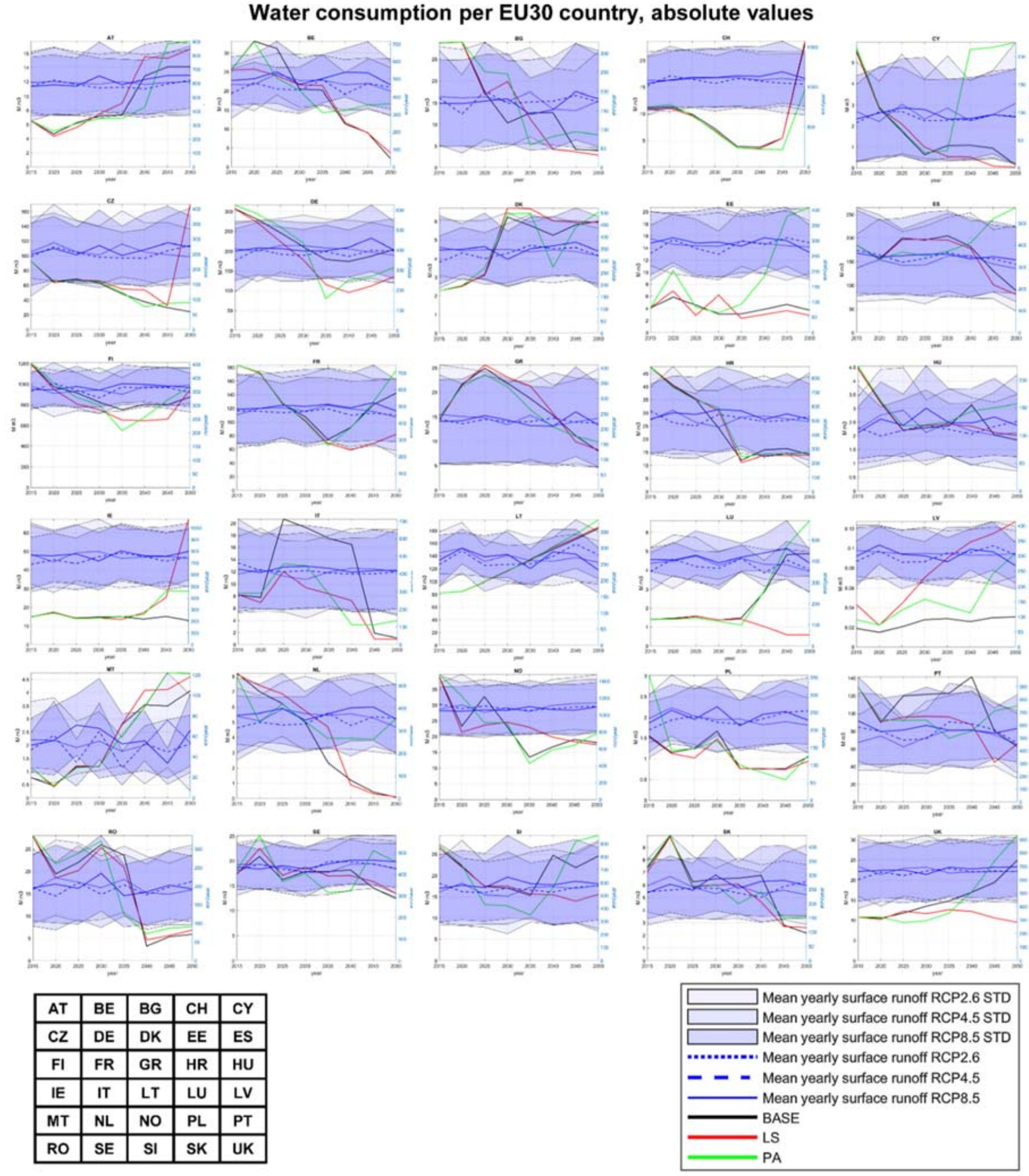
The variation between models for each RCP (calculated as the cross-model standard deviation) has also been used in the projected water availability per country (figure 9 and 10) showing significant variations between countries. In general variations between +/- 25% (e.g. for LU) and +/- 80% (CY). Figure 10, shows the same data basis as figure 9 albeit in absolute values to depict the span in water consumption (non-weighted with country area) and surface runoff levels between countries.

A selected country, Spain/ES, is plotted in figure 11 to depict within-country grid-scale differences between the RCMs and RCPs. In general, as here plotted for yearly means, the RCP4.5 and RCP8.5 scenarios show higher runoff levels than RCP2.6, although most significant for 2015 compared to 2050. From 2015 to 2050 a general decrease in surface runoff is with a significantly larger share of grid cells <100 mm/year in 2050 compared to 2015.



AT	BE	BG	CH	CY
CZ	DE	DK	EE	ES
FI	FR	GR	HR	HU
IE	IT	LT	LU	LV
MT	NL	NO	PL	PT
RO	SE	SI	SK	UK

Figure 9. Water consumption used by electricity generation for the three pathways, Base, LS and PA, as well mean yearly surface runoff per EU28+2 country for all three RCPs (blue lines) as well as the confidence interval calculated as the standard deviation across models (STD - shaded areas). All values are indexed relative to the 2015 level.



AT	BE	BG	CH	CY
CZ	DE	DK	EE	ES
FI	FR	GR	HR	HU
IE	IT	LT	LU	LV
MT	NL	NO	PL	PT
RO	SE	SI	SK	UK

Figure 10. Water consumption used by electricity generation for the three pathways, Base, LS and PA, as well mean yearly surface runoff per EU28+2 country for all three RCPs (blue lines) as well as the confidence interval calculated as the standard deviation across models (STD - shaded areas). All values are absolute (10^6 m^3 and mm/year respectively).

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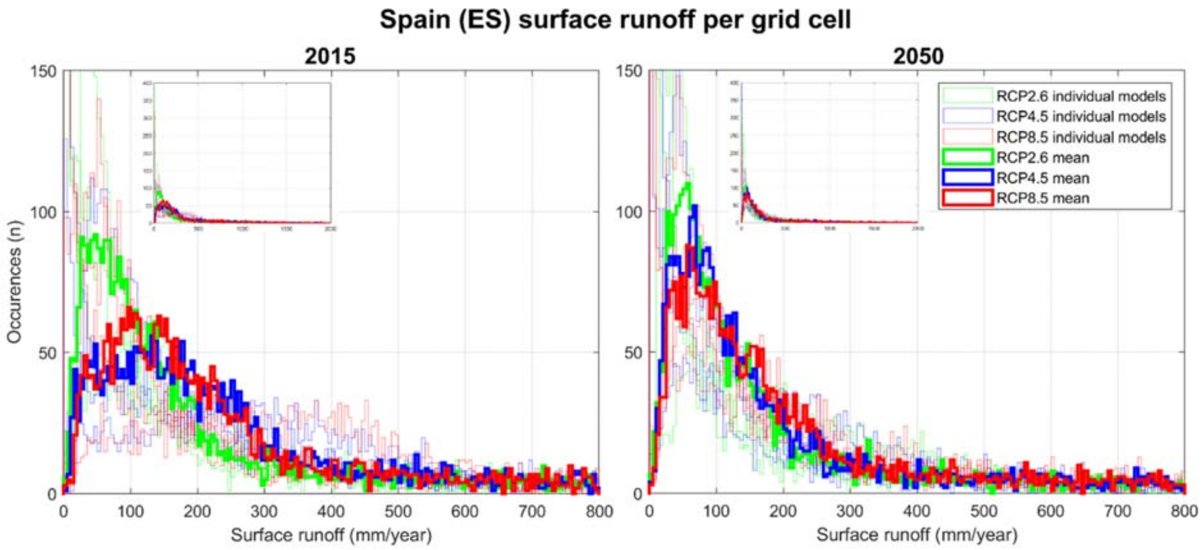

Figure 11. Histogram of the surface runoff (mm/year) for Spain (ES) for the RCM means (bold lines) as well as individual models (thin lines) for all three RCP scenarios (RCPs 2.6, 4.5 and 8.5) for the years 2015 and 2050 in 160 bins. Inserts; same results but showing a wider range of the data (400 bins).

Limitations and Perspectives

The analysis presented here addresses general levels on country-/yearly levels and, as such, is not able to account for natural variability (such as occurrences of drought) or sub-country level conditions as might be relevant for certain regions such as in Southern Europe. A separate and more detailed analysis would be able to address these issues.

Certain regions are known to experience an increased occurrence of (summer) droughts such as, at least, the Southern part of Spain (Kjellström et al. 2018). From figures 9-10, an increasing water consumption is seen for the PA pathway in Spain as caused partly by increasing concentrated solar power (CSP) shares in electricity production (having a high water consumption). Alongside, the water availability over Spain is seen to decrease for the RCP4.5 and RCP8.5 scenarios (for certain regions also RCP2.6), and especially for the southern parts where CSP is relevant. Thus; the coarse country-level division in TIMES-PAN-EU holds sub-country differences wherefore future electricity planning should obviously occur at local scales in relation to available water resources. This is also highly evident from figure 11.

Acknowledgements

This work has been supported by the REEEM project (grant agreement no. 691739) funded by the Horizon 2020 (LCE) EU research programme.

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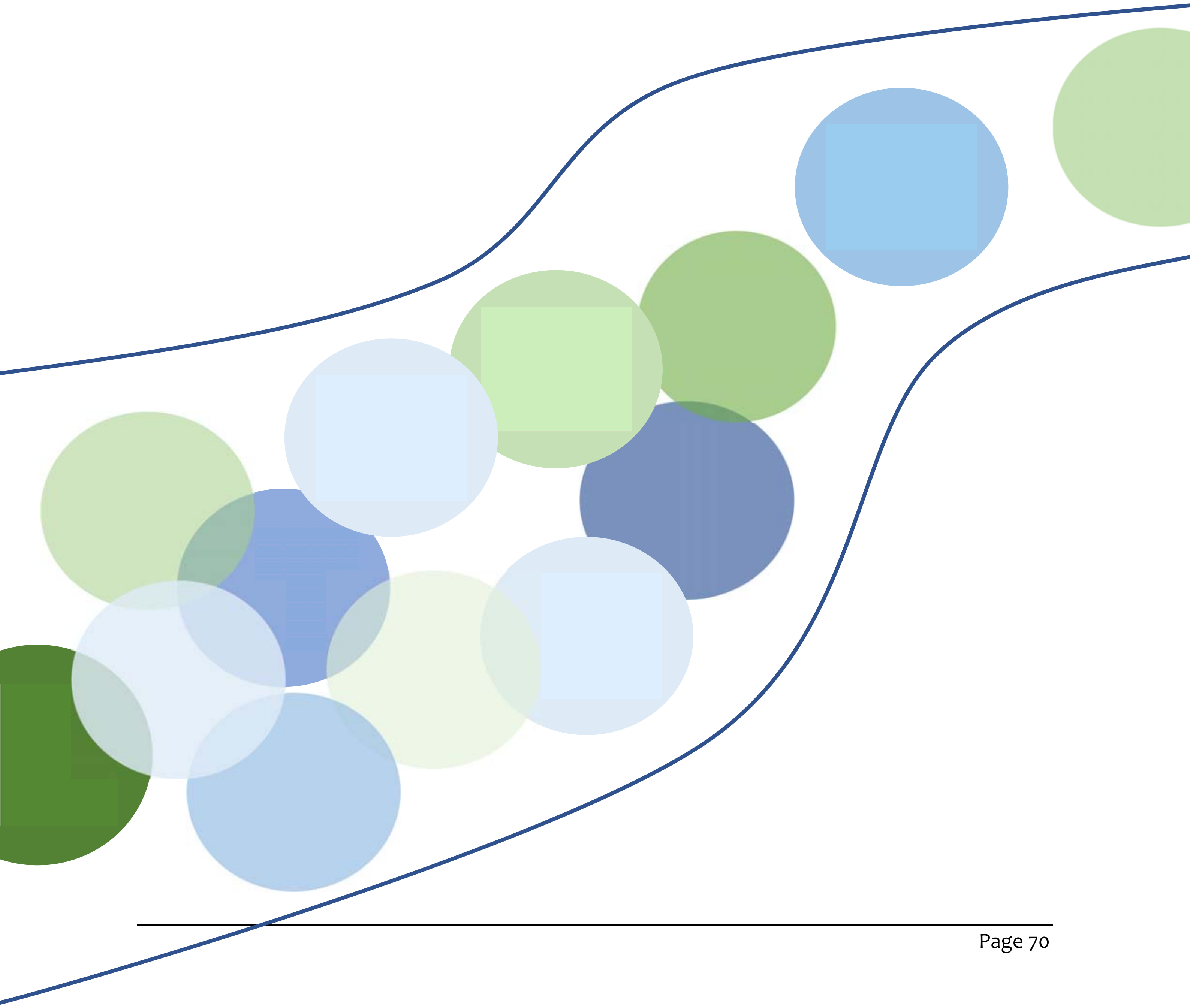
Appendix A

EU28 (+2) countries and their abbreviations.

	Country	**Abbreviation**	**EU28**	**EU28 (+2)**
1	Austria	AT	x	x
2	Belgium	BE	x	x
3	Bulgaria	BG	x	x
4	Switzerland	CH		x
5	Cyprus	CY	x	x
6	Czechia	CZ	x	x
7	Germany	DE	x	x
8	Denmark	DK	x	x
9	Estonia	EE	x	x
10	Greece	EL	x	x
11	Spain	ES	x	x
12	Finland	FI	x	x
13	France	FR	x	x
14	Croatia	HR	x	x
15	Hungary	HU	x	x
16	Ireland	IE	x	x
17	Italy	IT	x	x
18	Lithuania	LT	x	x
19	Luxembourg	LU	x	x
20	Latvia	LV	x	x
21	Malta	MT	x	x
22	Netherlands	NL	x	x
23	Norway	NO		x
24	Poland	PL	x	x
25	Portugal	PT	x	x
26	Romania	RO	x	x
27	Sweden	SE	x	x
28	Slovenia	SI	x	x
29	Slovakia	SK	x	x
30	United Kingdom	UK	x	x

Part II

Future Heating and Cooling Needs



Exploring long-term trends in future heating and cooling demands in a European context

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Keywords: Heating, Cooling, Buildings, Climate Change, Energy System Analysis

Abstract

This paper analyses the effects of future temperature changes on space heating and cooling demands in European buildings until 2050. The analysis is performed for two low-to-medium GHG emission climate scenarios and eight regional climate models and explicitly accounts for both absolute and relative climate changes. We employ population density as proxy for the spatial distribution of the demands to obtain the national space heating and cooling demands. Annual anomalies show an increasing warming with the RCP forcing (RCP2.6 and RCP4.5) and distance into the future (2026-2035/2046-2055). The relative warming increases towards the north-eastern parts of Europe as well as for higher altitude areas such as the Alps, the Pyrenees, the Iberian Peninsula and the Carpathian mountains. The occurrences per year > 22°C of 100 days or more are seen in Southern and Eastern Europe. The number of HDDs decreases throughout the European domain whereas the opposite is the case for CDDs. Almost all countries in northern and western Europe have a higher decrease in HDD for RCP4.5 (>10% decrease) than for RCP2.6 (5-10% decrease). As a basis for energy system analyses in the field of European heating and cooling strategies, this paper provides invaluable primary data input. Future work should focus on considering behavioural aspects of energy demand, the future development of the European building stock and the additional scenarios of population distribution.

1. Introduction

The building sector is regarded as a main contributor to the global energy consumption, and therefore also greenhouse gas emissions [1]. It currently accounts for 40% of the primary energy consumption in the US and EU [2] and 30% and 36% of energy-related CO_2 emissions globally [3] and for EU [4], respectively. In the European context, residential buildings make up around 75% of the total European building floor area [5], in which around 60% of these energy demands and emissions are related to heating and cooling applications [6]. In western countries, heating, ventilation, and air conditioning systems (HVAC) [7] together make up 50-70% of the total residential energy use [8]. Whilst there are large differences between European member states, with large shares of district heating in the Nordic region, for example, around 90% of heat generation occurs in the object it supplies [9].

Approaches to decarbonise the building stock through energy efficiency and renewable energy have therefore been a main focus of research during the past decades [10], and hold significant potential for future GHG reductions [11–13]. Currently, energy efficiency research areas include among others: improved thermal insulation [14], implementations within materials such as phase change and energy storage [15] smart energy management and control [16,17] and market mechanisms such as managing consumption in relation to fluctuating prices [18]. Approaches to analyse the decarbonisation of the residential heating sector often take a national or international perspective due to the complex interaction effects, e.g. between electricity and heat sectors [19].

The heating and cooling demands in buildings depend on the indoor temperature, the outdoor temperature and the thermal characteristics of the building fabric. Other factors could also be addressed, and these include e.g. snow cover [20], humidity, wind speed, cloud cover, etc. At the regional/national level often employed in large energy system models, the development of the heating and cooling demands depends on the construction and demolition rates, energy efficiency standards of newly built and renovated buildings and behavioural factors [21]. When analysing heat saving measures, the thermal characteristics of a buildings' envelope is the variable which can be varied the most, while the indoor temperature is typically varied in the narrow range of 18-22^{o}C as recommended by e.g. WHO [22,23]. Wider recommended indoor temperature is however seen in the range of 19-28^{o}C as e.g. in the ASHRAE housing recommendations [24]. The Danish building regulations [25] assume an indoor temperature of 20°C when calculating heating demand. To fulfil the regulations, the buildings need to be designed not to go over 27 and 28°C for more than 100 and 25 hours per year, respectively.

In the past 100 years, the mean global temperature for land and oceans combined has increased by approximately 1 C^{o}. For the future, an increase of further 1-4 C^{o} (relative to 1986-2005) by 2100, depending on the scenario, is projected by global climate models (GCMs) [26]. The regional variations in the projected warming are vast and are mainly dependent on distance to larger bodies of water. For Europe, which is the focus area of this study in the context of the REEEM project (see acknowledgements for details), the same overall patterns are seen as based on regional climate models (RCMs), which have a higher grid resolution and general higher accuracy [27–29]. In conjunction with the general warming, studies show confidence that extreme temperature occurrences, i.e. droughts, heatwaves and related magnitudes, duration, spatial extent and frequencies, will increase [26,30,31]. This clearly has implications for heat supply systems, which are already and will need to be dimensioned to meet the peak heating or cooling load during the year. Similar to the mean global temperature, and also related to heating and cooling demands, the minimum and maximum temperatures are also projected to increase, although at varying rates. In [32], the cold extremes are shown to increase faster than the warm extremes although some areas are projected to become drier, such as the Mediterranean, are likely to experience the highest increase for the warm extremes.

Heating and cooling demands are usually projected using correlations with economic and population forecasts. However, these approaches implicitly assume that the climate (for example outdoor temperature) remains the same; the climate will certainly change in the future. The present paper therefore proposes to calculate future heating and cooling demands in a simple manner while including the effects of climate change, i.e. the change of outdoor temperature. In literature, these calculations can have various forms such as in [33] where cooling- and heating degree-days are used to detect historical trends in cooling and heating demands. As argued in that study [33], the choice of cooling and/or heating algorithm vastly affects the resulting patterns and thus the future changes in cooling/heating demands. Another example is seen in [34] where not just temperature but also the relative humidity is used to predict the use of HVAC systems in Central America. The Danish experience is that every 1 degree Celsius increase reduces the heating demand by about 7% [35] and another study showed that out of four influencing factors on the heating demand in Stockholm, the choice of forcing climate model introduced the largest uncertainty (30%) followed by emission scenario (11%), RCM selection (10%) and initial conditions (5%) [36]. At the same time, the building attributes have been shown to have a large effect on the impact of climate changes on residential energy demands [7].

In order to properly asses the optimal combination of heat savings and heat supply in the building stock, knowledge about the future climate is needed, mostly the near-surface (outdoor) air temperature. Despite this, many studies analyse heat demand and savings based on static assumptions about the future climate, typically by employing the climate data for one year [25]. Not only the average annual temperatures, but also the diurnal, seasonal and annual cycles, as well as the year-to-year variability are important considerations for future heating and cooling demands. Hence the present paper aims to analyse the effects of changes of outdoor temperatures on European heating and cooling demands from a national energy system point of view. The methodology is applicable to any national energy system worldwide, while the results could be relevant for any country with the need for either heating or cooling. The novelty lies in: I) Calculation of heating degree days (HDD) and cooling degree days (CDD) for the full ensemble of shared state-of-the-art RCMs from the low-to-medium GHG emission scenario climate projections (RCP2.6 and RCP4.5 - eight models) over Europe in 12.5 km resolution. II) Translation of HDDs and CDDs into heating and cooling demand changes. III) Population-based weighting of these demand changes. IV) Derivation of changes in national heating and cooling demands. V) Identification of future "hot spots" and "cold spots" in Europe, i.e. locations with large heating and cooling demands and their relative changes. The entire work is based on openly available data and the results are provided as supplementary material.

The paper is structured as follows. Section 2 explains the methodology, section 3 presents the results, section 4 discusses them and puts them into context, and section 5 concludes.

2. Methodology

The methodology outline is as follows: The temperature data used in the present analysis is described in Section 2.1, while the calculation of HDDs and CDDs is described in Section 2.2. Hereafter, in section 2.3, the HDD and CDDs are combined with population density weights to reflect the geographical location of demands. Finally, in section 2.4 the results are aggregated into country level scales as this is often used in energy systems modelling. This methodology is outlined in Figure 1.

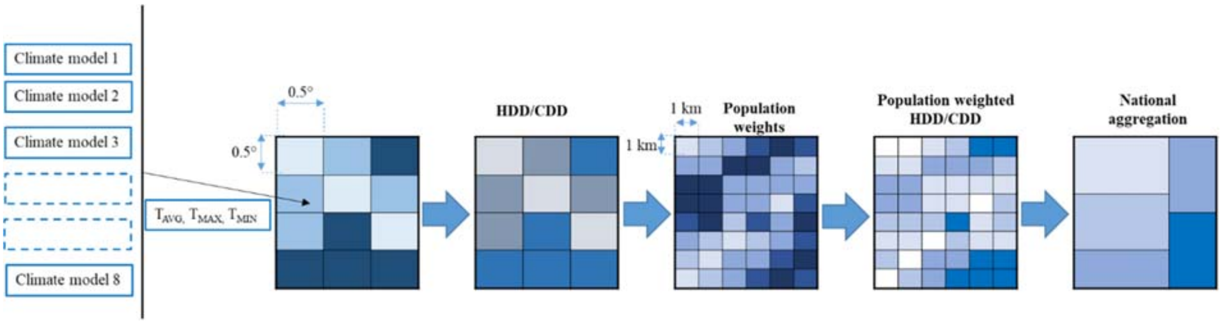

Figure 1. Overview of methodology applied in the present paper.

2.1 Temperature data

The study utilizes the low- to medium climate change scenarios RCP2.6 and RCP4.5 [26] up until the year 2050 and the study area covers Europe. To accommodate this, the climate change signal and the implications for future heating and cooling demands investigated here therefore employs the CORDEX database [37] which is the most recent effort of collecting (RCM) output from a wide range of contributing organisations and with continuous model additions. For future projections in CORDEX, the RCMs are forced along the model domain boundaries by global climate models (GCMs). For this study, we employed every available RCM/GCM combination shared by the RCP2.6 and RCP4.5 scenarios available at the 12.5 km^2 resolution, which is the finest CORDEX grid size. At the time of the study the ensemble comprised eight model combinations as listed in Table 1.

Table 1: The RCM and GCM models used in the study and the corresponding organisations.

No.	RCM model	Driving GCM model	Short name combined	Organisation
1	CCLM4	EC-EARTH	CCLM4_EC	Community Land Model (CLM) community
2	HIRHAM5	EC-EARTH	HIRHAM5_EC	Danish Meteorological Institute (DMI)
3	RACMO22	EC-EARTH	RACMO22_EC	Koninklijk Nederlands Meteorologisch Instituut (KNMI)
4	RACMO22	HADGEM2	RACMO22_HAD	Koninklijk Nederlands Meteorologisch Instituut (KNMI)
5	REMO2009	MPI-ESM-LR	REMO2009_MPI	Max Planck Institute (MPI)
6	RCA4	EC-EARTH	RCA4_EC	Swedish Meteorological and Hydrological Institute (SMHI)
7	RCA4	HADGEM2	RCA4_HAD	Swedish Meteorological and Hydrological Institute (SMHI)
8	RCA4	MPI-ESM-LR	RCA4_MPI	Swedish Meteorological and Hydrological Institute (SMHI)

As an initial analysis, prior to the specific heating and cooling demand calculations, the variables of near surface air temperature, daily maximum near-surface air temperature and daily minimum near-surface air temperature were analyzed to assess and understand inherent spatio-temporal patterns. In the climate modelling community, these variables appear as ‘tas’, ‘tasmax’ and ‘tasmin’ respectively, whereas we here use the terms Tmean, Tmax and Tmin. The analysis was done by extracting running 10-year means from 1996 to 2050 in 5-year steps. The ten-year periods are used due to the ‘near-future’ focus towards 2050 (longer term studies often employ thirty-year periods, e.g. [38]), which is a typical timeframe for energy system models while still regarded sufficient to represent a progression of patterns in climate time scales and account for variability. In this paper, results from 2010 and 2050 are mainly addressed. However, the period up until 2005 is considered historical in CORDEX, whereas 2006 and onwards is represented by RCP scenarios. Checks were therefore performed to assess the consistency between these two temporal subdivisions.

In order to analyse the climate change impact on temperature, long-term means are employed. For the ten-year periods the Tmean variable was calculated for each RCM/GCM model combination. Hereafter, the (historical) ensemble mean level (Figure 2a) as well as the future anomaly levels (difference from historical period) for each period and scenario (Figure 2b - 2e) was calculated as often seen climate model projection studies [39,40].

For the Tmax (figure A.1) and Tmin (Figure A.2) variables the same procedure was used as for Tmean with regards to the periods and future scenarios. Instead of absolute differences in temperature however, the number of days above or below certain thresholds was used for the historical period whereas for the two future periods the relative change in the corresponding number of days was calculated. The thresholds of 22 °C and 15.5 °C were used for Tmax (days above) and Tmin (days below) respectively as these are the thresholds used for the calculation of cooling and heating demands as outlined below [34].

To analyse the spatial inter-model variability, the standard deviation between models was calculated for all three variables of Tmean, Tmax and Tmin and for both RCP scenarios (RCP2.6 and RCP4.5) (inserts on Figures 2, A.1 and A.2). This was to serve as a measure of robustness highlighting potential differences between different regions within the European domain. For Tmean, the standard deviations were calculated based on projected inter-model Tmean values from the entire model ensemble. For Tmax and Tmin, the standard deviations were calculated between models based on the numbers of days per year above or below the thresholds described above.

2.2 Heating and cooling degree days

Following the analysis on RCM output (see above), the RCM data were then employed to calculate changes in the future HDD and CDDs over Europe from 2010 up until 2050 for the RCP2.6 and RCP4.5 scenarios. The starting point in the present analysis is that the future changes in heating and cooling demands are proportional to the future heating and cooling degree days (HDD and CDD, respectively). The future HDD and CDD are calculated for all grid cells (12.5 km resolution), stemming from the CORDEX RCM model outputs, covering EU.

The heating and cooling degree days were calculated per cell using equations 1-2 and 3-4 respectively as obtained from [33]. Heating degree days are calculated during the cold period (Oct 1 to March 31 – 183 days in non-leap years) and cooling degree days in the warm period (Apr 1 to Sep 30 – 182 days). All variables (Tmean, Tmax and Tmin) are included in the calculation of degree days depending on the criterion temperature (Equation 1 and 3 below).

The HDD and CDD (in K.d) is calculated for every cell *i* based on the methodology presented in [33]:

$$HDD_{i,t} = \begin{cases} T_{b,h} - T_{M,i,t} \\ \frac{T_{b,h} - T_{N,i,t}}{2} - \frac{T_{X,i,t} - T_{b,h}}{4} \\ \frac{T_{b,h} - T_{Ni,t}}{4} \\ 0 \end{cases} \text{if} \begin{cases} T_{b,h} \geq T_{X,i,t} \\ T_{M,i,t} \leq T_{b,h} < T_{X,i,t} \\ T_{N,i,t} \leq T_{b,h} < T_{M,i,t} \\ T_{b,h} \leq T_{N,i,t} \end{cases} \tag{1}$$

$$HDD_{i,y} = \sum_{t=1,t\in y}^{183} HDD_{i,t} \tag{2}$$

$$CDD_{i,t} = \begin{cases} 0 \\ \frac{T_{X,i,t} - T_{b,c}}{4} \\ \frac{T_{X,i,t} - T_{b,c}}{2} - \frac{T_{b,c} - T_{N,i,t}}{4} \\ T_{M,i,t} - T_{b,c} \end{cases} \text{if} \begin{cases} T_{b,c} \geq T_{X,i,t} \\ T_{M,i,t} \leq T_{b,c} < T_{X,i,t} \\ T_{N,i,t} \leq T_{b,c} < T_{M,i,t} \\ T_{b,c} \leq T_{N,i,t} \end{cases} \tag{3}$$

$$CDD_{i,y} = \sum_{t=1,t\in y}^{182} CDD_{i,t} \tag{4}$$

The symbols used in equations (1)-(4) have the following meaning:

With $T_{b,h} = 15.5°C$ – Base temperature for calculation of HDD

With $T_{b,c} = 22°C$ – Base temperature for calculation of CDD

$T_{Mi,t}$- Mean temperature in cell i in day t

$T_{X,i,t}$- Maximum temperature in cell i in day t

$T_{N,i,t}$- Minimum temperature in cell i in day t

$HDD_{i,t}$, $CDD_{i,t}$ – HDD and CDD in cell *i* and day *t*

$CDD_{i,y}$, $CDD_{i,y}$ - HDD and CDD in cell *i* and year *y*

The assumption behind the calculation of HDDs and CDDs [33] is that the heating season lasts for 183 days (1st of October to the 31st of March), while the cooling season lasts for 182 days (1st of April to the 30th of September). To account for variability between years and seasons in the RCM temperature output, 10-year averages are used with regards to all three temperature variables, Tmean, Tmin and Tmax (i.e. 2050 is the 2046-2055 average).

2.3 Applying weights to heating and cooling degree days[1]

After calculating HDDs and CDDs for every cell in EU in 5-year steps between 2010 and 2050, weights were applied to account for population density as a measure of demand rates as also seen in e.g. [9]. This is because aggregated building heating demands depend on the number/density of buildings as well as the heating or cooling degree days. The weighted demands are entitled HDDw and CDDw. For example, the heating demand decreases with increasing temperatures in both northern Norway and in southern Germany. However, due to differences in population density, southern Germany poses a substantially stronger influence on the demand as compared to northern Norway.

The weight of the cells are calculated as follows:

$$w_i = \frac{\sum_{j \epsilon i} P_{i,j}}{P_k} \tag{5}$$

Where:

w_i – weight of RCM grid cell (*i)*

$P_{i,j}$ – Population of 1x1 km cell which belongs to cell *j* and 12.5x12.5 km cell *i*

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[1] All the resulting data are available online as supplementary material.

P_k – Population of country *k*

i - 12.5x12.5 km cell

j – 1x1 km cell

k – EU countries

The population data within 1x1 km cells are obtained from GEOSTAT 2011 grid dataset (version updated in 2016) [41].

2.4 Country level scale

The weights of every 12.5x12.5 km cell *i* within a country *k* in EU are not very useful for high-level energy systems analysis at the national/international level. Regions in the multinational energy system models (for example, European) are usually countries, while the regions in national energy system models are subnational areas (for example, NUTS2 regions). Therefore, the HDDs and CDDs are aggregated to the national level *k*:

$$HDD_k = \sum_{i \epsilon k} HDD_i \cdot w_i \tag{6}$$

$$CDD_k = \sum_{i \epsilon k} CDD_i \cdot w_i \tag{7}$$

The ratios of space heating/cooling demands in different years should correspond to the ratios between HDDs/CDDs in the same years. The domestic hot water is assumed not to be directly affected by the increase of the change of the outdoor temperature.

3. Results

3.1 Mean temperature

The results from the analysis of the mean European near-surface temperatures from the CORDEX RCM ensemble (see Table 1) are shown in Figure 2. The annual historical means (Figure 2a) are included here for reference purposes, and show the expected north-south gradient and the influence of topography. The annual anomalies (Figure 2b-2e) unexpectedly show an increasing warming with the RCP forcing (RCP2.6/RCP4.5) and distance into the future (2026-2035/2046-2055). Further, these plots also show an increased relative warming compared to the reference period towards increased the north-eastern parts of Europe as well as for higher altitude areas such as the Alps, the Pyrenees, the Iberian Peninsula and the Carpathian mountains. As a measure for model robustness, the inter-model temperature standard deviations for each period and RCP have been plotted (Figure 2b – 2e, inserts) showing a general trend towards a higher robustness for the RCP4.5 model ensemble as opposed to the RCP2.6 ensemble. This could be explained by the relatively weak trend in the RCP2.6 scenario as often completely omitted from RCM climate change studies [42,43]. Further, higher inter-model deviation is seen for mountainous regions.

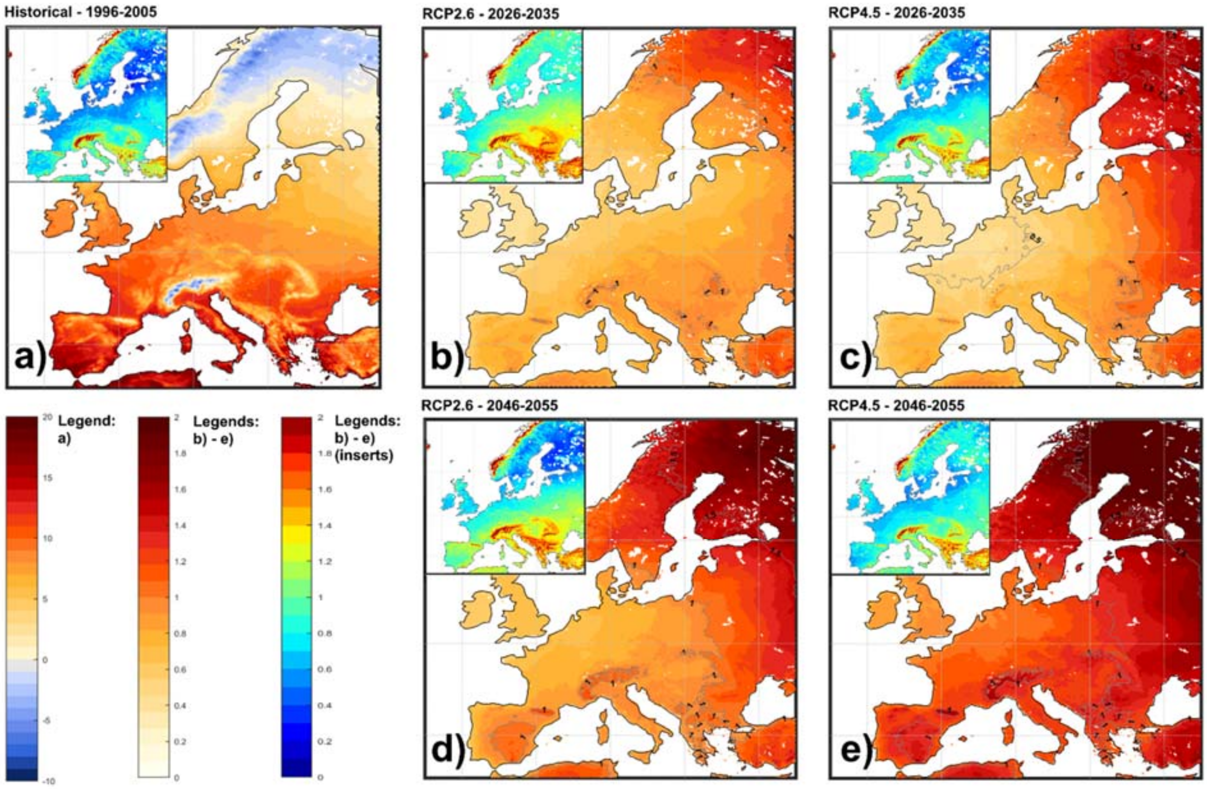

Figure 2. Plot a): 1996-2005 mean temperature (Tmean) from the eight-model CORDEX ensemble. Plots b)-e): Corresponding anomaly values (relative to historical period) for RCP2.6 (left) and RCP4.5 (right) for 2026-2035 (top) and 2046-2055 (bottom) including contour lines for the levels of 0.5, 1 and 1.5 °C. Plots b)-e) (inserts): The corresponding inter-model Tmean standard deviation for each scenario and period.

The results from the Tmax analysis is shown in figure A.1 employing the 22°C threshold as used in the HDD/CDD analysis presented below. For the historical period (Figure A.1a), obvious trends occur varying with the north-south location as well as altitude. In general, occurrences of 100 days or more > 22°C per year are seen in Southern and Eastern Europe whereas the higher areas in e.g. the Alps, the Pyrenees, the

Dinaric Alps have few or no similar occurrences (Figure A.1e-b). Also the distance to larger water bodies is seen to affect the occurrences such as in and around Hungary. In general, for the RCP2.6 and RCP4.5 scenarios, the location of the 50 and 100-day contours move towards the north. For example, the 50-day contour line moves from the areas around Berlin and Paris historically towards the coastal regions of the Benelux countries and the Baltic Sea for the RCP4.5 2046-2055 scenario (Figure A.1e). The largest changes in Tmax occur across mountain ranges in Southern Europe, Ireland and all across Norway and to some degree Sweden and Finland. As for Tmean, the smallest cross-domain inter-model standard deviation for Tmax is seen for the historical period followed by RCP4.5 and then RCP2.6 (Figure A1.b–e, inserts). Further, the largest inter-model spread is seen across central and southern Europe, mostly related to high-topography areas, although the Alps is a notable exception. The large inter-model spread over the Dinaric Alps has also been shown in [43].

The Tmin analysis results are shown in figure A.2. These results employ the 15.5°C threshold as used in the HDD/CDD analysis. As for Tmax, both the historical and the projected RCP results are mainly dependent on the latitude and topography. Thus, for the historical period, a higher number of days above the Tmin < 15.5°C threshold is seen in northern Europe and in mountainous regions (Figure A.2a). In broad terms, the threshold of 350 days/year with Tmin < 15.5°C is crossing central Europe whereas for mountain ranges, areas are seen as far south as southern Spain, southern Italy, Greece and Turkey. The largest relative changes days/year with Tmin >15.5°C, increasing with RCP scenario and interest period into the future, occur for southern Europe with changes up to 10% (Figure A.2b–e). This is natural as the northern regions with a large share of days within the threshold (350-365 days/year), would not experience large relative changes. Concurrently for the projected future, and again correlated with RCP scenario and interest period, the 350 days/year threshold moves northwards reaching the coastal regions of the North Sea and the Baltic sea. With regards to the Tmin inter-model spread, the highest levels are seen further south in the coastal Mediterranean regions as compared to Tmax and with minimal differences between RCP2.6 and RCP4.5 (Figure A.2b–e, inserts).

3.2 Heating and cooling degree days

This section presents the calculation of HDDs and CDDs at the 12.5km grid scale. Section 3.3 presents the results after weighting at a 1 km scale and section 3.4 presents the weighted results aggregated to a country level scale.

Resulting HDDs and CDDs for 2010 and 2050 for both RCP2.6 and RCP4.5 are presented in Figure A.3. On a general level, and unsurprisingly considering the warming trend represented by the RCP scenarios, the number of HDDs decreases throughout the European domain. For example, the Baltic countries and southern Finland move below 3000 HDDs in 2050, the high-topography areas of central Europe and Eastern Poland move below 2500 HDDs and a larger share of western France move below 1000 HDDs. Little differences in HDDs are seen between the RCP2.6 and RCP4.5 scenarios.

In an analogous manner, CDDs for 2010 and 2050 for both RCP2 are presented in Figure A.4 and correspondingly, the number off CDDs increase throughout the domain. In Northern continental Europe and the UK, the border depicting grid cells that do, or do not, show CDDs move towards the north encompassing southwest UK, North-western Denmark and larger shares of Norway, Sweden and Finland.

In central Europe, a larger share moves into the 10-50 CDDs range, in France, a larger share moves into the 50-300 CDDs range and for southern Europe, Spain especially, the area with more than 300 CDDs increases and even more so for RCP4.5. Between RCP2.6 and RCP4.5, a higher general CDD level is seen for 2010 for the latter whereas higher general CDD levels are seen for 2050 for the former. The corresponding relative changes in HDDs and CDDs for scenarios RCP2.6 and RCP4.5 are seen in Figure 3. For RCP2.6, the vast majority of Europe experiences decreases in HDD in the order of 5-10% whereas RCP4.5 shows decreases in the north-western part of Europe of 10-15%. For CDD, the most substantial changes until 2050 are also seen for north-western Europe where levels of 30-1000% are seen for RCP2.6 whereas the corresponding increase for RCP4.5 is both higher (50-1000%) and more widespread covering larger parts of the Mediterranean area.

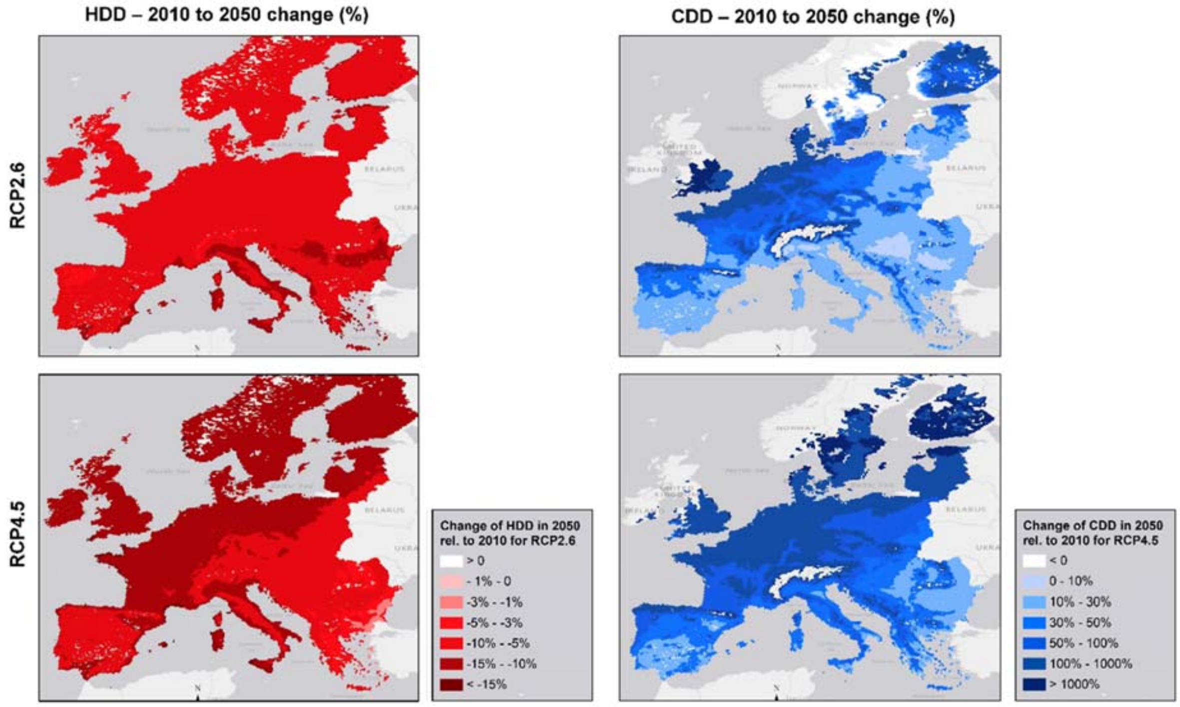

Figure 3. Relative differences in heating and cooling degree days (HDD and CDD) between 2010 and 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

3.3 Weighted heating and cooling degree days

In this section we present the results where heating and cooling demands, as presented in section 3.2, have been weighted (i.e. HDDw and CDDw). As stated, the weighting has been performed to account not only for the geophysical forcing but also the size and geographical location of the population which is here used as the indicator of heating and cooling demands over Europe. I.e., regions with higher demands should have higher weights than the regions with smaller demands. This is regarded as a central step prior to calculating country-level heating and cooling demands and is justified by the fact that the densities of heat demand and population are closely correlated [9].

Figure A.5 shows the HDDw levels in 2010 and 2050 for both RCP scenarios after weighting with population. From the figure, it is generally evident that areas or cells with a high population stand out with high HDDw levels. This is especially true for cells which at the same time shows high (unweighted) HDD levels. Examples include parts of Switzerland, the Balkans and around Czechia and Slovakia, but generally more densely populated areas. Examples where densely populated areas show weighted levels comparable to less densely populated areas, due to minor differences in (unweighted) HDD levels, include the Lisbon area and many smaller urban areas in Sweden and Finland.

The CDDw levels are presented in Figure A.6. From the Figure, it is clear that several urban areas will experience increased cooling demands by 2050, regardless of RCP scenario, including greater Paris, Lyon, Bordeaux, Brussels, Riga and Krakow.

3.4 Country-level weighted heating and cooling degree days

A key purpose of this paper is to highlight the impact of climate change on heating and cooling demands, both on a finest possible distributed grid but also on country-level scales to potentially serve as an input to larger scale energy system models (see appendix Table A.1). However, multinational energy system models usually cannot use demand days or population-weighted demand days as their inputs. Instead, we here present relative changes in demand days relative to a base year enabling the use of demand days by a multiplication on the present day or base-level value. Figure 4 presents the country-level relative changes in HDDw and CDDw for scenarios RCP2.6 and RCP4.5 between the years 2010 to 2050. From the figure it is evident that almost all countries in northern and western Europe have a higher decrease in HDD for RCP4.5 (>10% decrease) than for RCP2.6 (5-10% decrease). Also, Greece and Bulgaria experience only a <3% decrease in RCP4.5 compared 7-10% decrease levels for RCP2.6 (Figure 4). For CDD the opposite pattern is seen where the largest increase in cooling demand is seen for RCP4.5 especially for the Northern parts of Europe including UK, Germany and the Baltic countries (>100%).

Figures 5 and 6 present the changes of HDDw and CDDw levels respectively for both RCP scenarios in 2030 and 2050 relative to 2010. The bars show the relative changes in HDDw and CDDw levels for each RCP scenario averaged across all eight RCMs, while the inter-model coefficient of variation (normalized standard deviation) is represented with black lines.

In general, all countries are projected to experience a moderate decrease of HDDw between 2% and 12% across scenarios and years, as can be seen in Figure 5 and the variation between the two RCPs correspond to roughly 2-5%. Notable exceptions are however Cyprus and Malta, with 20-25% changes, which is due to very small heating demands in the reference years also. There is a slight tendency for the largest decrease in HDDw from 2010-2030 compared to 2030-2050. The difference between the country level HDDw for the two climate scenarios, RCP2.6 (Figure 5, top) and RCP4.5 (Figure 5, bottom), is in the general range of ~0 to 2.5 percentage points with the highest decrease for RCP4.5.

The projected country-level weighted cooling demands (Figure 6) exhibit different characteristics than the weighted heating demand (Figure 5). The countries plotted without values have low cooling demands (CDDw < 2) in the base year and the results show that their cooling demands in 2050 are also insignificant. The main share of countries affected by cooling demands in both 2010 and projection year (2030/2050), experience increased relative cooling demands in the range of 10-100%. For RCP2.6, the largest increase in CDDw is seen already in 2030 whereas the RCP4.5 scenario infers significant rises from 2030 to 2050. The differences between climate scenarios are much more distinct than in the case of heating demands – mostly in the range of a 10-50 percentage point difference.

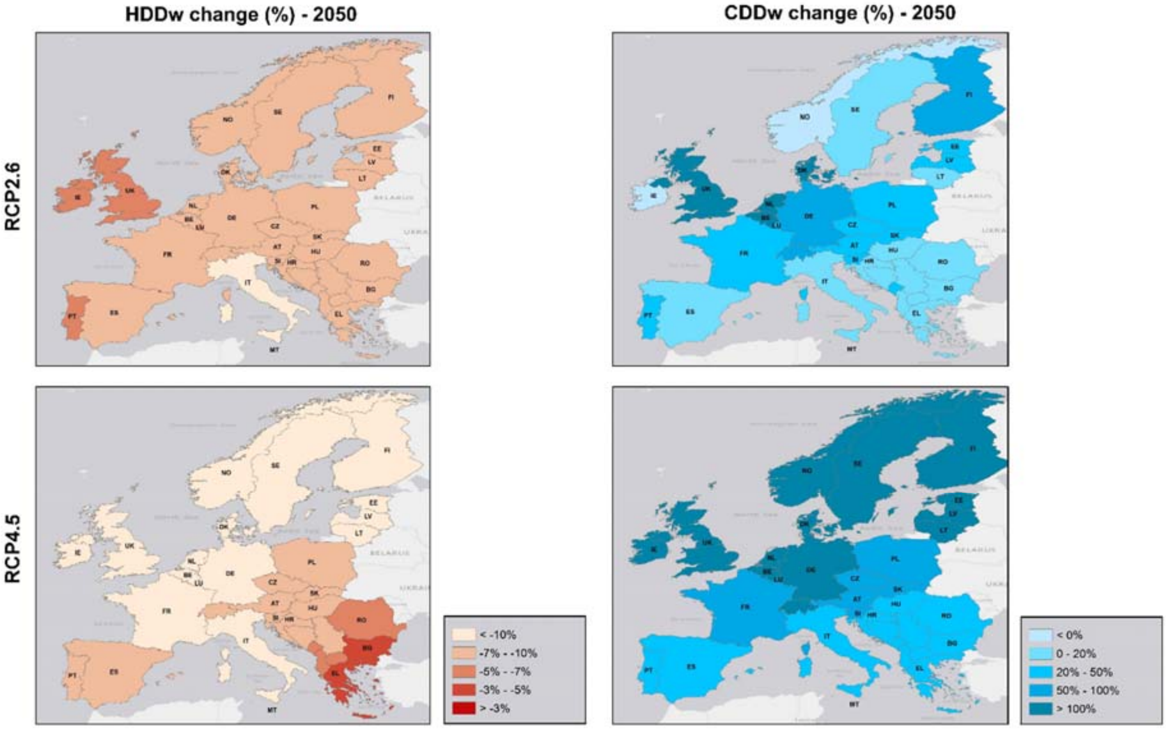

Figure 4. Country level relative changes in weighted heating and cooling degree days (HDDw and CDDw) from 2010 to 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

Figure 6 and Appendix Table A.1 present the ratio between CDDs in 2050 and 2010. However, the ratios were not calculated for the countries that had less than two CDDws in 2010 for two reasons: Firstly, due to the relative nature of the results, the ratios would be very high and thus difficult to present. Secondly, even with a strong increase, the future CDDs and thus the cooling demands would be too low to be economically supplied (too few full load hours).

For both HDDw and CDDw, there is, as expected, a tendency for the largest inter-model variability (represented by errorbars in Figures 5 and 6) to occur for countries within regions with larger uncertainties (see Figures 2, A.1 and A.2) or smaller countries.

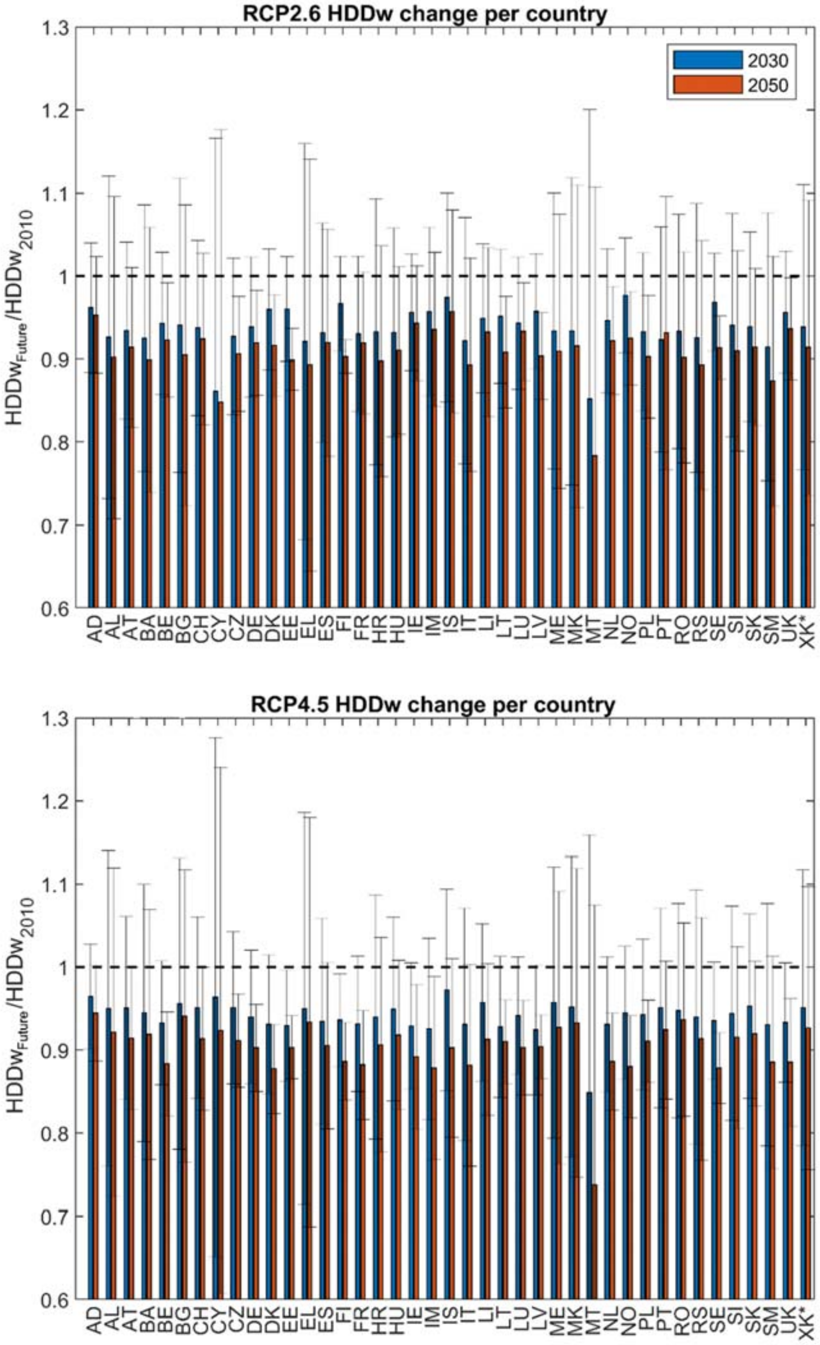

Figure 5. Changes in weighted heating demands per European country (HDDw) for RCP2.6 (top) and RCP4.5 (bottom) in 2030 and 2050 relative to 2010. The bars represent country means and the bars represent the coefficient of variation (standard deviation normalized by the mean) between the regional climate models (RCMs) within each respective country.

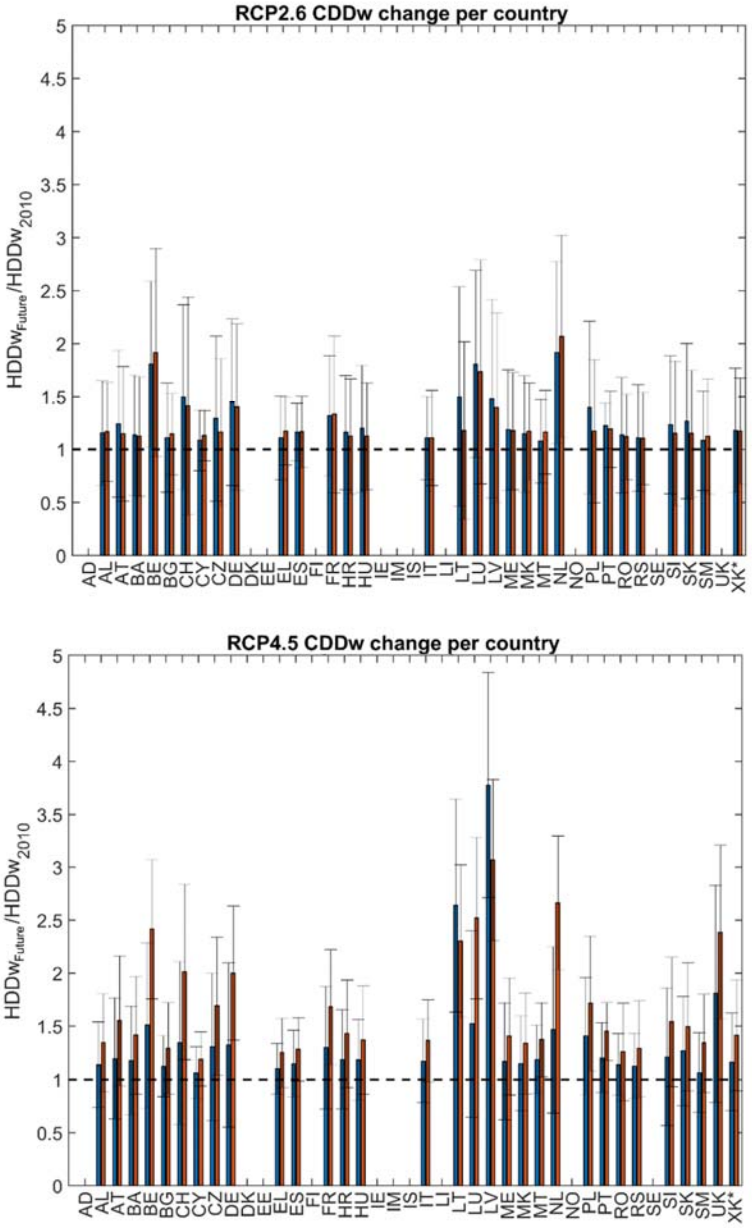

Figure 6. Changes in weighted cooling demands per European country (CDDw) for RCP2.6 (top) and RCP4.5 (bottom) in 2030 and 2050 relative to 2010. The bars represent country means and the bars represent the coefficient of variation (standard deviation normalized by the mean) between the regional climate models (RCMs) within each respective country. Countries with 2010 levels below two were omitted to avoid plotting high-end levels and due to lack of proper relevance in demand studies.

4. Discussion

The present paper analyses the change of HDDs and CDDs as a consequence of the change in outdoor temperatures for eight climate models under two climate scenarios (RCP2.6 and RCP4.5). The relative changes of HDDs and CDDs can be directly used to scale (up or down) the existing space heating and cooling demands to thereby obtain future levels; it is assumed not to affect the domestic hot water demand. Such a scaling implies the assumption that the inhabitants of buildings maintain the same behaviour over the analysed period i.e. neglecting the rebound effect [44], internal set temperature, heating and ventilation habits etc. [45]. For example, an increase in outdoor temperatures could translate into reduced heating demand, but it could also translate into increased indoor temperature as a result of the rebound effect or other non-technical effects. Up - or down-scaling of existing space heating and cooling demands could be applied to residential, commercial, public objects, etc. but applying the same procedure to industrial facilities should be done with caution since space heating accounts for very small share of heating demand in industrial facilities.

Changes in the outdoor temperature affects the profitability of heat saving measures. Namely, an increase of outdoor temperature in winter can be seen as "free" heat savings and thus make additional heat savings more expensive; the opposite applies for a reduction in outdoor temperature in winter (the converse is the case in summer). Another effect of increasing outdoor temperatures is an increase in the coefficient of performance (COP) of air-to-air heat pumps, i.e. they become more efficient. On the other hand, the economics of both heat supply (e.g. boilers) and demand side (e.g. insulation) measures is adversely affected by reduced winter heating demands, either in terms of length or magnitude, or both. For all of these effects, energy systems analysis should be applied at regional, national and international levels in order to explore these phenomena in the context of rapidly-changing national energy systems. This linkage is a part of ongoing research as implemented in e.g. the TIMES-DK energy model [46].

When calculating the change of HDDs and CDDs on a national level, the present approach takes into account that not all the regions have the same heating/cooling demands. For example, densely populated areas in West Germany have higher weights compared to sparsely populated areas in the eastern parts of Germany. On the other hand, the presented approach implicitly assumes that the distribution of heating demand within a country remains as in 2010 throughout the analysed period. It is well known that sub-national differences in the building stock and economic activity, including migration, are significant influencing factors for the distribution and future development of the residential space heating demand [47].

Even though a national-level redistribution of heating demand could happen in the future, and this redistribution itself is likely to at least partly be motivated by climate change, the authors consider them outside of the scope of the paper. Even more, such a change is likely to only affect countries of greater length in the latitudinal direction (i.e. north to south), such as Sweden and Italy, or for countries with both inland/coastal climates, e.g. France.

Although outdoor temperature is an important, externally given factor, the actual heating and cooling demands depend on the buildings' thermal characteristics, user behaviour and potential smart technologies affecting the energy consumption. Research has shown that user behaviour and smart technologies have a comparable importance [48]. Behavioural aspects alone can account for up to 100% variation in household energy demand within the same technically-defined system [45]. Hence results presented here only go some way towards estimating future building heating demands. The translation of these changes in Degree Days to changes in heating demands will therefore crucially depend on the development in user's behaviour and the degree to which they can be more sensitized to accept flexible energy demand, renewable and energy efficient technologies in the future [49–51].

The other factor not addressed here, that of buildings' thermal characteristics, will be fundamentally determined by the future development in the national building stock. Whilst most European Member States have ambitious targets in the context of (their national implementation of) the Energy Performance in Buildings Directive, such as all new buildings being passive standard from 2020, there is a large degree of uncertainty about long term improvements in the energy efficiency of buildings [52]. A large challenge in this area is the refurbishment of existing buildings, many of which are protected for reasons of cultural and/or social interest [53]. Hence the results presented here should be interpreted as indicative, as they essentially 'freeze' both of these two dimensions in order to focus on the climate. The results do illustrate, however, the consequence of assuming constant climate on assessments of future energy saving calculations. Under ceteris paribus conditions, future changes in heating and cooling demands need to be accounted for.

The range in outcomes from the RCM ensemble, as represented here by the inter-model coefficient of variation, justifies the use of multiple climate models and climate scenarios in the context of highlighting uncertainty levels to decision-makers. From Figures 5 and 6, it is evident that smaller geographical regions, such as Cyprus and Malta, induce a higher uncertainty. Also, for Latvia and Lithuania, a single RCM with CDD levels being much higher than the remaining models, and a slightly higher 2030 level compared to 2050, causes an apparent drop from 2030 to 2050 (Figure 6).

For the future RCP scenarios 6.0 and 8.5 [26] (not address here), the former would likely impose HDD and CDD results at levels comparable to RCP4.5, as decided by the resulting projected temperatures by 2050, whereas RCP8.5 would inflict highly reduced levels of HDD and vice versa for CDD. The net energy effect, as balanced by decreased HDD and increased CDD, has been shown to vary with the geographical location of the study area in question [54]. Similar trends of decreasing heating demands and increasing cooling demands have been found by [55] where, also, an increased risk of overheating in more extreme higher-range temperatures was detected under projected future climate change scenarios.

5. Conclusions

Against a background of uncertainty about future climate and the most cost-efficient approach to decarbonize the heating sector, the present paper analyses the effects of future temperature changes on space heating and cooling demands in European buildings. The analysis is performed for two low-to-medium GHG emission climate scenarios and eight regional climate models. By utilising minimum, maximum and mean daily temperatures in five-year steps between 2010 and 2050 to calculate HDDs and CDDs, we explicitly account for both absolute and relative climate changes. We subsequently utilised HDDs and CDDs to scale up/down the projected space heating and cooling demands in buildings and employed population density as proxy for the spatial distribution of the demands to obtain the national space heating and cooling demands.

When analysing the mean temperatures, it can be concluded that the annual anomalies show an increasing warming with the RCP forcing (RCP2.6 and RCP4.5) and distance into the future (2026-2035/2046-2055). The relative warming increases towards the north-eastern parts of Europe as well as for higher altitude areas such as the Alps, the Pyrenees, the Iberian Peninsula and the Carpathian mountains. The occurrences per year > 22°C of 100 days or more are seen in Southern and Eastern Europe. On a general level, following the warming trends represented by the RCP scenarios, the number of HDDs decreases throughout the European domain whereas the opposite is the case for CDDs. From the results, it is also evident that the temperature change in areas with high demands is the main driver for the change of national heating and cooling demands. Almost all countries in northern and western Europe have a higher decrease in HDD for RCP4.5 (>10% decrease) than for RCP2.6 (5-10% decrease). All countries in Europe are projected to experience a moderate reduction of heating demands between 5% and 10%, with the exception of Cyprus and Malta. The largest increase in cooling demands is seen for RCP4.5 especially for the Northern parts of Europe including UK, Germany and the Baltic countries (>100%). The main share of countries affected by cooling demands in both the base year and projection year experience increased relative cooling demands in the range of 25-75%. The relative implications of these results for the economic efficiency and relative attractiveness of efficient heat generation and saving options are clear, but a detailed energy system analysis is required in order to quantify and understand their relative importance.

The employed method derives robust estimates of future European heating and cooling demands, both at a high resolution of 12.5 km^2 and at the national level. However, the method overlooks population change and intra- and international migration as potential future drivers of changing energy demands. Especially in countries with a relative large north-south extent (e.g. Sweden and Italy) and those with coastal and inland climates, the future changes in heating and cooling demand due to subnational migration could be significant. In addition, the method overlooks two other important aspects, namely future building thermal characteristics and user behaviour, both of which will be crucial in understanding the way in which, and where, European heating and cooling energy service demands develop in the future. Despite overlooking these two factors, the results illustrate the implication of assuming a constant climate on the assessments of future energy saving calculations. Further work should therefore explore these two factors in the context of regional, national and international energy system analysis, in order to assess the impact and implications of the change in future heating and cooling demands on, for example, the total costs of the energy system, electricity and heating prices, and environmental emissions.

Acknowledgements

The work was supported by the REEEM project (grant agreement no. 691739) funded by the Horizon 2020 (LCE) EU research programme.

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Appendix

Table A.1. Country abbreviations and relative changes for HDDw/CDDw, RCP2.6/RCP4.5 and 2010-2030/2010-2050 respectively.

		RCP2.6				**RCP4.5**			
		HDDw		**CDDw**		**HDDw**		**CDDw**	
Country	**Abbreviation**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Andorra	AD	0.962	0.953	16.246	5.903	0.965	0.945	20.703	8.045
Albania	AL	0.926	0.902	1.156	1.168	0.950	0.922	1.140	1.345
Austria	AT	0.934	0.914	1.243	1.149	0.951	0.914	1.198	1.553
Bosnia and Herzegovina	BA	0.925	0.899	1.137	1.123	0.945	0.919	1.180	1.415
Belgium	BE	0.943	0.923	1.806	1.915	0.933	0.883	1.511	2.414
Bulgaria	BG	0.941	0.905	1.112	1.147	0.956	0.941	1.125	1.293
Switzerland	CH	0.937	0.924	1.497	1.411	0.951	0.914	1.343	2.013
Cyprus	CY	0.861	0.848	1.086	1.129	0.964	0.924	1.063	1.192
Czechia	CZ	0.927	0.906	1.294	1.164	0.951	0.911	1.305	1.690
Germany	DE	0.938	0.919	1.447	1.401	0.940	0.902	1.324	1.999
Denmark	DK	0.960	0.916	2.342	2.387	0.931	0.877	1.337	2.469
Estonia	EE	0.960	0.899	1.481	1.507	0.929	0.903	6.365	4.183
Greece	EL	0.921	0.893	1.110	1.173	0.950	0.934	1.101	1.250
Spain	ES	0.932	0.920	1.162	1.166	0.935	0.905	1.148	1.284
Finland	FI	0.967	0.903	1.092	1.667	0.936	0.886	7.663	6.154
France	FR	0.930	0.919	1.319	1.332	0.932	0.882	1.300	1.681
Croatia	HR	0.933	0.897	1.161	1.128	0.940	0.906	1.190	1.429
Hungary	HU	0.932	0.910	1.199	1.126	0.949	0.918	1.185	1.370
Ireland	IE	0.956	0.943	4.227	16.526	0.929	0.892	1.127	3.114
Isle of Man	IM	0.957	0.936			0.925	0.878		
Iceland	IS	0.974	0.957			0.973	0.903		
Italy	IT	0.922	0.893	1.109	1.110	0.931	0.882	1.175	1.362
Lichtenstein	LI	0.949	0.932	6.851	5.952	0.957	0.913	1.112	5.138
Lithuania	LT	0.951	0.908	1.499	1.177	0.928	0.910	2.639	2.302

Luxembourg	LU	0.943	0.933	1.806	1.734	0.941	0.903	1.523	2.519
Latvia	LV	0.958	0.903	1.479	1.397	0.924	0.904	3.776	3.067
Montenegro	ME	0.934	0.909	1.185	1.175	0.957	0.927	1.172	1.404
North Macedonia	MK	0.934	0.916	1.149	1.169	0.952	0.933	1.151	1.340
Malta	MT	0.852	0.783	1.079	1.165	0.849	0.738	1.188	1.372
Netherlands	NL	0.946	0.922	1.917	2.068	0.931	0.886	1.466	2.662
Norway	NO	0.977	0.925	1.674	1.337	0.945	0.880	1.009	4.236
Poland	PL	0.933	0.903	1.397	1.174	0.943	0.911	1.408	1.715
Portugal	PT	0.923	0.931	1.223	1.191	0.951	0.924	1.205	1.452
Romania	RO	0.933	0.902	1.136	1.119	0.948	0.937	1.141	1.259
Serbia	RS	0.925	0.892	1.108	1.105	0.940	0.914	1.126	1.288
Sweden	SE	0.968	0.913	1.434	1.270	0.935	0.878	1.663	2.757
Slovenia	SI	0.941	0.910	1.233	1.152	0.944	0.915	1.215	1.541
Slovakia	SK	0.939	0.914	1.268	1.152	0.953	0.920	1.266	1.495
San Marino	SM	0.915	0.873	1.084	1.125	0.931	0.885	1.064	1.341
United Kingdom	UK	0.956	0.936	3.159	3.313	0.933	0.885	1.809	2.386
Kosovo	XK	0.938	0.914	1.181	1.174	0.951	0.927	1.164	1.415

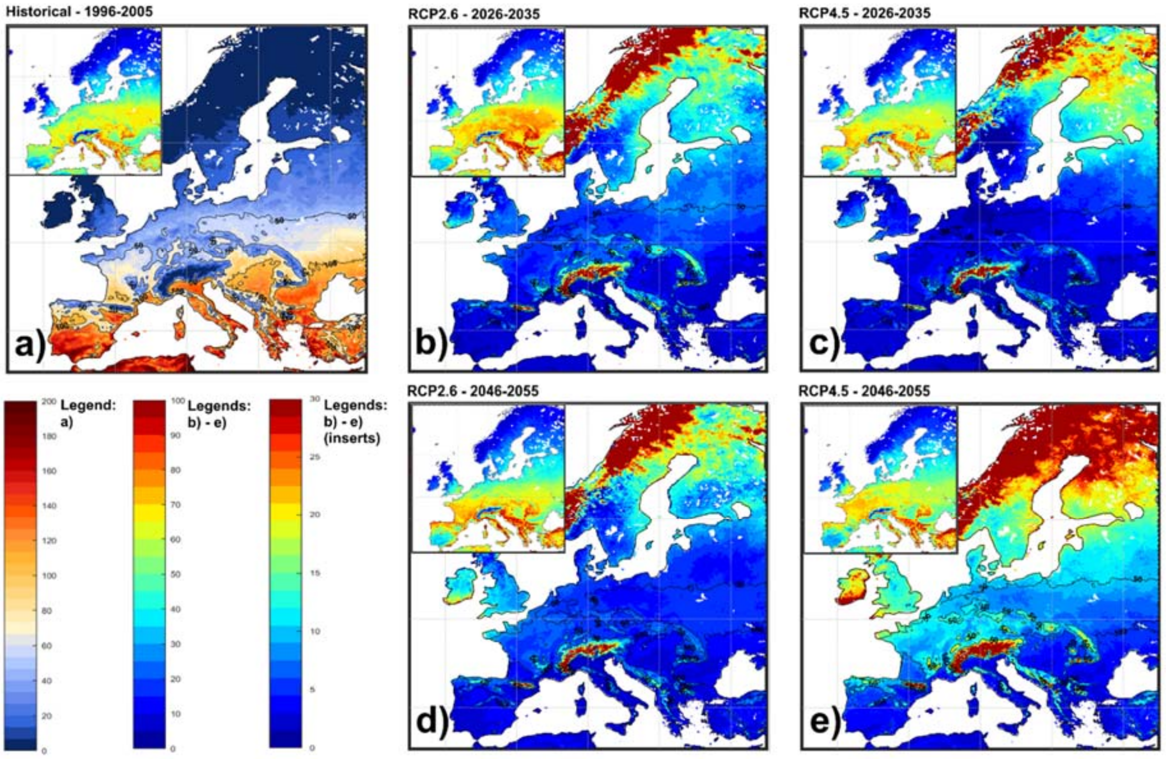


Figure A.1. Plot a): 1996-2005 number of days with a daily Tmax above 22 °C from the eight-model CORDEX ensemble. Plots b)-e): Corresponding changes (% - relative to historical period) for RCP2.6 (left) and RCP4.5 (right) for 2026-2035 (top) and 2046-2055 (bottom) including contour lines (50 and 100 levels - days/year where Tmax > 22 °C). Plots b)-e) (inserts): The corresponding inter-model standard deviation of days/year where Tmax > 22°C for each scenario and period.

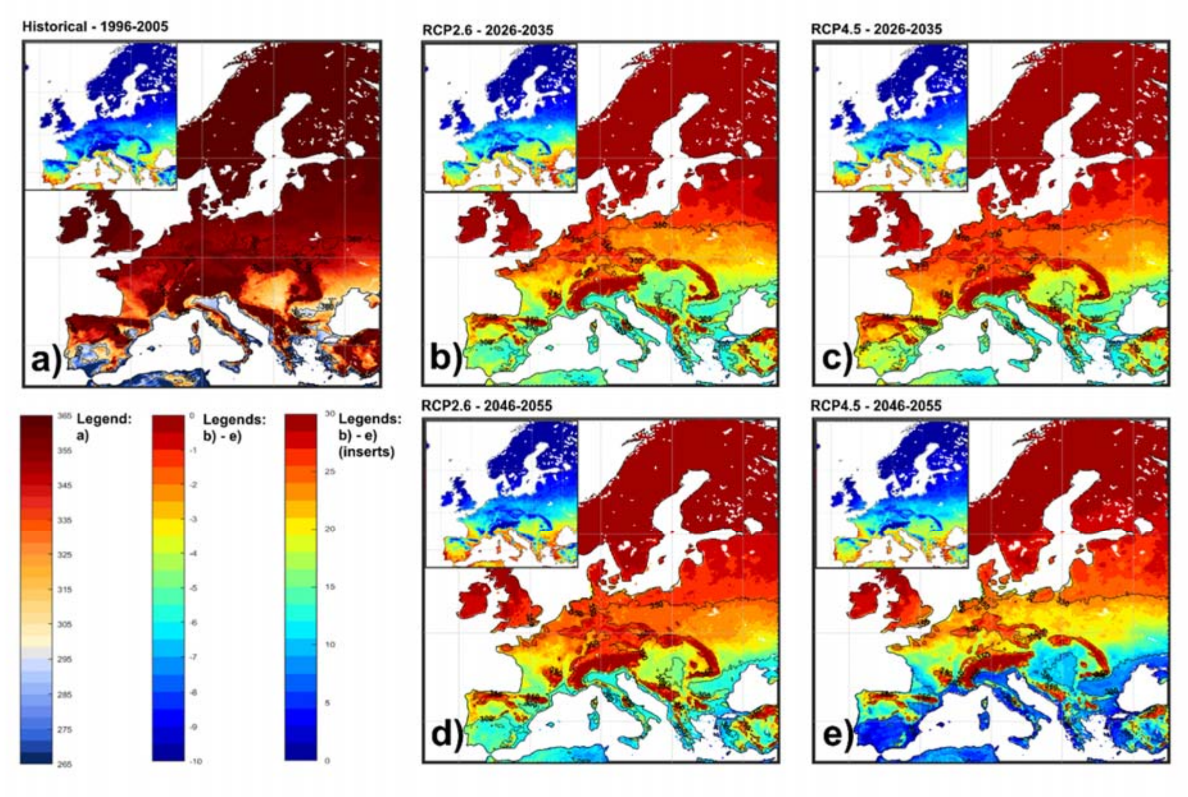


Figure A.2. Plot a): 1996-2005 number of days with a daily Tmin below 15.5 °C from the eight-model CORDEX ensemble. Plots b)-e): Corresponding changes (% - relative to historical period) for RCP2.6 (left) and RCP4.5 (right) for 2026-2035 (top) and 2046-2055 (bottom) including contour lines (300 and 350 levels - days/year where Tmin < 15.5 °C). Plots b)-e) (inserts): The corresponding inter-model standard deviation of days/year where Tmin < 15.5°C for each scenario and period.

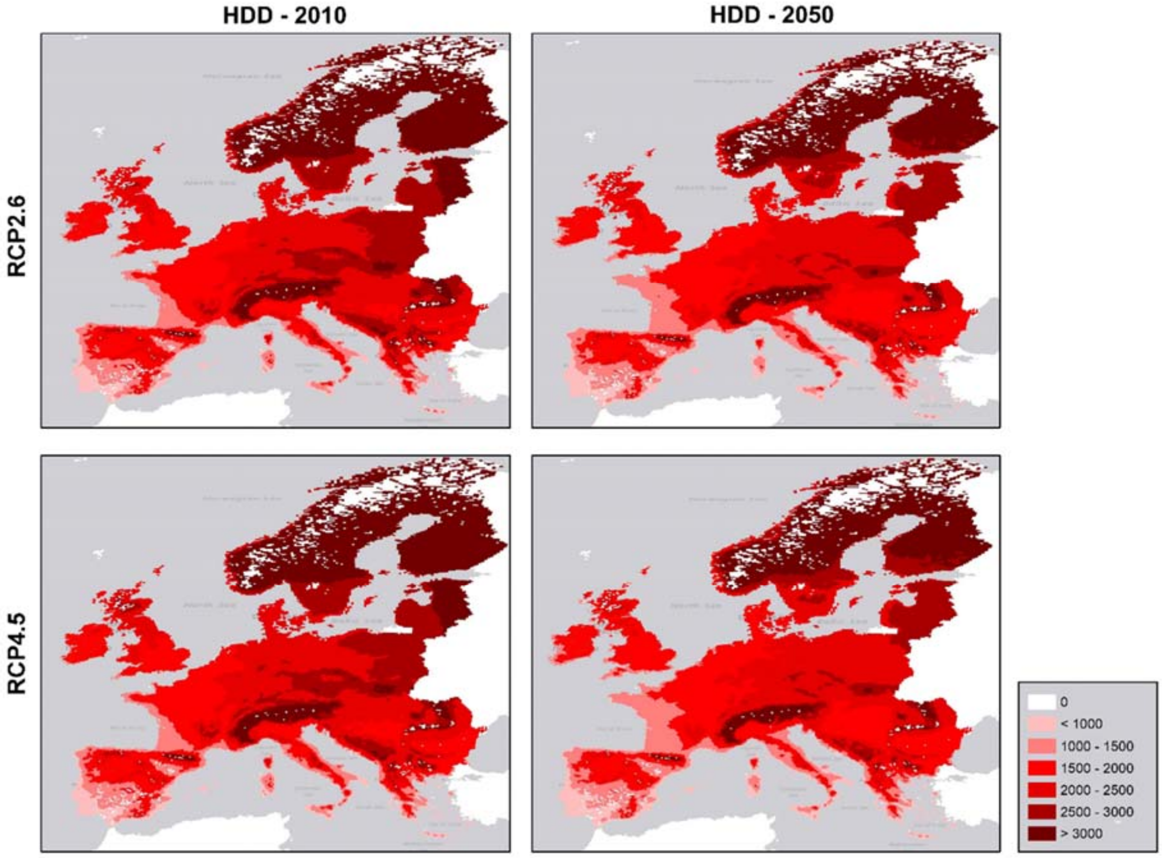


Figure A.3. Heating degree days (HDD) in 2010 and 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

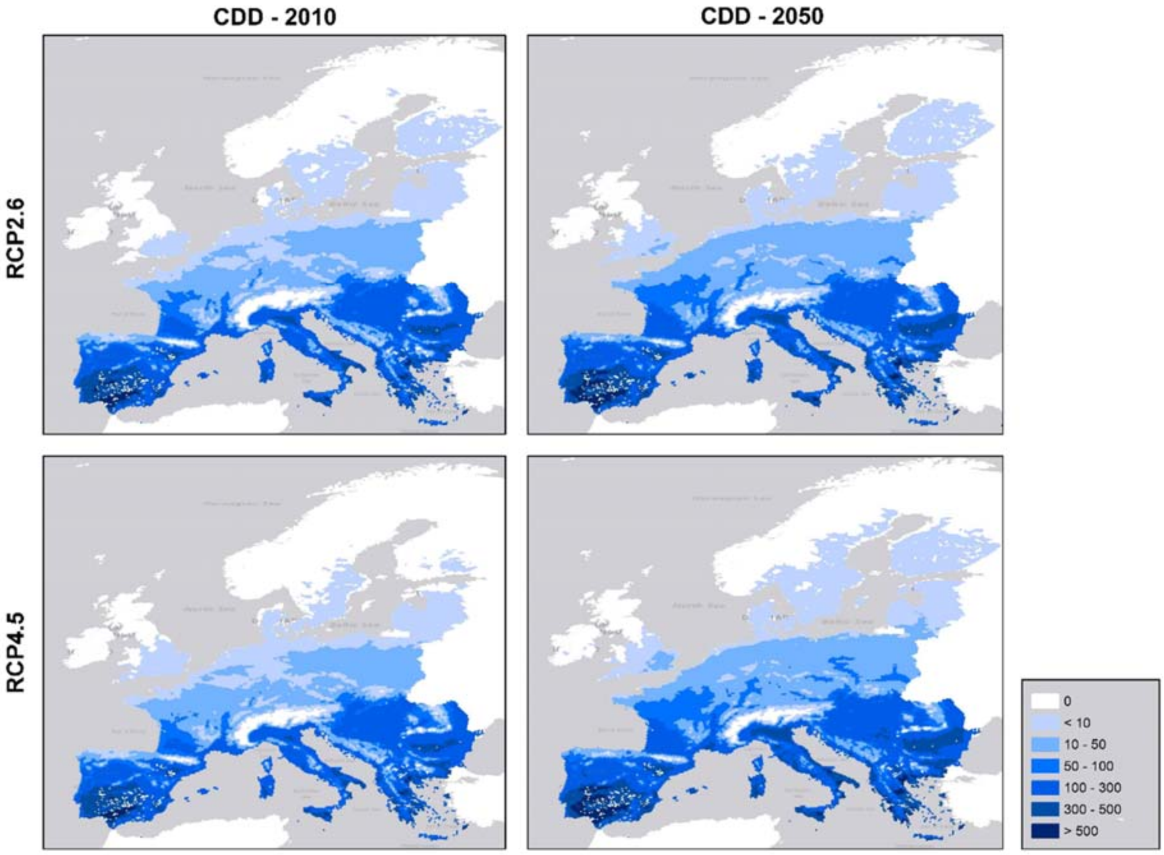


Figure A.4. Cooling degree days (CDD) in 2010 and 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

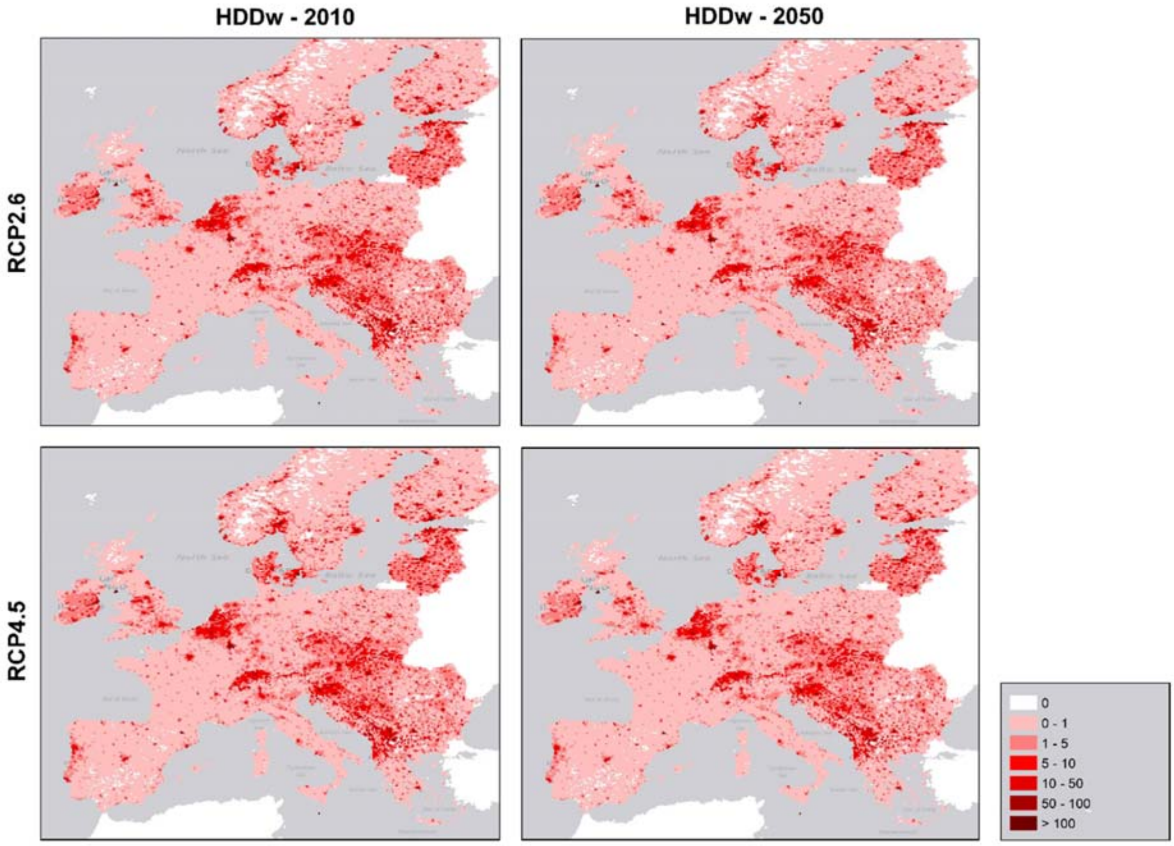


Figure A.5. Weighted heating degree days (HDDw) in 2010 and 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

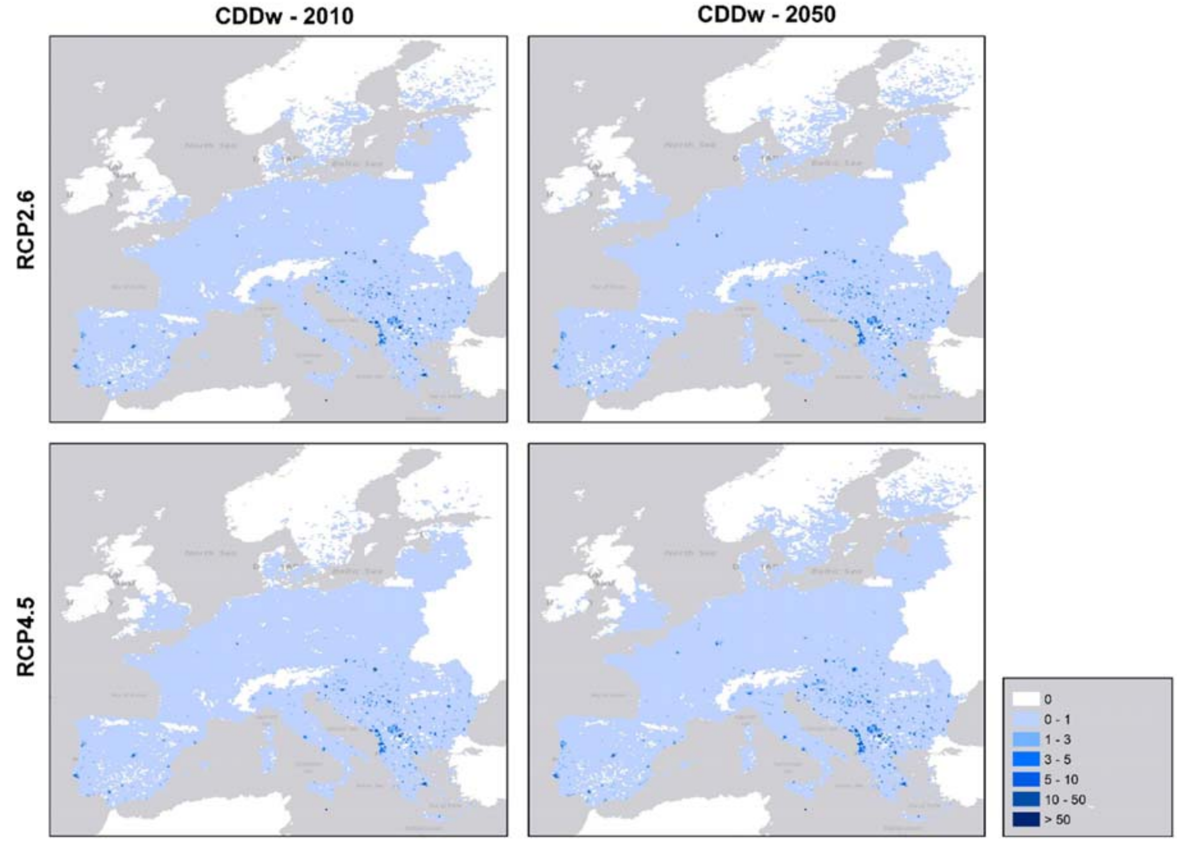
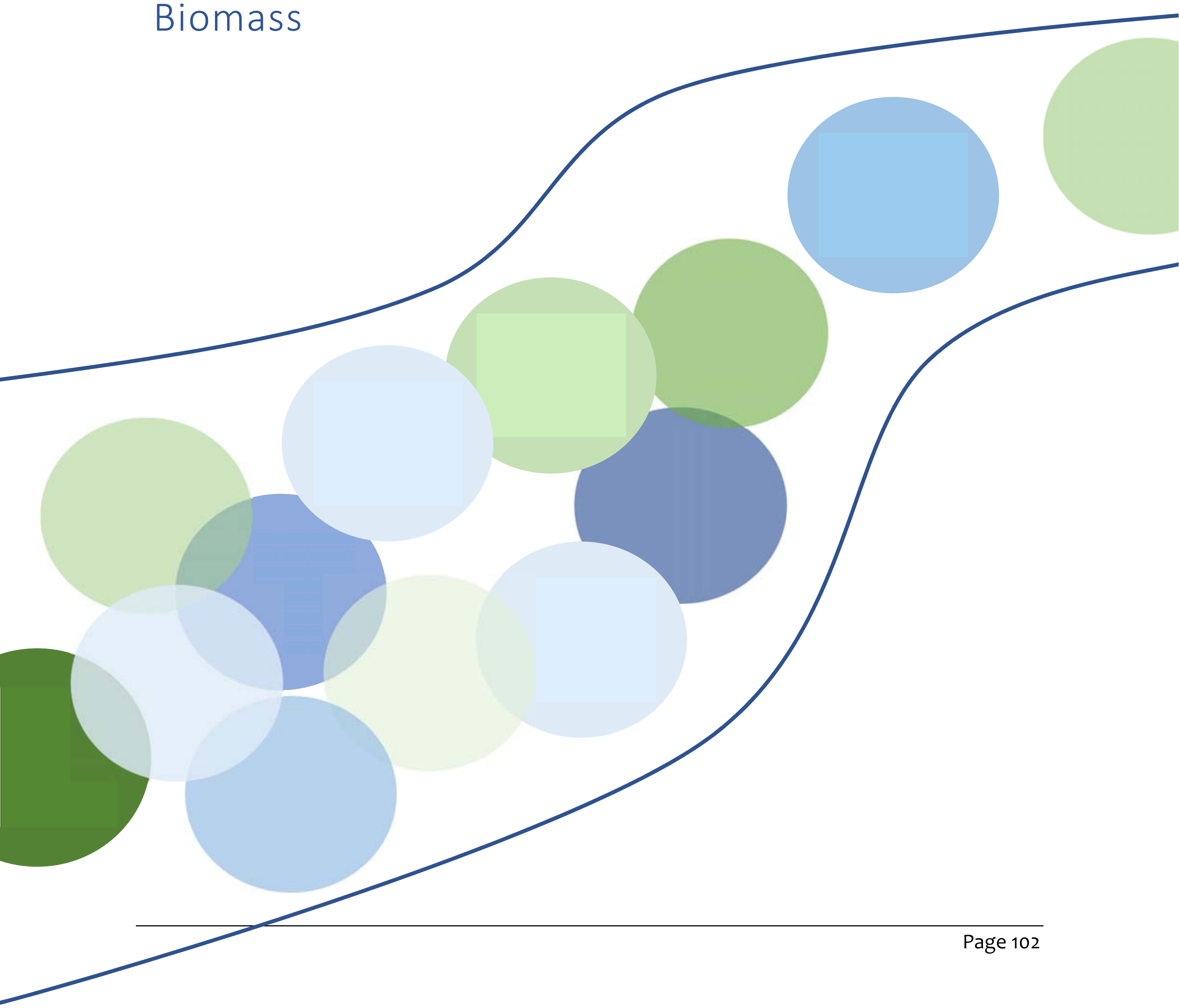


Figure A.6. Weighted cooling degree days (CDDw) in 2010 and 2050 for the RCP2.6 and RCP4.5 climate scenarios respectively.

PART III

Water Usage and Land-Use-Change Emissions from Biomass



Projected water usage and land-use-change emissions from biomass production (2015-2050)

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Submitted to Energy Strategy Reviews.

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Keywords: Energy system modelling, biomass production, water footprint, land use change emissions

Highlights

- Increased biomass production is needed to reduce CO_2 emissions by 80% in 2050
- Development of more advanced biofuels is a prerequisite for this transformation
- Oil crops are water and carbon intensive but may play a big role in the transition
- Estimates of emissions from land use change and water usage have high uncertainties
- Climate change is likely to affect biomass potential through water availability

Abstract

Increased biomass for energy production features as a key part of the transition to a competitive low-carbon EU energy society. Not all energy strategies however will lead to reduced emissions, and extensive biomass production inherently compete with, e.g., agricultural systems for key natural resources like water and land. This paper investigates the ramifications of three potential energy pathways for Europe developed by the H2020 REEEM project, ambitiously aimed at reducing CO_2 emissions to 80-95% compared to 1990, using different mixes of biomass. Their environmental footprint for 2015-2050 in terms of land-use-change emissions and water consumption are confronted with near-term climate change

projections. Finally, potential implications for the implementation and robustness of future European energy strategies are discussed, highlighting in particular the role of uncertainties in estimating the performance of biomass systems.

1. Introduction

Increasing the use of renewable energy is a key strategy of the European Union (EU) in order to reduce greenhouse gas emissions in accordance with the Paris Agreement and to keep the global mean temperature rise below 2ºC. A substantial share of the renewable energy needed for this transition is expected to come from biomass. Accordingly, increased utilization of bioethanol and biodiesel - derived from biomass conversion – promises to be a strong feature of future EU scenario pathways.

Recent estimates of the current EU biomass production (agriculture and forestry sectors, Camia et al. 2018) find that on average 1466 Mt of dry matter is produced annually; of this about 956 Mt originates from agriculture and 510 Mt from forestry. A very small additional contribution comes from other sources such as fisheries and aquaculture. Of the woody biomass production, roughly two-thirds comprises stem wood, the remaining one-third consists of branches, stumps and tops. In terms of agriculture, 54% of the biomass comprises dedicated economic production, e.g., grains and fruits, whereas the remaining 46% is by-products and residues such as leaves and stems with a potential for, e.g., bioenergy production, animal bedding or as means to maintain ecosystem services such as organic carbon levels in soil. Camia et al. (2018) finds that the evolution of agricultural biomass production in European has grown slightly from 1998 to 2015. This is explained mainly by an increase in the yields of main cereals such as maize, improvements in agro-management, and a general expansion of areas cultivated with oil crops (Camia et al. 2018).

First-generation biofuels are still the most important contributors to the European energy mix and generally refer to fuels that have been derived from food crops like starch crops (e.g. wheat, maize, barley), sugar crops (e.g. sugar cane, sugar beets), and from animal fats and vegetable oils (e.g. rapeseed, soybeans, palm oil). They inherently compete with food production for natural resources such as land and water and require high fertiliser inputs. Moreover, while substituting biofuels for, e.g., gasoline will in most cases lead to a reduction in greenhouse gas (GHG) emissions, first-generation biofuels may in some cases result, e.g., in negative energy savings and in increased GHG emissions instead (Bentsen and Felby, 2012, de Witt and Faaij 2010, Karp and Halford 2011). For example, Searchinger et al. (2008a) found that most studies failed to count the carbon emissions that occur as farmers worldwide respond to higher prices and convert forest and grassland to new cropland to replace the grain (or cropland) diverted to biofuels. Conversely, second generation and more advanced feedstocks have a comparably lower environmental footprint (e.g. Clark et al. 2013). These include lignocellulosic biomass or woody crops (e.g. miscanthus and switchgrass).

The objective of this study is to investigate and quantify the potential implications of increased biomass production in the context of different energy strategies towards a competitive low-carbon EU energy society. Thus, several studies (e.g. Robledo-Abad et al. 2017) have demonstrated negative implications associated with extensive use of biomass for energy purposes through impacts on, e.g., food, water and land systems. For this aim, we consider three future scenario pathways aimed at reducing the CO_2-

equivalent emissions in Europe by at least 80% by 2050 compared to 1990. These pathways were developed as part of the H2020 REEEM project (REEEM 2019, Montenegro and Fahl 2017) and have been analysed using an updated version of the TIMES-PanEU linear optimization model (Kypreos et al. 2008).

TIMES-PanEU is an energy system model, which optimizes the energy system cost based on energy demands, energy technologies, and policy requirements. For all REEEM pathways, increased biomass production is found to play a critical role in the transition to a future European energy system based mainly on renewables. TIMES-PanEU distinguishes six types of biomass: three kinds of first-generation biofuels: oil crops, sugar crops and starch crops and three kinds of second-generation and other advanced biofuels: grassy crops, woody crops and “other biomass potential” (e.g. crop and wood residues). Like other integrated modelling approaches, biomass is implicitly assumed to be ‘carbon neutral’. Likewise, constraints on energy production imposed by water resources are not included in the model (e.g., Larsen and Drews, 2019).

In this paper, we further detail the energy strategies derived from energy system modelling. Specifically, we analyse the impacts of increased bioenergy in terms of: (a) GHG emissions from land use change (LUC) related to biomass production and (b) the demand for water resources considering both present and climate change conditions. Since grassy crops are not considered by any of the three pathways, they are not considered per se in our analysis.

The structure of the paper is as follows: Section 2 describes the TIMES-PanEU energy system model, the narratives behind the three scenario pathways, and methods used to estimate emissions from biomass-induced LUC and the water footprint. Finally, climate projections of future water availability are discussed in brief. Section 3 presents the results with respect to the projected biomass production, the associated GHG emissions and water usage and confronts the latter with, e.g., climate projections of water availability. Section 4 discusses the results and Section 5 concludes on our findings.

2. Methodology overview

This section provides an overview of the different elements in the analysis of future European biomass production within the scenario pathways developed in the REEEM project (REEEM 2019).

2.1 Energy system modelling

TIMES (The Integrated MARKAL-EFOM System) is a model generator developed as part of the IEA-Energy Technology System Analyses Program (IEA-ETSAP) (Loulou et al. 2005, Wright et al. 2016, Gargiulo et al. 2016). TIMES is a bottom-up, technology explicit, dynamic partial equilibrium model of energy markets that combines two complementary, systematic approaches to energy systems modelling, i.e., a technical engineering approach and an economic approach. Optimized solutions are pursued through the use of linear programming. A TIMES model aims to minimise the total discounted system costs, taking into account all the costs allocated to the energy system in a given time frame while meeting the demand services exogenously given as input.

In the present paper, we explore the potential role of biomass as part of the transition towards a low-carbon EU energy system using the Pan European TIMES model (TIMES-PanEU), which was built using the abovementioned TIMES model generator and is currently maintained by the University of Stuttgart. This model was originally developed in the NEEDS project (2004-2008) (Kypreos et al. 2008). Within the REEEM project, TIMES-PanEU has been further elaborated and comprises the core of an integrated assessment framework.

TIMES-PanEU includes GHG emissions and local air pollutants and covers the EU28 countries as well as Norway and Switzerland (30 regions). The model time step is 5 years starting from 2010 and ending in 2050. The model represents the EU Emission Trading Scheme (EU ETS) and uses country specific data covering all sectors (Industry, Commercial, Households, Agricultural and Transport) related to energy supply and demand. It commences from the potential of different energy sources in a particular country and includes public and industrial generation of electricity, industry, agriculture, refineries, inventory power stations and the end-use service demands such as heating, lighting and transportation.

2.2 Policy pathways

The ramifications of three different scenario pathways is explored. Biomass availability is assumed to be the same for all pathways, and overall emission reduction targets rather than specific biomass targets drive the use of biomass. Along the different pathways the utilisation of biomass is found to be consistently cost-competitive, and the balance between sectors to vary according to where policies or consumers' attitudes drive decarbonisation efforts the most. The full range of biomass and conversion options is considered in all sectors except Transport, including solids, bioethanol, biodiesel, biogas, and hydrogen production. In the Transport sector, biofuels derived from woody crops are not used whereas all other types are.

"Coalitions for a low-carbon path" (Base). This baseline scenario pathway represents a future where energy carrier suppliers take on the highest burden in an ambitious decarbonisation of the EU energy system, while consumers observe it mostly passively or respond to policies as they come. After optimization, *biomass is particularly utilized in the Industry sector*. The pathway resembles two of five scenarios proposed by the EU Commission (EU 2017). Emission targets for sectors included in the EU ETS are complied with and overshot in some instances, leading to 83% reduction in energy-related CO_2 emissions by 2050 compared to 1990. For non-EU ETS sectors, coalitions of more and less willing EU Member States emerge, setting more and less ambitious decarbonisation targets.

"Local solutions" (LS). This narrative suggests a future where consumers are increasingly concerned about climate change, and especially households therefore engage in the transition towards a low-carbon energy system, by choices on appliances, energy efficiency measures and transportation technologies. Along this pathway*, biomass is highly prioritized in the Transport sector to meet the sector-specific targets*. EU Member States are set on a course to 80% reduction in energy-related GHG emissions by 2050 as compared to 1990. Like in the former pathway, coalitions of more and less willing countries set different targets for sectors not covered by the EU ETS, depending on their geographic location, economy and domestic availability of resources.

"Paris Agreement" (PA). This scenario pathway describes a future where the EU undertakes an ambitious decarbonisation effort, with a target of 95% reduction of CO_2 emissions by 2050. This overshoots the Paris

Agreement pledges. Both energy carrier suppliers and consumers engage in the challenge. *The available amount of biomass in the different sectors is a critical point in the transition, and here priority is given to electricity generation due to the availability of biomass carbon capture and storage as a mitigation option*.

Further discussion of these pathways may be found in Gardumi et al. (in prep.).

2.3 Estimating emissions from biomass-induced land use change

The Intergovernmental Panel on Climate Change (IPCC) defines LUC as a “change in the use or management of land by humans, potentially leading to a change in land cover” (Smith et al. 2014).

Mitigation scenarios that aim to fulfil the requirements of the Paris Agreement generally assume significant LUC, i.e., to support large-scale CO_2 removal from the atmosphere by means of, for example, afforestation/reforestation, avoided deforestation, and increased biomass production with, e.g., carbon capture and storage (Harper et al. 2018). That said, while the deployment of bioenergy is likely to offer significant potential for climate change mitigation, it also carries considerable risks. In particular, in terms of the emissions associated with LUC (e.g., Berndes et al. 2011, Creutzig et al. 2015).

The net emissions from LUC are highly ambiguous due in parts to large uncertainties in the carbon density of areas undergoing change. And contrary to fossil fuel combustion, which always represent a carbon source, land can serve both as a carbon source or carbon sink. Changing forest into farmland in general releases carbon from the soil and vegetation and represents a carbon source. In contrast, growing perennial grass on carbon-depleted land may increase carbon sequestration in the soil and represents a carbon sink. As a result, proper accounting of the net carbon flux from biofuel-induced LUC is needed to determine whether the use of bioenergy in the energy system results in a net benefit with respect to GHG emissions.

TIMES-PanEU considers biomass to be carbon neutral and does not explicitly account for LUC emissions. To assess the implications of increased biomass production within TIMES-PanEU, we therefore assess emissions from LUC based on existing estimates of GHG emissions induced by different types of bioenergy technologies.

Estimates of global GHG emissions from biomass production-induced LUC as a function of energy units have been reported by many authors. Direct LUC (dLUC) involves changes in land use on areas already being used for biomass production, such as the change from food or fibre production, including changes in crop rotation patterns, conversion of pasture land, and changes in forest management. Similarly, indirect LUC (iLUC) refers to conversion of natural ecosystems to agricultural land, or expansion of agricultural areas. A wider definition of iLUC includes changes in crop rotation patterns and/or intensification on land used for food or feed production.

Warner et al. (2013) has critically reviewed different modelling approaches employed to estimate biomass-induced LUC, and collected global estimates of LUC emissions corresponding to different bioenergy technologies from different sources. These results were reprinted in IPCC AR5 (WGIII) (Smith et al. 2014, Creutzen et al. 2015).

Figure 1 (Table 1) summarizes the data collected by Warner et al. (2013), grouped into the five categories considered by TIMES PanEU: oil crops (e.g. rapeseed, soybeans and palm oil), sugar crops (e.g. sugar cane, sugar beets), starch crops (e.g. wheat, maize, barley), woody crops (e.g. poplar, eucalyptus and pine), and other biomass potential (e.g. crop residues, wood residues).

The large observed variation seen in Figure 1 may partly be ascribed to different bioenergy crops, geographical locations, climates, and management practices; in addition they may be explained by (Warner et al. 2013):

- Disparities in LUC modelling philosophy, structure, and features such as dynamic vs. static models.
- Differences in pathways under study and reference pathways, assumptions adopted, and definitions employed.
- Data availability and quality.

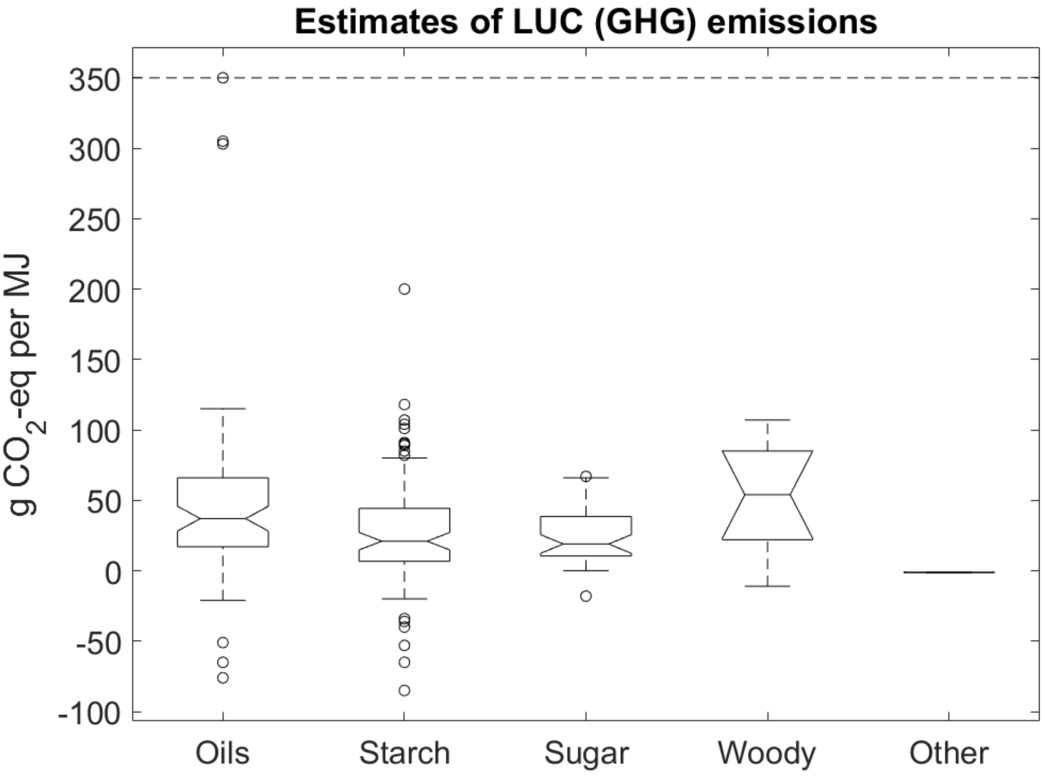

Figure 1. ***Estimates of GHG emissions from biofuel production-induced LUC****. Values are from Warner et al. 2013 and references herein (marked by an asterisk (*) in the References section). It is noted that "these estimates of global LUC are highly uncertain, unobservable, and unverifiable. They are also dependent on assumed policy, economic contexts, and inputs used in the modelling. All entries are not equally valid, nor do they attempt to measure the same metric despite the use of similar naming conventions, such as indirect LUC. In addition, many different approaches to estimating GHG LUC have been used. Therefore, each paper has its own interpretation and any comparisons are risky".*

Whether land used for biomass production is found to have a positive or negative effect on GHG emissions depends on the level of competition for typical agricultural crops, management practices, and the relative change in soil carbon.

Table 1 summarizes the main results from Figure 1, i.e., the median, the 25th and 75th percentile of values found for each of the five biomass types. The length of the whiskers are 1.5 times this interquartile range and indicate the upper, respectively, lower limits for outliers. These statistics will be used to connect LUC emissions with the projected bioenergy production from TIMES-PanEU and to assess the uncertainty (see Results).

Table 1: *Estimated GHG emissions from bio-fuel induced LUC. The median value, 25th and 75th percentiles are calculated from data collected by (Warner et al. 2013 and references herein).*

	Emissions from biomass-induced LUC (g CO_2 equiv. per MJ)			
	Median	25th pctl.	75th pctl.	No. data pts.
Oil crops	37	17	66	76
Starch crops	21	6.8	44.3	44
Sugar crops	19	10.5	38.5	89
Woody crops	54	22	85	10
Other biomass potential	-1.1	-1.4	-1.0	13

For comparison, values for oil and gas found referred in IPCC AR5 (WGIII) are set at 1836 – 4212 g CO_2 equiv. per MJ and 1044 – 3348 g CO_2 equiv. per MJ (Bruckner et al. 2014), respectively. It must be noted however that these results are based on a full life-cycle analysis.

2.4 The water footprint of biomass production

Estimates of the water footprint (WF) of the projected bioenergy production are obtained using an analogous approach to the one described above. As in the case of GHG emissions related to LUC, estimates of water usage related to different kinds of bioenergy sources, e.g., energy crops, residues, etc. have been reported by several authors. Here we combine data from Gerbens-Leenes et al. (2009), Mekonnen & Hoekstra (2011), and Mathioudakis et al. (2017) (see Table 2).

The WF is provided for up to three types of water. The “green” water footprint refers to water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants during growth. Green water generally comprises the majority of the water used during production. “Blue” water is water used for irrigation, that is, surface or groundwater. The water demand for irrigation ranks second-highest in terms of the need for water resources. Finally, “grey” water designates polluted water, including additional water usage in terms of diluting the polluted water prior to its release into natural water streams.

Table 2 shows the estimated amount of water needed (m^3) per unit of energy produced (GJ). Oil crops like rapeseed and woody crops are seen to have a much larger WF than, say, sugar crops. In the case of woody crops, the WF is exclusively associated with green water. The lowest water demand is associated with the use of residues from wood and crops, e.g., for third generation biofuels. In this instance, the majority of the water is associated with, e.g., traditional agriculture and therefore do not count towards the reported water usage per unit of energy. The large variability in between the estimates can be attributed to, e.g., data collection under different climate and environmental conditions, crop management practices and to different analysis methods.

*Table 2: Weighted global average WF for different types of biomass categorised into oil crops, starch crops, sugar crops, woody crops and other biomass potential (including residue). For each category, the average WF related to blue and total water usage (across different biomass sources) and the associated standard deviations (in parenthesis) are indicated. *in the calculation of the total WF sunflower straw is treated as an outlier and not included.*

	m³ per unit of energy (GJ)							
		Mekonnen & Hoekstra 2011			**Gerbens-Leenes et al. 2009**			
	WF_{tot}	Green	Blue	Grey	Green	Blue	Green	Blue
Barley	102.0	119	8	13	31	39	39	70
Cassava	126.3	106	0	3	127	21	107	18
Maize	87.3	94	8	19	30	20	67	43
Potatoes	93.3	62	11	21	58	47	56	46
Rice, paddy	141.0	113	34	18	54	31	121	70
Rye	130.3	140	2	10	42	36	92	79
Wheat	155.0	126	34	20	39	54	89	123
Sorghum	297.0	281	10	9	102	78	238	182
Starch crops	**Blue WF: 44.3 (23.2) – Total WF: 141.5 (62.8)**							
Sugar beet	48.7	31	10	10	19	27	24	35
Sugar cane	80.7	60	25	6	23	27	49	58
Sugar crops	**Blue WF: 30.3 (6.3) – Total WF: 64.7 (14.5)**							
Oil palm	150.0	150	0	6				
Rapeseed	319.3	145	20	29	154	229	165	245
Seed cotton	487.0	310	177	60				
Soy beans	337.0	326	11	6				
Sun flower	449.0	428	21	28				
Jatropha	485.0				165	231	239	335
Oil crops	**Blue WF: 109.4 (105.9) – Total WF: 371.2 (119.2)**							
	Mathioudakis et al. 2017							
	WF_{tot}	Green	Blue	Grey	Green	Blue		
Sugar cane bagasse	17.2	12.2	5	1.1				
Corn stover	23.8	21.9	1.9	4.5				
Paddy rice straw	19.3	14.9	4.4	2.4				
Wheat straw	22.4	17.7	4.7	2.9				
Sugar beet pulp	5.1	3.9	1.2	1.2				
Cassava stalks	22.6	22.6	0	0.5				
Rapeseed straw	34.9	30.7	4.2	6				
Cotton stalks	54.5	34.7	19.8	6.7				
Sunflower straw	57.6	54.9	2.7	3.7				

Sugar cane bagasse	7.5	5.3	2.2	0.5				
Corn stover	16.9	15.6	1.3	3.2				
Paddy rice straw	25.3	19.5	5.8	3.2				
Wheat straw	21.4	16.9	4.5	2.7				
Sugar beet pulp	6.5	4.9	1.6	1.5				
Cassava stalks	6.9	6.9	0	0.2				
Soybean straw	12.1	11.7	0.4	0.2				
Rapeseed straw	23.1	20.3	2.8	4				
Cotton stalks	11.5	7.3	4.2	1.4				
Sunflower straw*	179.9	171.5	8.4	11.4				
Other biomass	**Blue WF: 4.0 (4.3) – Total WF: 21.6 (14.4)**							
Pinea	352.4	491.4			213.4			
Eucalyptusa	133.7	157.8			109.5			
Woody crops	**Blue WF: 0 – Total WF: 243.0 (109.4)**							

2.5 Climate projections of water availability

Optimized energy pathways derived from TIMES-PanEU, representing a future European energy system with an increased use of biomass, are not constrained by water availability.

To assess the influence of climate change on the availability of water resources at the country level, and in turn validate the scenario pathways, we consider regional climate projections from the CORDEX repository (Georgi and Gutowski 2015). Simulations for Europe (Kjellström et al. 2018, Jacob et al. 2014) are available at a horizontal grid resolution of ~12.5 km and are readily accessible for both historic and future periods. Future projections from global climate models (GCMs) for RCP2.6, RCP4.5 and RCP8.5 (Meinshausen et al. 2011), downscaled using regional climate models (RCMs), and subsequently used for this analysis are indicated in Table 3, where the acronyms refer to different GCM-RCM combinations found in CORDEX.

Table 3: *GCM-RCM model combinations used to assess water availability. The number in parenthesis indicate the number of ensemble members used in this study.*

RCP2.6 (6)		**RCP4.5 (4)**		**RCP8.5 (8)**	
RCM	**GCM**	**RCM**	**GCM**	**RCM**	**GCM**
RCA4	EC-EARTH	RCA4	EC-EARTH	RCA4	EC-EARTH
RACMO22	CNRM-CM5	RACMO22	CNRM-CM5	RACMO22	CNRM-CM5
CCLM4	EC-EARTH	CCLM4	EC-EARTH	CCLM4	EC-EARTH
REMO2009	MPI-ESM-LR	REMO2009	MPI-ESM-LR	REMO2009	MPI-ESM-LR
REMO2015	EC-EARTH			REMO2015	EC-EARTH
HIRHAM5	EC-EARTH			HIRHAM5	EC-EARTH
				WRF36	MPI-ESM-LR
				ALADIN63	CNRM-CM5

The "total runoff" (or "mrro" in "CORDEX terms") represents the "net precipitation", i.e., precipitation minus the actual evapotranspiration. This is a "proxy" for the water balance and an estimate of the blue water that is available for human and natural systems and for replenishing surface as well as sub-surface reservoirs. Annual country level estimates - based on monthly CORDEX data for the period of 2010 to 2050 – are calculated for EU28 plus Norway and Switzerland for all of the model combinations shown in Table 3. Only cells with a +50% overlap with the country in question are included. Finally, a multi-model mean is calculated for each RCP scenario and for each five-year period prescribed by the energy system model.

3. Results

This section describes the results from TIMES-PanEU and subsequent detailed analysis of the projected biomass production.

3.1 Biomass production and it's carbon footprint

Figure 2(a) shows the projected total biomass production (in energy units) found for the three scenario pathways. While the "shape" of the evolution differs slightly, in all three cases the total biomass production is projected to increase by about a factor of two from 2015 to 2050. In terms of the total transformation of the energy system (results not shown) projected by TIMES-PanEU this corresponds to an increasing share of the total energy consumption across all sectors from ca. 8% to ca. 20-22% for bioenergy. As indicated by Figure 2(a), in energy units the Base pathway prescribes a slightly lower total biomass production than the other two pathways (the prescribed biomass availability is the same across pathways). Figures 2(a), 2(b) and 2(c) show detailed results for the five biomass sources considered by TIMES-PanEU: oil crops, starch crops, sugar crops, woody crops and other types of biomass. The results clearly suggest that other biomass sources, oil crops and woody crops will play a dominant role in the future energy system transition compared to starch and sugar crops. Interestingly, in a recent study by the Joint Research Centre (JRC) (Camia et al. 2018) the current share of oil crops measured in annual dry mass units produced is found to be significantly smaller than that of biomass from sugar and starch crops (not counting residues). Along all three pathways, the energy production from oil crops increases at a higher rate than any other source, that is, until around 2030. From this point onwards, the production decreases again. In Base and PA, oil crops are all but phased completely out by 2050, whereas in LS it remains an important contributor. The importance of wood, which has always played a large role in the European energy system – both as an economic crop and in terms of residue - generally increases, in particularly along the PA pathway.

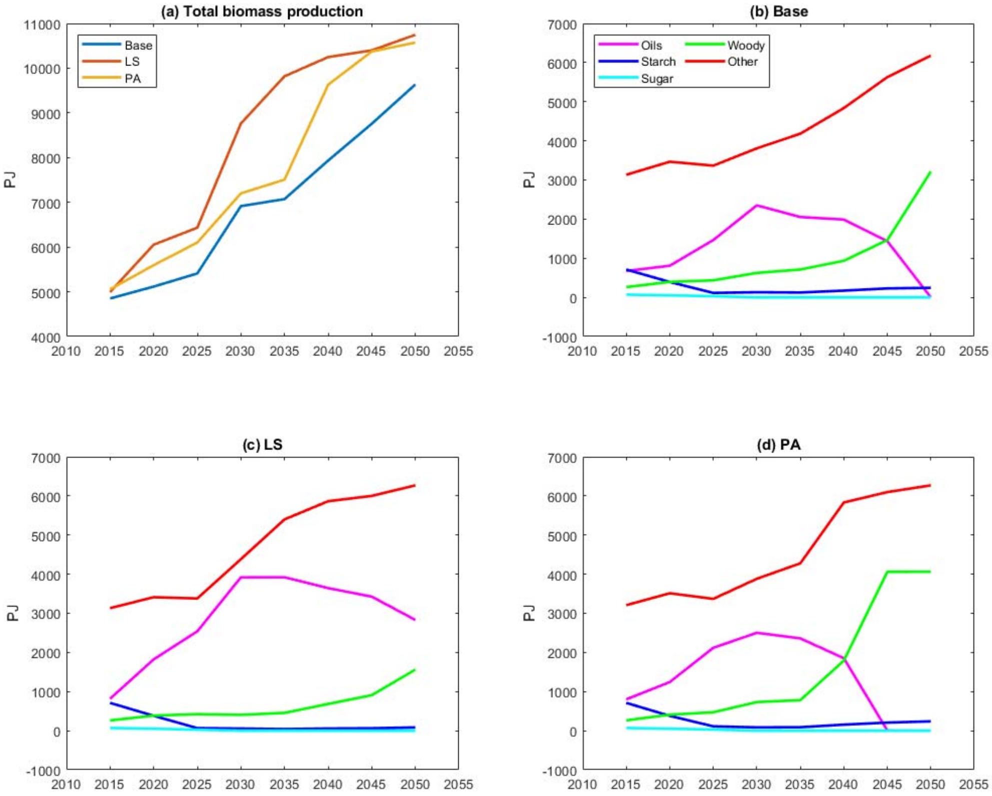

__Figure 2. Total biomass production per scenario pathway__. __a__. Projected total EU28 biomass production (PJ) for 2015-2050 for Base, LS and PA pathways. __b__., __c__. and __d__. Projected biomass production, disaggregated into five different biomass types for the Base, LS and PA scenarios respectively: oil crops (magenta), starch crops (blue), sugar crops (cyan), woody crops (green) and other kinds of biomass, including residue (red). The projected amounts of biomass are seen to be generally increasing for 2015-2050 for all types except for oil crops, where the trend declines after 2030 at different rates.

Figure 3 shows the GHG emissions associated with the increased biomass production indicated in Figure 2 using the methodology described in Section 2.3. The full lines designate results obtained using the median values, cf. Table 1, whereas the dashed lines were obtained using conversion factors corresponding to the 25th and 75th percentiles and provides a conservative measure of the uncertainty. The dominant sources of emissions are oil crops followed by woody crops, both of which are also associated with the largest uncertainties. Conversely, “other” biomass sources representing, e.g., second- and third generation biofuels, based on residue from crop and wood production account for slightly negative emissions despite representing the largest share of the bioenergy production.

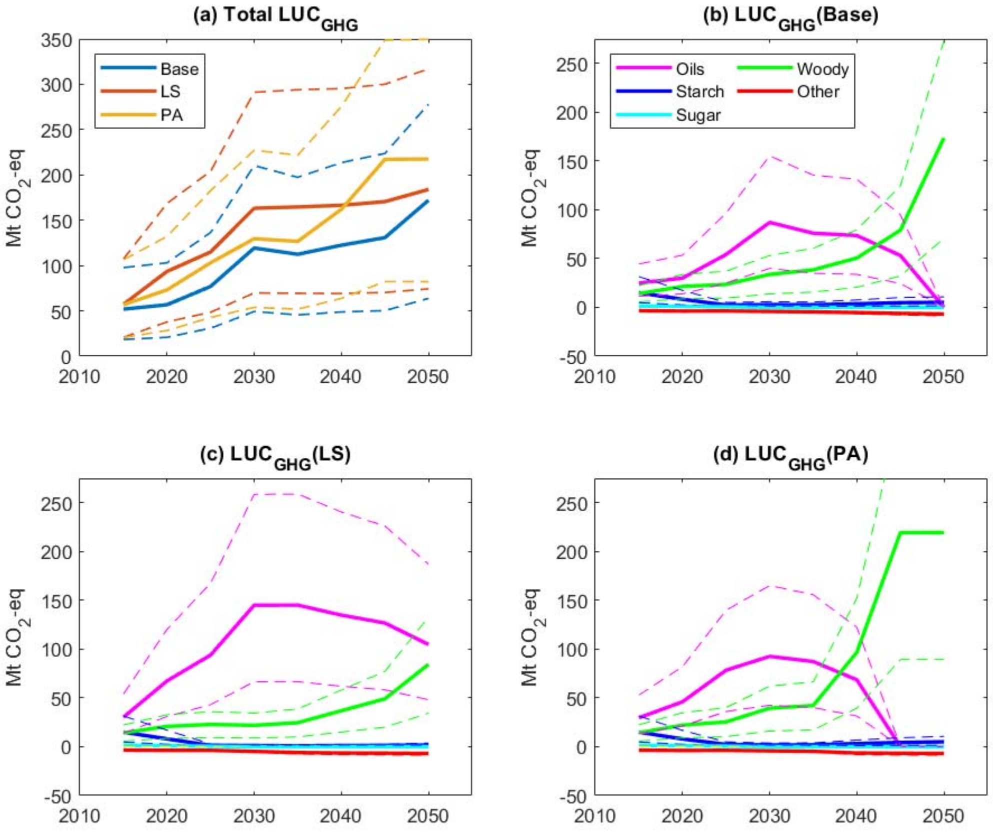

__Figure 3. Total carbon intensity per scenario pathway__. __a__. Projected total EU28 LUC emissions (CO2-eq) related to bioenergy farming for Base, LS and PA pathways. __b__., __c__. and __d__. Projected LUC emissions (CO2-eq), disaggregated into five different biomass types for the Base, LS and PA scenarios respectively: oil crops (magenta), starch crops (blue), sugar crops (cyan), woody crops (green) and other kinds of biomass, including residue (red). Full lines indicate that median factors were used to associate biomass production (cf. Figure 2) with LUC emissions (cf. Table 1). Dashed lines indicate that factors corresponding to the 25th and 75th percentile, respectively, were used. LUC emissions are seen to be primarily associated with oil and woody crops production.

3.2 Water footprint

Crop productivity whether in terms of conventional agriculture for feed or food or for biomass is highly susceptible to water availability. Figure 4 shows the estimated water footprint, i.e., green plus blue water, corresponding to Figure 2 (see also section 2.4). Full lines correspond to the mean conversion factors shown in Table 2, whereas dashed lines – again as a measure of uncertainty - correspond to plus or minus one standard deviation. For all three scenario pathways, the maximum water usage is achieved already around 2030, where the total water footprint in Europe associated with an intensification of biomass production is between two and five times that of 2015. This may in particular be attributed to the aforementioned increase in bioenergy production from oil crops, cf. Figure 4(b-d), with a very large water footprint. After 2030, the water usage is reduced only slightly. As the role of oil crops decline towards 2050 (in PA and Base oil crops are effectively removed from the energy mix) the water demand for biomass production is thus wholly or partially compensated by woody crops. That said, since the water used by woody crops is (at least in principle) entirely green water, the biomass production does not per se compete with other critical uses of freshwater, e.g., drinking water or agriculture for food.

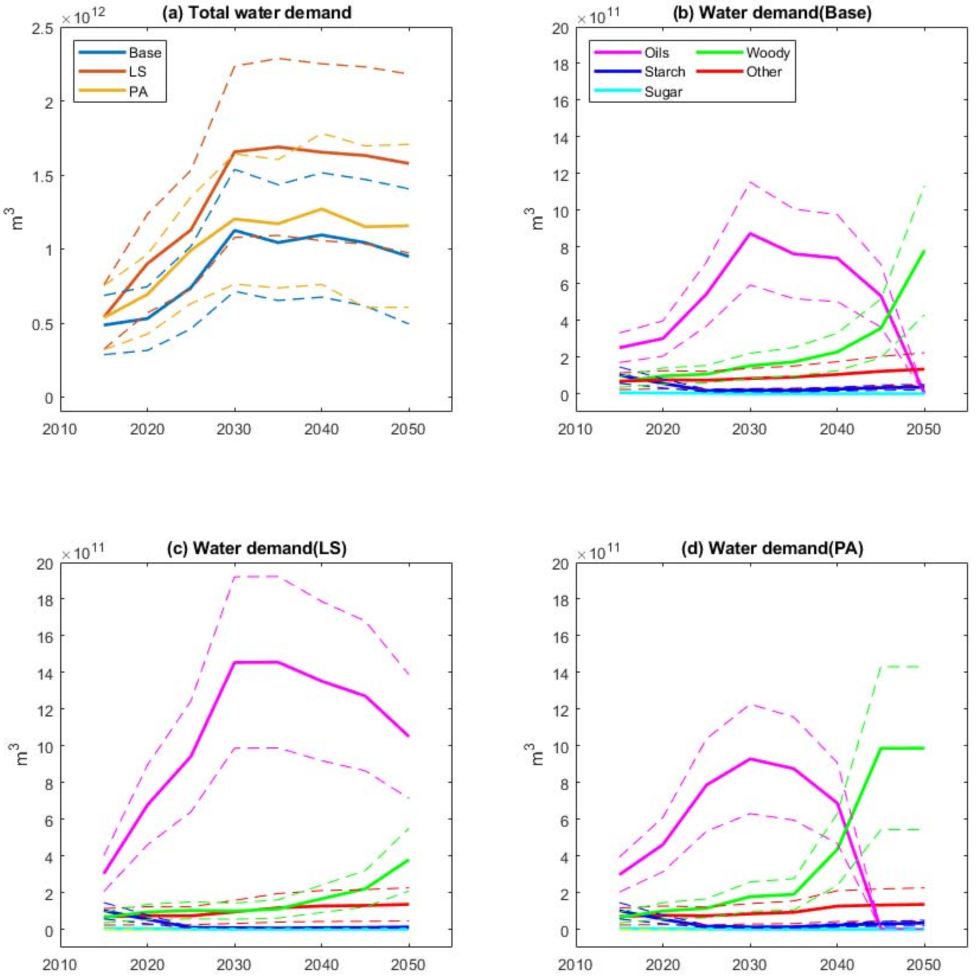

__Figure 4. Total water demand per scenario pathway__. __a__. Projected total EU28 water demand for 2015-2050 for Base, LS and PA pathways. __b__., __c__., __d__. Projected water demand related to bioenergy farming, disaggregated into five different biomass types: oil crops (magenta), starch crops (blue), sugar crops (cyan), woody crops (green) and other kinds of biomass, including residue (red). Full lines indicate that mean factors were used to associate biomass production (cf. Figure 2) with water usage (cf. Table 2). Dashed lines are indicative of mean factors plus/minus one standard deviation. Oil crops and woody crops lead to higher demand for water resources compared to other bioenergy sources.

Figure 5 depicts the water demands of biomass production for each of the EU28 countries plus Norway and Switzerland relative to the 2015 level. Coloured lines indicate the three scenario pathways with full and dashed lines corresponding to the total and blue water footprints, respectively. The figure clearly show the large national and pathway differences with respect to preferred biomass options. Energy strategies involving large amounts of in particular oil crops but also to a lower degree starch crops and sugar crops generally incur large water demand both when considering the total water and blue water footprints. Between the EU countries, we see variations ranging from mostly net reductions in the water usage (e.g., Denmark, DK) to increases in the order of 20 times the 2015 level in a few cases (e.g., Bulgaria, BG). Strategies, e.g. as in Belgium (BE) and Switzerland (CH), involving increased use of woody crops and/or second- or more advanced-generation biofuels based on other biomass potentials are easily identified by the large differences between the relative total and relative blue water footprints.

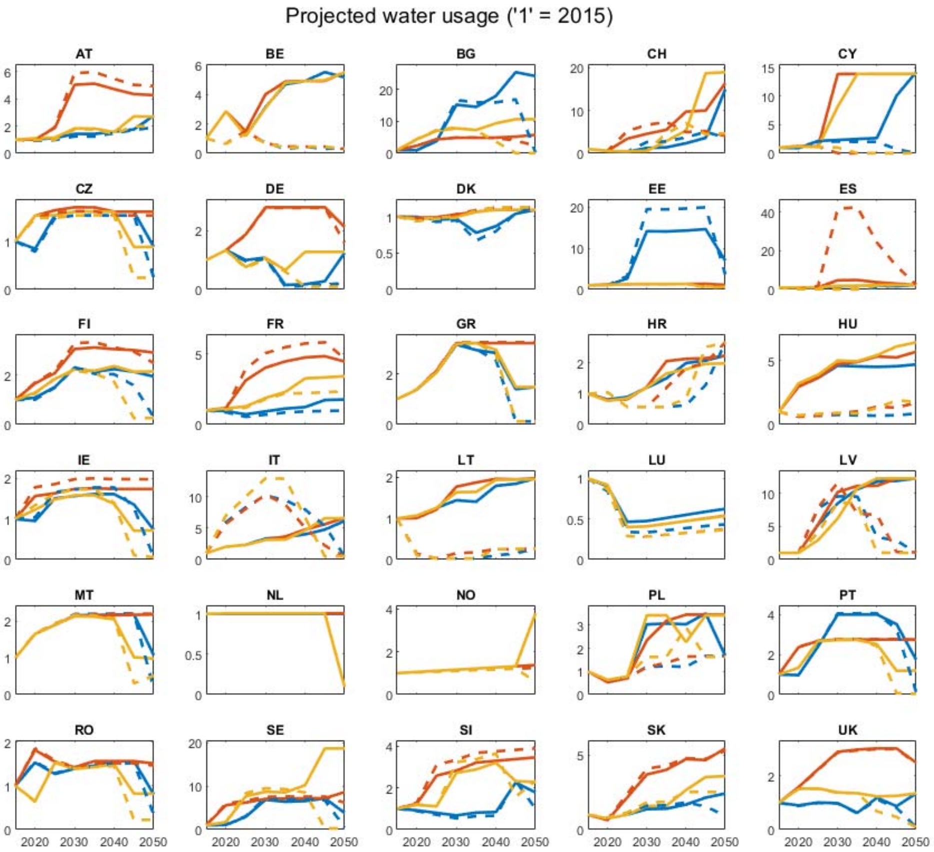

__Figure 5. Water usage for biomass production per country and per scenario pathway__. Projected water usage from biomass production for EU28 countries plus Norway (NO) and Switzerland (CH). The multiplicative factors shown on the y-axis are relative to 2015 levels (i.e. 2015 = 1). Full blue, red and yellow lines represent total water footprint along the Base, LS and PA pathways, respectively. Dashed blue, red and yellow lines similarly represent the blue water footprint.

3.3 Potential water stresses

As already today water stress is an issue in many European countries, water is likely to be a critical factor in order to upscale the European biomass production as indicated in Figure 5. This is geospatially illustrated in Figure 6, which is based on the Aqueduct data set provided by the World Resources Institute (Luo et al., 2015). The figure shows a ranking of European countries based on a near-term projection of water stress in 2020, considering the total annual water withdrawals from the municipal, industrial, and agricultural sectors, expressed as a percentage of the total annual available blue water. The lowest water stress is found in the Northern and Central-East European countries, whereas in the high end, we find South and South-West Europe. Considering the impacts of climate change, this picture is highly likely to persist. Figure 7 shows the multi-model mean of 18 climate change projections of the net annual precipitation (i.e., blue water) accounting for the evapotranspiration (cf. Section 2.5). Results are indexed relative to the 2015 level (“100”). Red colours indicate increased water availability, while blue colours indicate reductions. Comparing Figures 6 and 7, it is evident that many of the countries suffering from water stress already in 2020 are likely to suffer further reductions in the net precipitation, potentially leading to increased water stress in 2050 unless careful water management strategies are implemented. Conversely, increased net annual precipitation in North and Central-East Europe could increase water availability for the benefit of, e.g., further biomass production.

Figure 8 breaks down the expected climate impacts on water resources for each of the EU28 countries plus Norway and Switzerland. The fitted trend lines mostly agree with the results shown in Figure 7. Individual stars depict the mean annual net precipitation change for each of the 5-year periods modelled by TIMES-PanEU based on the multi-model means of climate projections for RCP2.6, RCP4.5 and RCP8.5, respectively. It is evident that for regional climate projections of changes to the water availability until 2050, the inter-annual natural variability dominates as compared to the scenario forcing. How this might affect energy strategies prescribing increasing amounts of biomass will be discussed below.

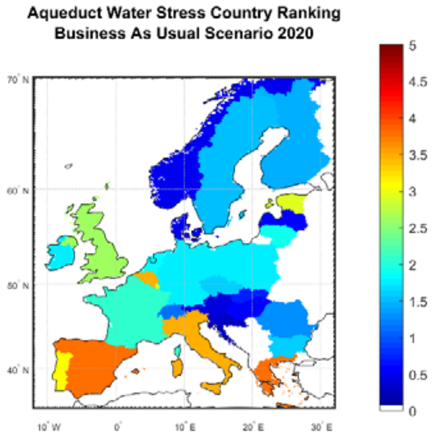

Figure 6. Expected water stress for European countries in 2020*. Based on data from (Luo et al., 2015). The country ranking is based on a business-as-usual scenario. Country water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percentage of the total annual available blue water. Higher values indicate more competition among users.*

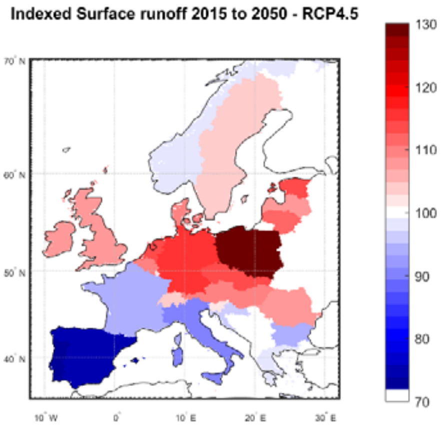

__Figure 7. Climate projections of European water availability__. The map shows relative projections of surface water runoff from precipitation for EU28 countries plus Norway and Switzerland for 2050 using 2015 as the baseline (index "100"). Red colours indicate increased water availability; blue colours decreased water availability relative to 2015.

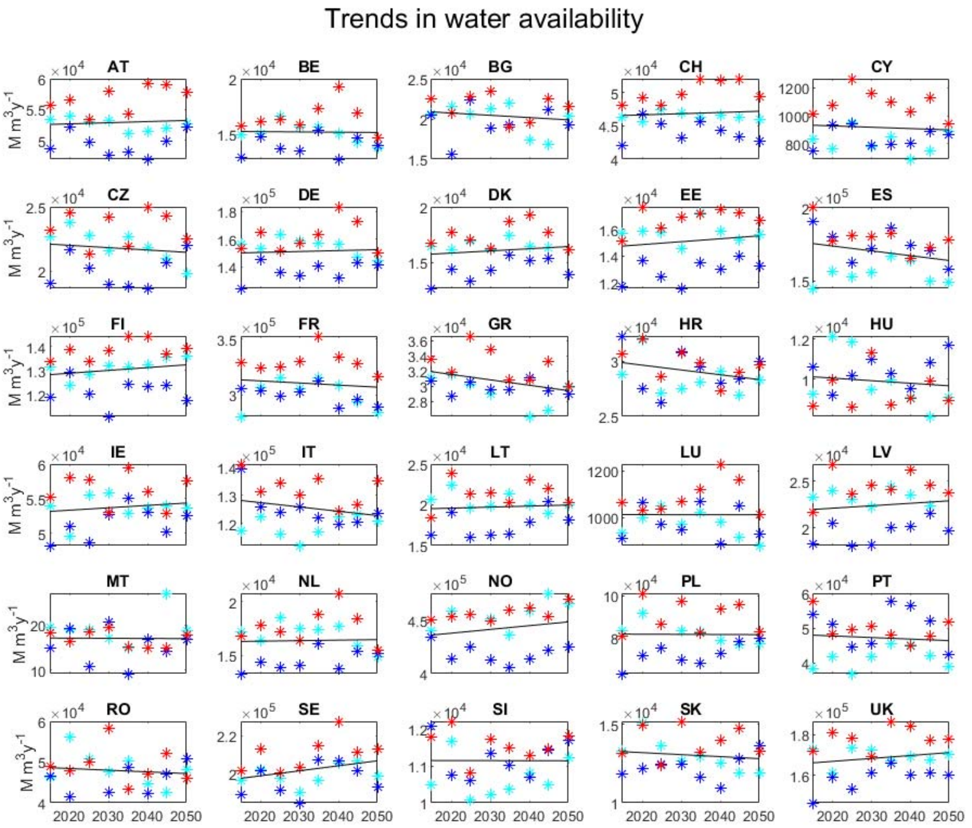

__Figure 8. Future trends in water availability per country__. Results are shown for EU28 plus Norway (NO) and Switzerland (CH). Coloured stars depict regional climate projections (multi-model means, see text) for surface water runoff for 2015-2050 for RCP2.6 (cyan), RCP4.5 (blue) and RCP8.5 (red); trend lines indicate the best linear fit to the data (in a least squares sense).

4. Discussion

Base, LS and PA indicate different pathways towards at least 80% reduction in GHG emissions from energy consumption in 2050 compared to 1990. One of the scenario pathways, PA, even strives to overshoot this target to demonstrate that a 95% reduction is feasible (in practice only approx. 80% reduction could be obtained within the constraints passed on to the energy system model). In all three strategies, biomass plays a critical role in the transformation of the energy system, contributing a share of 20% or more of the total energy consumption in Europe in 2050. This is expected to come from advanced biofuels first and foremost, woody crops and – at least for a transitional period - oil crops. In Base, LS, and PA traditional first-generation biofuels based on sugar crops are effectively phased out by 2050. In the former two this also applies to starch crops, whereas in PA the production of starch crops persists at 2.5 times that of the production in 2015, contributing a mere 2% to the energy production from biomass (results not shown).

The highest potential for bioenergy production clearly stems from second- or more advanced biofuels converted from waste and residue of conventional food and fibre production. Along all three pathways (Figure 2) this biomass resource is thus fully exploited (within set constraints on biomass availability). As illustrated by Figures 3 and 4 (Tables 1 and 2), this other biomass potential carry the lowest water footprint compared to starch, sugar, oil and wood crops. Similarly, it leads to negative emissions for biomass induced land use change and further reduce additional demands for farmland for bioenergy production. The availability of this resource is however limited as it is inherently linked to conventional agriculture and forestry. In the absence of more efficient conversion techniques (from biomass to biofuel) or more raw material, the use of less attractive options is therefore required in order to reduce GHG from energy consumption by as much as 80% in 2050 (compared to 1990).

Here the proposed role of oil crops is particularly interesting. Of the three sources of first-generation biofuels considered by the energy system model, it has the highest water and carbon footprint even considering uncertainties (cf. Table 1 and 2). Thus, one could ask the question if oil crops would still have been favoured, had TIMES-PanEU explicitly considered these parameters? On the other hand, oil crops of which rapeseed is the preferred choice in Europe has a high conversion efficiency (~80% in TIMES-PanEU) compared to sugar (60%) and starch crops (30-40%) and are easily processed into biodiesel for the transport sector. Arguably, for this reason it is logical that oil crops within our modelling framework even past 2050 continues to play an important part along the LS pathway; whereas they play a transitional role in the other two, where they are eventually substituted by biomass production for more advanced biofuels and woody crops between 2040 and 2050.

Whether it is realistic that the European production of oil crops can be upscaled in the short term as suggested by all of the three scenario pathways is another question. Currently, the economic production of oil crops in Europe stands at only 5.2% (Camia et al. 2018). To fulfil the ambitious goals suggested by TIMES-PanEU, significant changes in land use have to take place. Conversely, some authors like van Duren et al. (2015) have questioned the high conversion efficiency indicated above, arguing that the energy efficiency of rapeseed biodiesel is still fairly low and spatially heterogeneous across Europe. Unless major technological advances are achieved, it should therefore not be considered a feasible option to replace fossil fuels by biofuels produced from rapeseed.

The results from TIMES-PanEU suggest that woody crops will play an important role in the future European system. This is particularly true for the PA pathway, where woody biomass production in 2050 is projected to increase by a factor of 15 compared to 2015. The discussion of land available for such a transition notwithstanding, LUC emissions originating from the production of woody biomass are sparsely studied compared to other types of biomass and thus estimates of the carbon intensities are accordingly less robust. This is aptly reflected in Figure 1, where zero lies on the boundary of the extreme range but not in Figure 3, where the spread is illustrated by means of the 25th and 75th percentiles. For the latter, LUC emissions related to biomass production may in some cases be comparable with emissions from fossil fuels. For real life circumstances this depends on a variety of factors, including local management practises, geographical location, technologies, and how residues and waste from bioenergy production are used (e.g. bioashes on soil, Venturini et al. 2019).

Hence the 'carbon neutrality' of bioenergy is an assumption that implies that the CO_2 sequestrated during growth of biomass equals to the CO_2 released in, e.g., combustion. Such carbon neutrality may appear as a reasonable assumption for biofuels deriving from fast growing species, but may not apply for slower growing biomass from forests (Cherubini et al. 2011a, Zanchi et al. 2012). Key factors such as biomass growth, harvesting year and the time-horizon are thus of outmost importance when estimating the climate impact from forest bioenergy. For example, Cherubini et al. (2011b) revealed that within a window of 20 years, the climate impact of CO_2 from boreal forest bioenergy is close to that of CO_2 from combustion of fossil fuels, while for longer time horizons the impact consistently decreases. Assuming zero GHG emissions from bioenergy can therefore be very misleading, particularly when assessing short to medium term decarbonisation goals.

In Europe, approximately 75% of the annual increment to EU forests is harvested, resulting in annual additions to both the carbon sink and carbon stock. Nabuurs et al. (n.d.) estimate that the EU forestry sector accounts for an overall emissions reduction of about 13% compared to the total EU emissions. Considering uncertainties, c.f. Figure 3, however, it is evident that the potential of the forestry sector towards climate change mitigation (as a carbon sink) urgently needs to be revisited and held up against other biomass use in bioenergy sub-products within EU scenario pathways.

Under the current guidelines for emission accounting endorsed by the IPCC and Conference of the Parties (COP), National Greenhouse Gas Inventories are divided into six sectors: energy; industrial processes; solvent and other product use; agriculture; forestry and other land-use change; and waste (IPCC, n.d.; UNFCCC, 2003). Carbon dioxide (CO2) emissions from bioenergy combustion are accounted in the Forestry and Other Land Use sector and not in the Energy sector to avoid double counting (IPCC, 2006, 2019). Approximately 45% of the EU emissions are covered by the EU-ETS. Emissions from the sectors not included in the EU ETS are addressed in the Effort Sharing Decision (ESD). At present, land-use change and forestry (LULUCF) emissions are not included neither on the EU-ETS nor in the ESD. Only New Zealand have included forest credits adopting the Permanent Forest Sink Initiative that co-exists with the ETS system.

Increased water demand for bioenergy production is prescribed by all pathways. On a European level, this amount to at least a doubling of the water consumption (Figure 4) associated with biomass production; though with great variations between the countries (Figure 5) depending on the national energy strategies proposed by the model. Here increased water usage is particularly associated with having a high fraction of oil or wood crops as in the cases of France and Italy (results not shown). Both of these countries suffer already today (at least regionally) from considerable water stress due to a mismatch between the available amount of natural water resources and a high demand from different economic sectors (Figure 6), including water requirements by conventional and renewable energy generation (Larsen & Drews 2019). It is evident that in Southern Europe lack of sufficient water could negatively affect the potential for growing water intensive crops like rapeseed and other oil crops, as is proposed by TIMES-PanEU. This may be even more true, when one factors in the expected negative impacts of climate change (Figures 7-8) on water availability along the Mediterranean - in particularly in the long term. Combined, it is not recommendable to include a large fraction of, e.g., oil crops as part of the national energy strategies in this region but to plan for the use of less resource intensive biomass types.

Climate change is in general likely to have both positive and negative impacts on the water availability and the biomass potential in Europe. Here we do not consider extremes like flood or droughts that may become more frequent and/or severe due to climate change and in turn negatively affect yields or incur great damages to essential infrastructure (e.g. IPCC 2014). Rather, as shown in Figure 7 and Figure 8, state-of-the-art regional climate projections indicate that many North and Central European countries on the longer term are likely to experience a net increase in annual precipitation, which coupled with increased atmospheric CO_2 levels - and in Northern Europe a prolonged growing season - in principle should be beneficial to biomass productivity. Still, this will hardly be enough to balance the potential requirements by water intensive biomass production. Moreover, in the shorter term, i.e., for the analysis period we consider in this study (2015-2050), climate trends are mostly negligible, the main climate impact on biomass production stemming from natural (year-to-year) variability (Figure 8), and which provided biofuels are storable, will average out.

5. Conclusion

In this paper, we investigate the water and carbon footprint associated with increasing amounts of bioenergy in the European energy system - from ca. 8% in 2015 to ca. 20-22% in 2050 - as part of an ambitious transition to a low carbon EU energy society. Three different scenario pathways (2015-2050) derived from the TIMES-PanEU energy system model are analysed:

- In “Coalitions for a low-carbon path” (Base) bioenergy from second- and more advanced generation biofuels dominate, followed by an increasingly larger share of biomass harvested from wood crops. Oil crops play a strong transitional role in the bioenergy mix, but are all but phased out in 2050 just like starch and sugar crops.
- In “Local solutions” (LS) advanced biofuels alongside bioenergy produced from oil crops are the major contributors. The use of oil crops peak around 2030 but is still very important in 2050 although their role is slowly taken over by woody crops towards the end of the period.
- In “Paris Agreement” (PA), which prescribes emission reductions of 95% in 2050 compared to 1990, advanced biofuels also take the centre stage, complemented by an increasing use of wood crops and starch crops. As in the Base pathway, oil crops play a transitional role and are phased out by 2050.

The main findings from our analysis are:

Increased biomass production is needed to reduce CO_2 emissions by 80% in 2050

For all three pathways, increased utilization of biomass products is found to be consistently cost-competitive and to found to play a critical role in the transition to a future European energy system based mainly on renewables.

Development of more advanced biofuels is a prerequisite for this transformation

Biofuels produced from residues and waste are superior in terms of water and land usage and lead generally to negative emissions related to land use change. In all the three scenario pathways, the availability of these biomass resources is fully exploited. This is however still not enough to cover the projected demand for bioenergy, and hence more efficient biomass conversion techniques are needed and/or access to more raw material. Traditional biomass sources such as starch crops, sugar crops, oil crops and woody crops are associated with comparably larger land use change emissions and/or water demand. They inherently compete with food and fibre production for land and water resources.

Oil crops are water and carbon intensive but may play a big role in the transition

In failing to satisfy the demand for second- and more advanced biofuels, first-generation biofuels are likely to play an important transitional role on the way to a decarbonized energy system. While oil crops currently represents only about 5% of the European biomass production and, TIMES-PanEU suggests that the high efficiency of the conversion from oil crops to, e.g., biodiesel, coupled with an increasing need for decarbonizing the transport sector, will carve out a much larger part for them in the European energy system in the coming 20 years. After ca. 2030 oil crops all but vanish out of the energy mix in two out of the three scenario pathways to be supplanted by, in particular, a higher share of woody crops.

Estimates of emissions from land use change and water usage have high uncertainties

The large uncertainties related to emission and water consumption factors, connecting planned energy production with their environmental footprint, must clearly be considered if future energy strategies are to be successful. While bioenergy production is generally assumed to be 'carbon neutral', in practice this may far from be the case and depend inherently on management practices, technologies used, crop and soil types, reference time period considered, etc. Similarly, global studies clearly demonstrate that the water footprint of biomass varies significantly with local conditions. Robust strategies for decarbonisation of the European energy system should embrace this, for example, by prioritizing biomass production associated with low inherent uncertainties, or could minimize uncertainties by optimizing the geographical distribution of biomass sources. That said it is evident that the potential of forestry, already posing as a significant source of European biomass today, and of oil crops urgently needs to be revisited. Both sources features strongly in all three of the scenario pathways and more knowledge is clearly needed in order to reduce the huge uncertainties surrounding both water use and land use change emissions.

Cimate change is likely to affect biomass potential through water availability

Climate change is likely to have both positive and negative impacts on water availability and will therefore affect Europe's biomass potential. General climate trends until 2050 are weak though and dwarfed by natural interannual variability. Hence gradual changes to precipitation patterns are likely to be superseded by advances in water technologies and management practices. If current trends are to continue however it will be increasingly important to factor in the impacts of climate change on biomass strategies. Increased occurrence and intensity of extremes like droughts is another matter, which may have severe ramifications for biomass production at a regional or even European level. This point was not studied in this paper, though.

In conclusion, it is important to recognize the need for “downscaling” EU strategies to the national level and further to the regional and local levels, where overall targets are confronted by “reality” in the form of, e.g., land and water resources as well as competition from other socio-economic sectors. Capacities and resources vary amongst regions. Hence, for example, water availability, which is a critical factor for biomass productivity, may loom as a barrier for expanding the share of bioenergy production in some countries, in particular, Southern Europe. This is further likely to be exacerbated by climate change. To some extent, this can of course be circumvented by smart, informed choices on management practices and the types of biomass to pursue. Oil crops like rapeseed, are highly energy efficient, but also associated with high emissions and a high water usage compared to other kinds of biomass. Thus it must be carefully considered, whether this kind of crop is the optimal focus for a potentially water stressed country such as France even for a transitional period.

Acknowledgements

This work has been supported by the REEEM project (grant agreement no. 691739) funded by the European Union’s Horizon 2020 (LCE) EU research and innovation programme.

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