European Commission

JRC SCIENCE FOR POLICY REPORT

WATER – ENERGY NEXUS IN EUROPE

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(editors)

2019

EUR 29743 EN

Joint Research Centre

This publication is a Science for Policy report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication.

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JRC115853

EUR 29743 EN

PDF	ISBN 978-92-76-03385-1	ISSN 1831-9424	doi:10.2760/968197
Print	ISBN 978-92-76-03386-8	ISSN 1018-5593	doi:10.2760/285180

Luxembourg: Publications Office of the European Union, 2019

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How to cite this report: Magagna D., Hidalgo González I., Bidoglio G., Peteves S., Adamovic M., Bisselink B., De Felice M., De Roo A., Dorati C., Ganora D., Medarac H., Pistocchi A., Van De Bund W. and Vanham D. Water – Energy Nexus in Europe, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-03385-1, doi: 10.2760/968197, JRC115853.

CONTENTS

Abstract 1

Acknowledgements 3

Executive summary 5

1 Introduction 9

2 Overview of the current water and energy sectors in the EU 13

  2.1 The energy sector 13

  2.2 The water sector 14

  2.3 The energy system and the environment 16

  2.4 Water needs of the energy sector 18

    2.4.1 The water footprint of the EU energy sector 21

  2.5 Energy needs of the water sector 23

    2.5.1 Drinking water supply 23

    2.5.2 Wastewater treatment 24

    2.5.3 Desalination for municipal use 25

3 The sustainability of the EU water-energy system up to 2050 29

  3.1 Long-term freshwater needs from the EU energy sector 29

  3.2 Generation adequacy in the EU power system 31

4 Possible options for solving water-energy issues in the EU 37

  4.1 Technology options for reducing the water needs of the EU energy system 37

  4.2 Technology options for saving energy in the EU water system 38

  4.3 The potential of desalination plants to integrate renewable power generation 39

  4.4 Water allocation between and within WEFE sectors 40

  4.5 Joint management of water and energy resources 42

5 Conclusions and policy recommendations 47

  5.1 Conclusions 47

  5.2 Policy recommendations 49

References 53

List of boxes 60

List of tables 61

List of figures 62

ABSTRACT

The interdependencies between water and energy are commanding increasing attention. Water is used throughout the energy industry for producing fuels, cooling thermal power plants, and generating electricity in hydropower plants. Conversely, the water system needs energy for collecting, pumping, treating and desalinising water.

The synergies between water and energy depend on the availability of water resources. The in-depth analysis in support of the Communication from the European Commission, *A clean planet for all: a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy* [European Commission 2018a], pointed out that 'climate change is a threat multiplier that can undermine – both inside and outside the EU – security and prosperity, including economic, food, water and energy systems'. The EU has set ambitious decarbonisation goals for the future, which could be very difficult to achieve if the water system becomes too stressed. A switch to a low carbon energy system will have to be managed with care, since some low carbon energy systems (e.g. a number of bioenergy systems) could use water more intensively than the systems they replace [European Commission 2018b].

These issues make clear that the use and management of energy and water resources need to be addressed simultaneously, bearing in mind the fundamental difference between energy and water: that energy can be renewable, but water resources are finite. Only with a nexus approach is it possible to maximise opportunities in both systems, increasing energy efficiency in the water sector, using the water system to add flexibility to the power system, extracting more energy from water, and reducing the water footprint of the energy industries.

The nexus is addressed by the Joint Research Centre's Water Energy Food and Ecosystem Nexus (WEFE) project, which analyses, in an integrated way, the interdependencies and interactions between water, energy, agriculture, and the environment. These interactions have so far been largely neglected. WEFE provides the means to develop a holistic understanding of the broader system as opposed to its individual assets.

The results of the analyses provide insights for the development of two types of measure, strategic and operational, that could support the design of cross-sectoral water-energy policies.

The strategic measures are long-term, high-impact actions that require a paradigm shift in policy design, such as:

- Continuing the drive for decarbonisation but introducing water-related criteria (e.g. water footprint) in long-term energy policies, to balance decarbonisation and water sustainability goals.

- Integrating the management of water and energy resources to ensure the flexible operation of the energy system without affecting agriculture and water supply.

- Understanding the role of desalination as a viable source of freshwater.

The operational measures are based on existing technological solutions which could make an immediate impact. We can already:

- Develop and include energy efficiency indicators and targets for the water sector, which could help unlock upgrades to the sector, leading to savings in both energy and water.

- Research water- and energy-saving technologies.

- Improve the gathering of data from different water uses, which is fundamental to a better understanding and management of water-energy interactions, and other interdependencies in the WEFE nexus.

ACKNOWLEDGEMENTS

This report has benefited from valuable discussions and data provided by JRC colleagues, Marijn Van der Velde, Pablo Ruiz Castello, Noemi Cazzaniga, Ragnar Jonsson, Andrea Camia, Renate Koeble, Adrian O'Connell, Luisa Marelli, Arnulf Jäger-Waldau, Nicolae Scarlat and Francois Dallemand.

It also profited from access to data provided by colleagues, Xose-Luis Varela Irimia and Alreta Wloadrczyk (DG GROW), and input from Annika Johansson and Fernando Diaz Alonso (EUROSTAT).

The authors would like to thank the reviewers, Dolores Ibarreta Ruiz (JRC.C6), Serenella Sara (JRC.D1), Vangelis Tzimas (JRC.C7), and Stephen Davies (JRC.DDG2) for their time and valuable input, which helped to improve the overall quality of the report.

The authors would also like to thank Sara André, Thomas Telsnig, Nicola Magnani and Iratxe González Aparicio (JRC.C7) for their assistance in improving the graphical content.

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EXECUTIVE SUMMARY

Society today faces the problem of increasingly scarce water resources, generating competition for water between the various economic sectors. Droughts and floods have the potential to undermine the functioning of sectors such as the energy and food production industries, with consequent societal and economic impacts. Energy and water are inextricably linked: we need ‘water for energy’ for cooling, storage, biofuels, hydropower, etc., and we need ‘energy for water’ to pump, treat and desalinate. Without energy and water, we cannot satisfy basic human needs, produce food for a rapidly growing population or achieve economic growth.

The Joint Research Centre’s project, WEFE Nexus (Water Energy Food and Ecosystem Nexus), carries out integrated analyses of the interdependencies between agricultural and energy water demand, drinking and urban water provision, and ecosystem flow requirements. Sectoral policies have often underestimated, if not neglected, these interdependencies. WEFE Nexus is designed to support cross-sectoral EU policymaking by developing an understanding of the broad system as opposed to its individual assets.

This report provides a first summary of WEFE Nexus findings as regards water and energy issues in Europe.

Policy context

Although the interdependencies between water and energy are well known, and have become a subject of increasing attention for the scientific and policy communities, the development and implementation of water and energy policies remain largely disconnected at EU and Member State levels. As the EC launches a public consultation on the review of water and energy management policies, the WEFE Nexus project supports the design and implementation of cross-sectoral policies intended to improve the resilience of water-using sectors and the preservation and sustainability of freshwater resources.

Policies being looked at by the EC include the Fitness Check of the Water Framework Directive (WFD), which promotes sustainable water use. The Fitness Check focuses on improvements in the sustainable management of water and the state of water bodies, and strategies to reduce the risk of flooding across the EU[1]. Other policies include the drafting of National Energy and Climate Plans (NECP)[2], which identify strategies and measures to help the EU and Member States to meet 2030 climate targets; and the possible addition of energy savings in the water sector to the Energy Efficiency Directive’s Energy Efficiency Obligation Schemes (EEOS)[3].

Key findings and conclusions

Water availability is among the key constraints affecting the European energy sector, which currently requires 74 billion m^3/year of freshwater, similar to the water needs of agriculture. The decarbonisation of the energy system could reduce its water needs by 38 % by 2050[4], yet water availability will play an essential role on the way to climate neutrality by 2050.

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[1] https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2017-5128184/public-consultation_en)

[2] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1490877208700&uri=CELEX:52016PC0765

[4] Based on [Capros et al. 2016].

At the same time, projections indicate that water resources are expected to be under major stress, primarily due to climate change. Higher water stress is expected in Mediterranean regions and extreme weather variability is also expected in north-west Europe. That may lead to increased strain in regions where freshwater is key for cooling thermal power plants or where hydropower capacity plays a significant role in the power system.

On the other hand, the EU currently needs 50 billion m^3/year for public water supply. The energy consumed to collect, pump and treat that water represents 2.6 % of EU electricity consumption, which might seem low, but it accounts for 30-40 % of municipal energy bills. The efficient management of water and the deployment of existing energy efficiency technologies and measures can make a significant contribution to energy savings, helping to achieve Europe's 2020 energy efficiency targets.

Although the water-energy nexus is clearly evident, it has yet to be reflected in the respective regulatory frameworks, which remain largely disconnected and unconcerned with issues of reciprocal impact and opportunity. There is significant added value in developing an integrated model that bridges this gap and feeds into future policy development. This report presents a first attempt at coupling water and energy model-based assessments to better understand the water-energy nexus.

The policy recommendations stemming from this work are presented at two levels: strategic and operational. Strategic measures are long-term actions that may require a paradigm shift in policy design, while operational measures are based on technological solutions which already exist and could make an immediate impact.

The strategic actions include:

- **Introducing water-related criteria in long-term energy policies.** The decarbonisation of the energy system will lead to an overall reduction of water used by the energy industry. However, increasing energy production from biomass and hydropower would increase the water footprint of the energy system. The inclusion of criteria such as water footprint in long-term energy policies would allow for informed trade-offs between decarbonisation goals and water sustainability.

- **Developing integrated management of water and energy resources to ensure the functioning of the energy system without affecting agriculture and water supply.** Energy-related criticalities are expected across several EU regions. At local level, the integration of water and energy modelling will allow for the identification of regions at risk in terms of future water availability and the vulnerability of the energy system. This integrated approach would also help provide more flexibility to the energy system through optimised use of hydropower resources for balancing and storing renewable energy.

- **Understanding the role of renewable-powered desalination as a viable source of freshwater.** Desalination could become a fundamental part of the public water supply, especially in light of climate change impacts on available resources. However, desalination techniques are highly energy intensive, and may impact the functioning of the energy system. Renewable-powered desalination plants may offer a viable alternative.

As regards the operational actions, we can already:

- **Develop and include energy efficiency indicators and targets for the water sector.** We already have viable technologies that could drive energy and water savings through the reduction of losses and leakages in water networks and the optimisation of wastewater treatments. The inclusion of energy efficiency indicators and targets in water policies could stimulate improvements in this area.

- **Research water- and energy-saving technologies**. Energy- and water-saving technologies (e.g. air-based and advanced cooling systems, advanced materials for improved waste-heat recovery and smart meters) are currently too expensive in terms of the efficiency of power plants and design requirements. Research could help to improve the technical and economic feasibility of these technologies.

- **Improve the gathering of data from different water uses.** The analyses that have formed the scientific evidence of this report highlight how complete and accurate data from different water uses are fundamental for the understanding of the extent of water-energy interactions, and other interdependencies in the WEFE nexus.

Related and future JRC work

The information conveyed in this report builds upon detailed analysis described in a number of scientific and technical reports and peer-reviewed articles, as listed below:

JRC116389	Water-Energy-Food-Ecosystem Nexus
JRC116387	Interrelations between energy and water
JRC114513	Hydropower technology market report 2018
JRC115853	Water-Energy Nexus in Europe
JRC116125	Freshwater use from the European energy sector
JRC115157	Analysis of the water-power nexus in the West African Power Pool
JRC109346	Proceedings of the Workshop on Water-Energy-Food-Ecosystems (WEFE) Nexus and Sustainable Development Goals (SDGs)
JRC115915	An assessment of large scale PV-RO desalination in the extended Mediterranean region
JRC114177	EC Position Paper: The Water, Energy, Food and Ecosystem (WEFE) Nexus
JRC115710	The water footprint of the European Union energy sector
JRC115605	Options to improve energy use in urban wastewater treatment: a European scale analysis
JRC112990	Overview of the water requirements for energy production in Africa
JRC114030	A geospatial assessment of small-scale hydropower potential in sub-Saharan Africa
JRC114008	Freshwater use from the European Energy Sector
JRC113700	Freshwater use from the European Energy Sector
JRC113696	Projected fresh water use from the European energy sector
JRC113580	SETIS Magazine: The relevance of the water-energy nexus for EU policies
JRC110927	Impact of a changing climate, land use, and water usage on Europe's water resources: A model simulation study
JRC109944	The water-power nexus of the Iberian Peninsula power system: WATERFLEX project
JRC109941	Water-related modelling in electric power systems: WATERFLEX Exploratory Research Project: version 1
JRC107240	Quantifying the Water-Power Linkage on Hydrothermal Power Systems
JRC108347	Models, methods, and challenges for assessing the interactions between the power and water resources
JRC104642	Quantifying the water-power linkage on hydrothermal power systems: A Greek case study
JRC104481	WATERFLEX Dissemination activities: Contributions to the workshop "Understanding the Water-Energy Nexus: Integrated Water and Power System Modelling"
JRC104640	Hydro-related modelling for the WATERFLEX Exploratory Research Project: Version 0
JRC104764	The water-energy nexus and the implications for the flexibility of the Greek power system
JRC115915	An assessment of large scale PV-RO desalination in the extended Mediterranean region

The lessons learnt from this first integration of water and energy analyses for Europe can be applied to achieve an understanding of ever-evolving policy scenarios, especially in the increasing push towards a net-zero-emission Europe in 2050. It can therefore be expected that the methodologies presented in this report will be used to understand the water-energy implications of i) increases in hydrogen demand (as a storage option and for transport), ii) the future role of carbon capture, utilisation and storage (CCUS), iii) the increase in demand for desalination, and iv) the more stringent energy and climate targets required to meet the Paris Agreement.

Quick guide

The report is structured as follows:
Section 2 gives an overview of the water and energy sectors in the EU.
Section 3 describes the main challenges associated with the water-energy nexus in the EU.
Section 4 proposes some solutions to those challenges.
Section 5 summarises the main conclusions and recommendations derived from the current analyses carried out by the WEFE project.

1 INTRODUCTION

Water is used throughout the energy industry, especially for the production of primary energy and for transforming it in power plants and oil refineries. Water reservoirs are a major carbon-free power generation source that provides key flexibility services to the energy system, helping to balance intermittent generation from wind and solar and changes in demand, and accounting for virtually all the energy storage capacity of the power system. On the other hand, the water system needs energy for collecting, pumping, treating and desalinising water.

These interdependencies between water and energy are well known and they have become a topic of increasing attention for the scientific and policy communities [Albrecht et al. 2018]. According to the IEA [International Energy Agency 2012, International Energy Agency 2016] the extraction, transport and processing of fossil fuels, and the irrigation of biofuels feedstock crops – and is vulnerable to physical constraints on its availability and regulations that might limit access to it. A more water-constrained future, as population and the global economy grow and climate change looms, will impact energy sector reliability and costs. Global water withdrawals for energy production in 2010 were estimated at 583 billion cubic metres (bcm, energy-related water withdrawals during the 2010-2014 period ranged between 398 and 583 billion m^3 per year (around 10 % of total water abstraction for all purposes) and consumption ranged between 48 and 66 billion m^3 (3 % of the global water consumption), while the total energy consumption of the water sector was approximately 1 % of the world's total[5] [International Energy Agency 2018]. In this period the EU accounted for 12 % of energy-related withdrawals (48-70 billion m^3 per year) and 10 % of consumption at the global level (5-7 billion m^3 per year), while the water demand from the energy sector accounted for 42 % of the total EU water abstraction [International Energy Agency 2018].

Water-related issues have significant financial impacts on the energy sector. According to the Global Water Report of the Carbon Disclosure Project [CDP 2018], the impacts on mineral (including coal) extraction companies and power utilities amounted respectively to USD 20.5 billion (approximately EUR 17.4 billion) and USD 9.6 billion (approximately EUR 8.1 billion), due to increased operation costs, reduced or disrupted production capacity, fines and penalties or enforcement orders, impacts on company assets and increased compliance costs. Respondents to this survey report that they are exposed to substantive water risk, affecting their operations directly or along the value chain (e.g. 69 % of fossil fuels, 91 % of mineral extraction, and 86 % of power generation companies).

The water-energy nexus is still perceived by the World Energy Council as a relative low-impact and low-uncertainty issue, but this trend has been changing in recent years and the water-energy nexus is becoming "among energy leaders' top uncertainty issues in China, the Middle East, and parts of the Americas" (Figure 1, top) and also in Europe (Figure 1, bottom) [World Energy Council 2017, World Energy Council 2019a]. If this trend continues, the water-energy nexus will become one more "critical uncertainty" that "needs to be part of the energy leaders' dialogue and scenario analysis" [World Energy Council 2019b].

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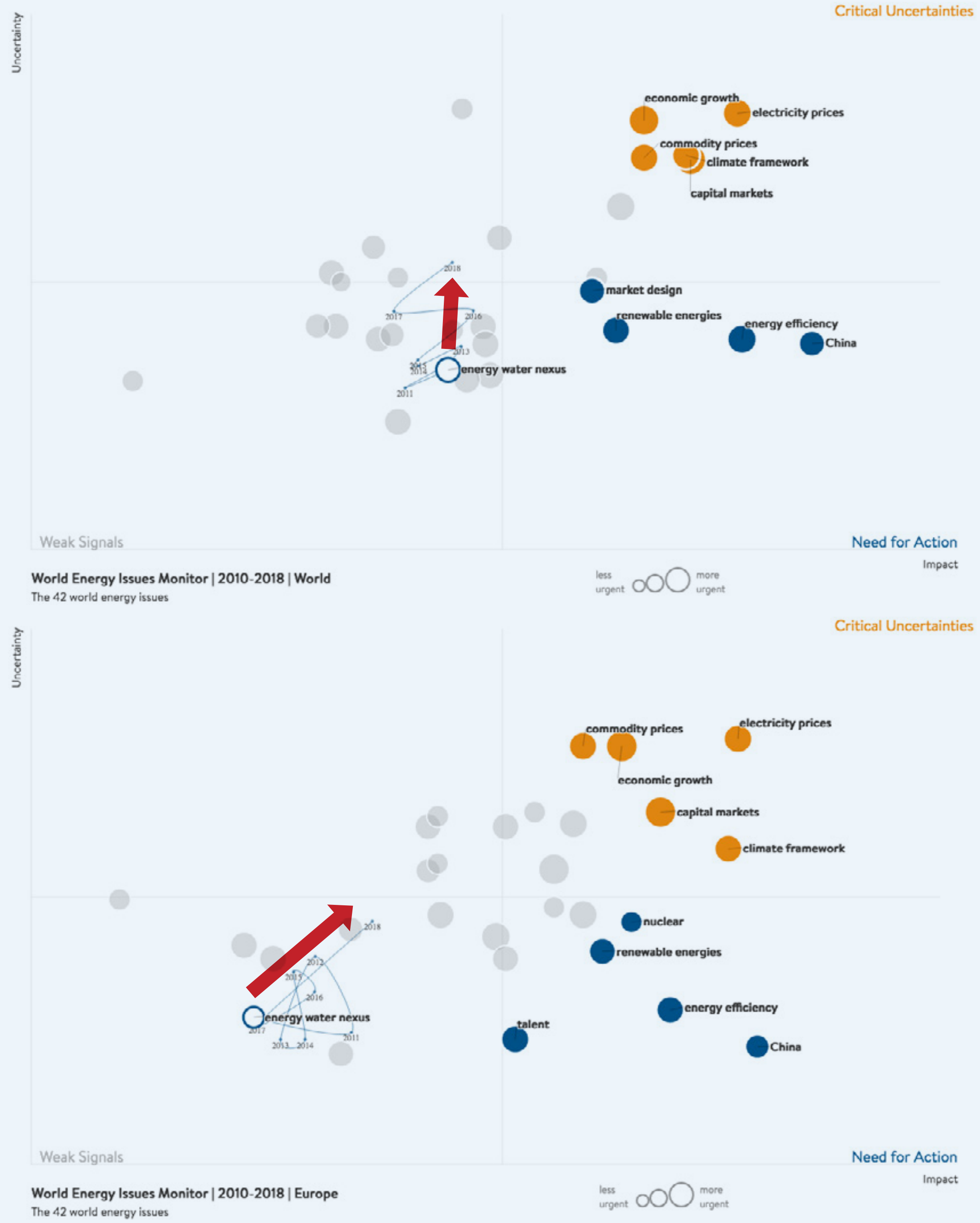
[5] That is approximately equal to the current final energy consumption of Australia, and roughly equal to 4 % of the global electricity consumption.

Increasing water and energy needs, or changes in water availability due to climate change, could have significant effects on the future energy system. For instance, the IEA expects the water consumed by the global energy sector to rise by almost 60 % to 2040 while the energy used in the water sector would more than double in the same period [International Energy Agency 2018]. These problems are expected to become very acute in developing countries, where water availability is necessary for increasing energy access, but also in the EU, which has ambitious long-term decarbonisation goals for 2050 that depend on carbon-free energy sources. These goals could be very difficult to achieve if the European water system becomes too stressed, since some of these energy sources (such as wind and solar) will increase the flexibility needs (storage and balancing) of the power system, which are provided to a great extent by water reservoirs, and some other sources (such as biofuels nuclear) are very water-intensive.

Although the water sector is not as energy-intensive as other industries, its operation may offer some solutions for saving energy through energy efficiency measures and for

Figure 1. The water-energy nexus among the energy issues from 2010 to 2018 (red arrows) [World Energy Council 2019b]



increasing the flexibility of the European power system. This flexibility is already provided by balancing wind and solar fluctuations and storing excess renewable production during periods of low demand, but further flexibility may be achieved by powering water treatment and desalination plants with wind or solar power, or by using the distributed storage capacity of water supply and distribution networks for hydroelectric accumulation.

All the above considerations denote that the use and management of energy and water resources need to be addressed simultaneously. Only with a nexus approach is it possible to take full advantage of the opportunities to increase energy efficiency in the water sector; to exploit the possibilities of the water system as a source of flexibility for the power system; to extract more energy from water; and to reduce the water footprint of the energy industries. However, as highlighted in [Jacobsen 2014] :

> *'There is no coordination between the water and energy sectors and even less between the related sectors such as agriculture, forestry, trade and mining. Thus, at the heart of the problem, in Europe and elsewhere, is a lack of policy integration: the energy, water and more recently "climate" sectors are highly developed within themselves but only limited effort is made to account for, and manage, the extensive links between them'.*

According to a recent systematic review, 'the use of water-energy-food nexus methods to systematically evaluate water, energy, and food interlinkages or support development of socially and politically-relevant resource policies has been limited', 'the use of specific and reproducible methods for nexus assessment is uncommon', 'nexus methods frequently fall short of capturing interactions among water, energy, and food – the very linkages they conceptually purport to address', and 'many nexus methods are confined to disciplinary silos – only about one-quarter combine methods from diverse disciplines and less than one-fifth utilize both quantitative and qualitative approaches' [Albrecht et al. 2018].

The Joint Research Centre is trying to overcome the above limitations by means of the Water Energy Food and Ecosystem Nexus (WEFE) project, analysing the interdependencies and interactions between water, energy, agriculture, water supply and treatment, and the environment. WEFE provides the means to develop a holistic understanding of the broader system rather than of individual assets. This is essential because acting from the perspective of individual sectors cannot help tackle the societal challenges of the future.

The overall objective of the WEFE project is to help, in a systemic way, the design and implementation of European policies with water dependency. By combining expertise and data from across the JRC, it will inform cross-sectoral policymaking on how to improve the resilience of water-using sectors such as energy, agriculture and ecosystems. Thus, the WEFE project aims to:

- Help implement several sectoral EU policies, such as the Water Framework Directive, Common Agricultural Policy, Energy Union and the EU Development Policy, enhance their coherence and analyse the most significant WEFE interdependencies by testing policy, institutional and technological options.

- Analyse the most significant interdependencies by testing strategies, policy options and technological solutions under different scenarios for Europe and beyond.

- Evaluate the impacts of changing availability of water due to climate change, land use, urbanisation, demography and geographical areas of strategic interest for the EU.

- Deliver country and regional scale reports, outlooks on anomalies in water availability, a toolbox for scenario-based decision-making, and science policy briefs connecting the project's recommendations to the policy process.

- Develop practical guidance to allow the identification of a portfolio of measures accounting for the synergies and trade-offs needed for the integrated achievement of the Agenda 2030 Sustainable Development Goals (SDGs).

The WEFE project enables the decision-making process of policymakers through the integration of the different aspects of scientific research that JRC undertakes in specific sectors such as agriculture, energy and environmental policies; whilst at the same time supporting the specific goals of sectoral policies.

This report provides a first summary of the findings produced within the WEFE project as regards water and energy issues in Europe.

2 OVERVIEW OF THE CURRENT WATER AND ENERGY SECTOR IN THE EU

This section gives an overview of the status of the water and energy sectors in the EU, highlighting the current policies affecting them, and the respective dependencies and impacts.

2.1 The energy sector

The EU energy industry is interconnected with all other sectors of the economy. In 2015[6], around 10 000 enterprises in the EU energy sector employed almost 2 million people and generated a turnover of EUR 2 000 billion[7]. According to EUROSTAT, the energy industry consists of four parts: i) construction of energy infrastructure, ii) extraction of fossil fuels where water is needed for coal mining and oil and gas extraction), iii) manufacture of fuels and energy equipment, where water is used for refining oil products, and iv) the supply of electricity, gas, steam, and air conditioning, which uses water for cooling thermal power plants and hydropower generation.

EU energy policies are designed to ensure that European citizens can access secure, affordable and sustainable energy supplies. The main initiatives to date are:

- The **Energy Union**[8] strategy, focused on boosting energy security, the internal energy market, energy efficiency, the use of renewable energy, and research and innovation.
- The measures considered in the **Energy Security Strategy**[9].
- The support to build a modern **interconnected energy grid**[10] across Europe.
- The **Clean Energy for All Europeans**[11] package, focused on i) energy efficiency first, ii) achieving global leadership in **renewable energies**[12], and iii) **consumers**[13].
- The **Energy Efficiency Directive**[14], outlining feasible energy savings opportunities across the EU.

The European Commission's **strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy**[15] is designed to achieve net-zero greenhouse gas emissions by 2050, and to that purpose includes a series of intermediate **targets for 2020 and 2030**[16] (on emissions reduction, improved energy efficiency, and the share of renewables in the EU's energy mix).

Figure 2 shows how much energy was produced, imported, transformed and used at EU level in 2016. The energy available after transformation (for final consumption,

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[6] Throughout the report all references to statistical data refer to the latest available year.

[7] https://publications.europa.eu/en/publication-detail/-/publication/99fc30eb-c06d-11e8-9893-01aa75ed71a1/language-en

[8] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/building-energy-union.

[9] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/energy-security-strategy.

[10] https://ec.europa.eu/energy/en/topics/infrastructure.

[11] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans.

[12] https://ec.europa.eu/energy/en/topics/renewable-energy.

[13] https://ec.europa.eu/energy/en/topics/markets-and-consumers.

[14] http://data.europa.eu/eli/dir/2012/27/oj

[15] https://ec.europa.eu/clima/policies/strategies/2050_en

[16] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2020-energy-strategy and https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy.

exports, and other minor uses) amounted to 1955 Mtoe[17]. This quantity was the sum of the primary energy directly used (903 Mtoe), plus the primary energy transformed into electricity and secondary fuels (1406 Mtoe), minus transformation losses (329 Mtoe). The primary energy production of the EU amounted to 39 % (768 Mtoe) of the energy available after transformation in 2016.

The energy sector requires water to produce primary energy (hydropower and extraction of fossil fuels) and transform it in power plants and refineries (cooling). Often only the quantification of the volume of water required in refineries and thermal power plants (expressed in terms of withdrawal, consumption and return flows) is undertaken, since water availability and water temperature drive operational constraints. In 2015, the water withdrawn by the energy sector for the production of primary energy and the transformation into electricity and derived fuels accounted for 74 billion m^3 as highlighted in Figure 2.

Hydropower currently produces approximately 10 % of electricity in the EU, is a very flexible carbon-free power generation source that provides significant balancing services, and accounts for virtually all the energy storage capacity of the power system. In terms of hydropower, water availability is framed in a broader water management perspective due to the multi-purpose nature of reservoirs, beyond electricity generation [Eurelectric 2011]. Reservoirs are also used for energy storage, irrigation, residential and industrial water supply, flood protection, fishing and recreation. Given the relevant role that hydropower reservoirs play, understanding their impact on water resources is becoming increasingly vital, especially in terms of water consumption through evaporation [Hogeboom et al. 2018], effects of climate change on water availability in the reservoirs and management of freshwater resources with other uses [Eurelectric & VGB-Powertech 2018a].

2.2 The water sector

The water sector consists of different processes, whose purpose is to extract, treat, and transport water from the sources to end uses and back. These include groundwater and surface water extraction, transport and distribution, treatment, desalination, and wastewater collection, treatment and reuse [International Energy Agency 2016].

In the European Union, about 500 million people enjoy public water services. At a rate of use in the order of 245 litres per person per day, this means around 50 billion m^3 of yearly water abstractions [Eurostat 2018, GWI 2019]. The recorded public water supply in the EU amounted to 49 billion m^3 according to EurEau [EurEau 2017], of which roughly 80 % is returned to the environment after use and treatment. The urban water cycle, including drinking water supply and wastewater treatment, has small energy requirements compared to the total EU energy needs, but they are significant at the local level. According to the IEA Outlook [International Energy Agency 2016], water supply and distribution and wastewater treatment account for about 50 % each of the total energy demand of the urban water sector in Europe[18], for a total of about 70-80 TWh in 2014, which is approximately the gross electricity generation of Belgium. The use of electricity in the water sector is projected to increase globally, exceeding 4 % of the global electricity requirements by 2040 (Figure 3).

Many European policies focus on ensuring and safeguarding freshwater availability for citizens and business alike, providing safeguards for water use and discharge, including, for example, the run-off temperature of warm effluent from water.

The **Water Framework Directive (WFD)[19]**, adopted in 2000, provides the legislative framework for water management in Europe. The WFD covers all surface and ground waters, addressing both quantity and quality. Member States have to establish River Basin Management Plans (RBMPs) with a 6-year planning cycle. Its main objective is to protect and enhance the status of aquatic ecosystems and promote sustainable water use based on long-term protection of available water resources. Implementation of the WFD is in progress. The second set of river basin management plans, covering the period 2016–2021, were finalised in 2016/2017. At present, good status is achieved for 76 % of the groundwater area, and for ca. 40 % of the surface waters [Poff et al. 2007, Moran et al. 2018, WWF 2018, European Commission 2019].

The **Floods Directive (FD)[20]**, adopted in 2007, requires that Member States establish flood risk management plans every 6 years in a cycle coordinated and synchronised with the Water Framework Directive.

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[17] Mtoe stands for million tonnes of oil equivalent.
[18] The EU and other European countries, as defined by the IEA
[19] http://ec.europa.eu/environment/water/water-framework/index_en.html
[20] http://ec.europa.eu/environment/water/flood_risk/index.html

Figure 2. EU energy flow diagram in 2016, with estimated freshwater requirements of the most water-intensive energy sectors in 2015. Source: JRC, based on EUROSTAT 2018

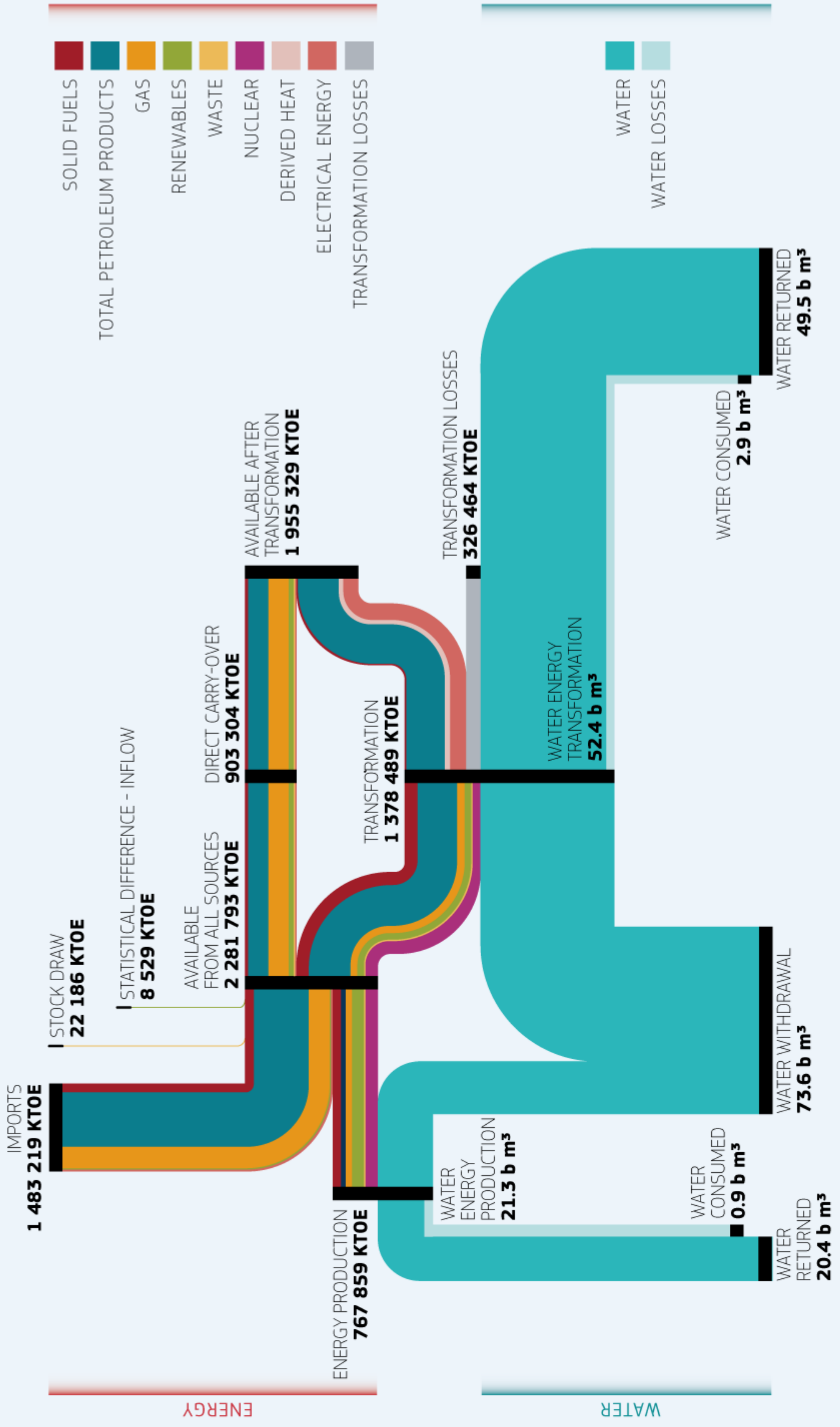
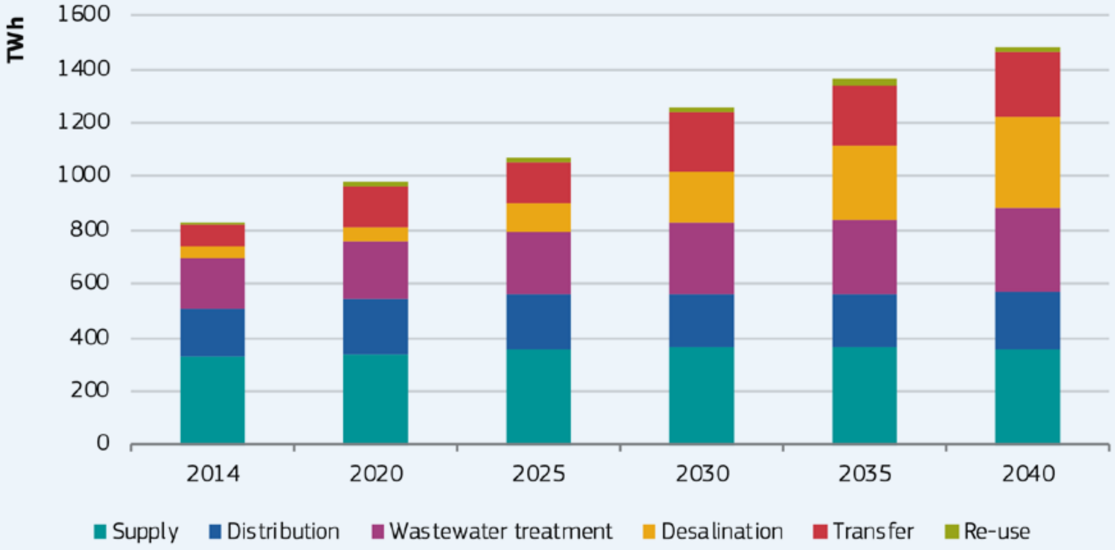


Figure 3. Electricity consumption in the water sector by process. Source [International Energy Agency 2016]



Apart from the WFD and the FD, there are four older European directives addressing specific aspects of water resources management:

- The **Nitrates Directive (ND)**[21], adopted in 1991, aiming to protect water quality across Europe by preventing nitrates from agricultural sources from polluting ground and surface waters and by promoting the use of good farming practices. Since 2000, the Nitrates Directive forms an integral part of the Water Framework Directive and is one of the key instruments in the protection of waters against agricultural pressures.

- The **Urban Wastewater Directive (UWWD)**[22], adopted in 1991. Its objective is to protect the environment from the adverse effects of urban and industrial wastewater discharges and concerns the collection, treatment and discharge of wastewater.

- The **Drinking Water Directive**[23], adopted in 1998, concerns the quality of water intended for human consumption. Its objective is to protect human health from the adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean.

- The **Bathing Water Directive**[24], adopted in 1975 and updated in 2006, aims to safeguard public health and protect the aquatic environment in coastal and inland areas from pollution.

In 2012, the European Commission published the communication, **A Blueprint to Safeguard Europe's Water Resources**[25], based on an analysis of the first River Basin Management Plans and other available information. The communication sets out the actions needed to ensure that all activities that impact on water are sustainable, thereby securing the availability of good quality water for sustainable and equitable water use. Key recommendations include the need for full implementation of the WFD and related water policies, and the need to integrate water policy objectives with other policies, including the Common Agricultural Policy (CAP) and energy policy.

A Fitness Check of the EU water legislation focusing on the WFD and following the publication of the second **River Basin Management Plans** is to be completed in 2019[26].

2.3 The energy system and the environment

The energy system affects environmental sustainability at different scales, as illustrated, for example, by the planetary boundaries framework [Steffen et al. 2015], which identifies nine critical processes that regulate the Earth system functioning. Those processes are limited by

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21 http://ec.europa.eu/environment/water/water-nitrates/index_en.html
22 http://ec.europa.eu/environment/water/water-urbanwaste/legislation/index_en.htm
23 http://ec.europa.eu/environment/water/water-drink/legislation_en.html
24 http://ec.europa.eu/environment/water/water-bathing/index_en.html
25 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52012DC0673
26 http://ec.europa.eu/environment/water/fitness_check_of_the_eu_water_legislation

certain boundaries (Figure 4 a) that should not be exceeded to keep the Earth system in a safe operating space. Some of those boundaries are currently violated (e.g. climate change) due to human activities. On the global level the planetary boundary freshwater use is considered to be in the safe zone, but on the local level many regions in the world experience significant amounts of water stress [Mekonnen & Hoekstra 2016].

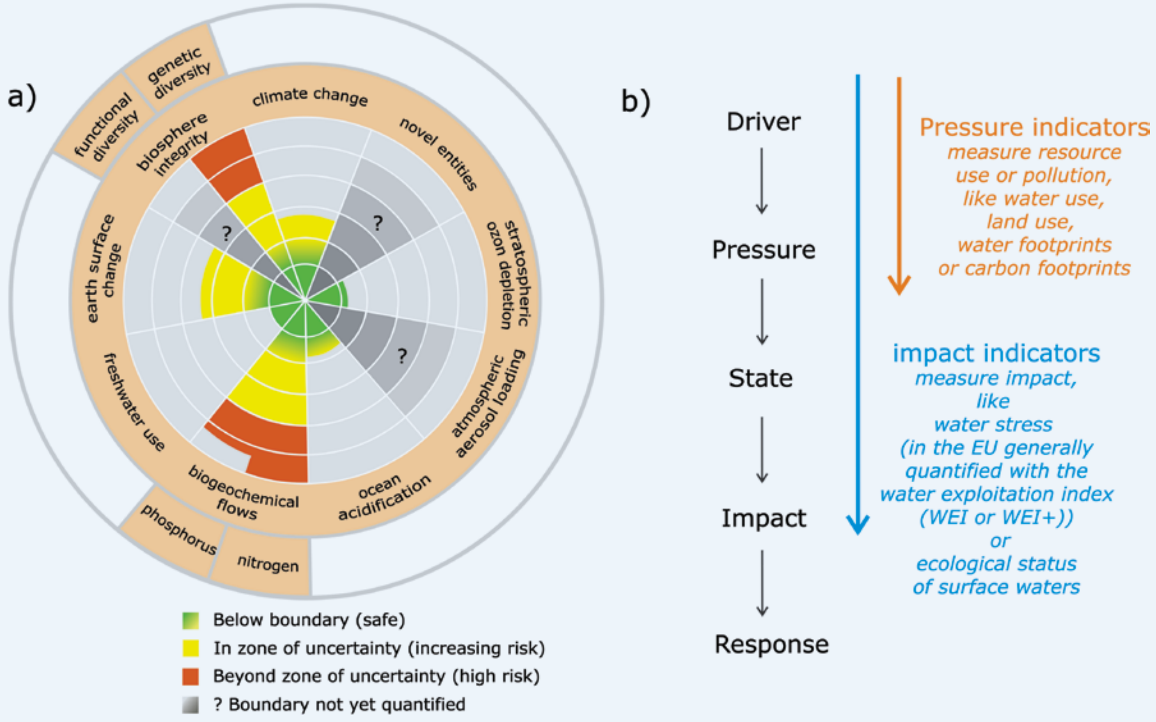
The most obvious pressure of the energy system on the environment is the emission of greenhouse gases, mostly CO_2. In 2016 the EU emitted 4 441 Mt CO_2-equivalent[27], of which 3 348 Mt CO_2-equivalent was due to fuel combustion. Agriculture is responsible for 430 Mt CO_2-equivalent. This pressure affects the planetary boundaries 'climate change' and 'ocean acidification', and leads to several environmental impacts.

The energy system also puts direct pressure on the planetary boundary 'earth surface change', for which the key control variable is deforestation. Unsustainable forestry for wood used for energy and particular first generation biofuels like palm oil are direct drivers of deforestation [Curtis et al. 2018].

The energy system also directly affects the planetary boundary 'biosphere integrity'. The more than 25 000 hydropower plants in Europe, which provide approximately 10 % of EU electricity, have been identified as one of the main drivers affecting the status of rivers and resulting in loss of connectivity, altered water flow, and sediment transport [European Environment Agency 2018], although they have the lowest carbon footprint of all power generation technologies and for that reason are crucial for meeting EU emission targets. The construction of dams for hydropower and irrigation is one of the most important causes of biodiversity loss in rivers [Zarfl et al. 2014, WWF 2018]. In Europe, 60 % of surface water bodies fail to reach the objective of 'good ecological status' required by the Water Framework Directive [Poff et al. 2007, Moran et al. 2018, WWF 2018, European Commission 2019].

Energy extraction and production in the EU requires the use of large quantities of water (21 billion m^3), and water is also used for transforming energy in refineries and power plants (52 billion m^3) [Medarac et al. 2018]). Part of the water in reservoirs is lost due to evaporation (6.8 billion m^3/year, which is 9 % of the energy-related withdrawals in 2015). The energy system thereby affects the planetary boundary 'freshwater use', contributing to the impacts of water stress and water pollution. The latter includes thermal pollution, which mostly impacts the local environment around energy facilities. It also includes chemical pollution, e.g. in fracking.

Figure 4. a) Planetary boundaries [Steffen et al. 2015] and b) DPSIR (Driver-Pressure-State-Impact-Response) framework [OECD 2013] and its relationship with pressure and impact indicators [Vanham, Leip et al. 2019].



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[27] Source: EEA table [env_air_gge]

The energy system also produces significant amounts of air and soil pollutants, solid and liquid waste.

2.4 Water needs of the energy sector

Freshwater resources are not evenly distributed in Europe, since there are various climatic zones with different precipitation and evapotranspiration patterns. The availability of water resources may constrain the operation of the energy system in many ways, mainly affecting:

- The generation and efficiency of thermal power plants, that depend on the amount and the temperature of water available for cooling.
- The output of coal mines, which depends on the amount of water available for washing, dust suppression, and transportation.
- The output of hydropower plants which depends on the inflows into the reservoirs.
- The production of biofuels which depends on the water available for energy crops.

The impact of the energy sector on water resources is usually described by assessing water withdrawal and consumption factors. A detailed overview, based on a literature review of water withdrawal and consumption factors, of the water used for the production of solid fuels, oil, gas, for oil refining, and for power generation can be found in [Medarac et al. 2018]. Other indicators of water use intensity are described in Box 1.

The EU energy sector is one of the main users of water. According to the information collected by EUROSTAT [Eurostat 2018], the water abstraction for the cooling of power plants alone (as reported by EUROSTAT) has exceeded that reported for public water supply and agriculture in almost all years from 2000 to 2015, as shown in Figure 5.

However, as described in [Medarac et al. 2018], the information contained in the EUROSTAT water database [Eurostat 2018] is affected by significant limitations due to

Box 1 Indicators of water use

Water Withdrawal (WW): freshwater withdrawal or abstraction for an economic activity. Also referred to as gross water abstraction or withdrawal.

Water Consumption (WC): the portion of WW that is not returned to the original water source after being withdrawn. WC equals WW minus return flow. WC occurs when water flows to the atmosphere through evaporation or is incorporated into a product or plant. Also referred to as consumptive water use, net water abstraction or blue water footprint.

Water Footprint (WF): the amount of water consumed (WC) along a supply chain [Hoekstra & Mekonnen 2012]. The WF includes a blue and green water component. Blue water refers to liquid water in rivers, lakes, wetlands and aquifers; whilst the green component refers to water held in the soil and available to plants.

Water Exploitation Index (WEI): indicator of water stress, relating water uses to water availability:

- **WEI_Abs** - Water withdrawal (WW) to water availability;
- **WEI+** - Water consumption (WC) to water availability; WEI+ typically ranges between 0 and 1. Values above 0.2 are 'critical' in terms of water scarcity [EEA 2016];
- **WEI_Energy** – water abstractions of the energy sector as a ratio of the sum of available internal (local) and external water (interregional or cross-border inflow);
- **WEI_AbsIntExt** – all water abstractions as a ratio of the sum of available internal (local) and external water (interregional or cross-border inflow);
- **WEIAbsInt** – all water abstractions as a ratio of the total available internal (local) water.

Sources: [Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. & Mekonnen 2011, Hoekstra & Mekonnen 2012, European Environment Agency 2016, Eurostat 2018, Medarac et al. 2018, Vanham et al. 2018].

Figure 5. Historical water abstraction for energy (cooling), agriculture, public water supply, manufacturing industry, and mining reported [Eurostat 2018]. The number of MS reporting information on freshwater for energy cooling abstraction is provided for each year.

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data gaps in the time series and the classification of the energy sector. Data gaps are related to the reporting done by Member States, with some countries providing information only every two or three years (e.g. Germany), hence justifying the spikes of Figure 4 for certain years (on average only 15 Member States report per year). In terms of classification, the EUROSTAT database contains information only with regard to water abstraction of water employed for 'electricity generation – cooling'. Whilst cooling of power plants is expected to account for the majority of water used by the energy sector, this figure, however, provides an incomplete estimation of energy sector water abstraction, since processes such as fuel extraction and oil refining are not specifically accounted for.

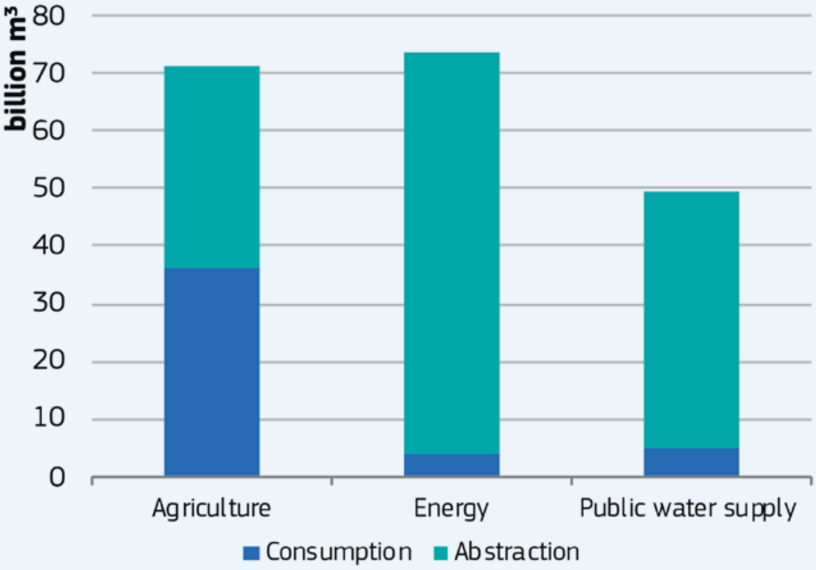
The JRC analysis [Medarac et al. 2018] quantifies specifically, by sector and by location, the amount of water currently used by the EU energy system, as well as the expected energy-related water demands up to 2050 based on the Energy Reference Scenario published by the European Commission in 2016 [Capros et al. 2016]. The same methodology could be applied to consider new EU energy scenarios (such as those used for developing the 2050 strategic long-term vision [European Commission 2018a]) once they become publicly available.

comparison, the data for 2015 reported by countries to EUROSTAT are incomplete, e.g. only 12.5 billion m^3 for electricity (cooling) and mining, while for 2010, EUROSTAT reported a larger value, 70.5 billion m^3. The JRC study [Medarac et al. 2018] estimated that the total freshwater withdrawal by the EU energy sector in 2015 amounted to 74 billion m^3, exceeding withdrawals for public water supply [Eurostat 2018], and agriculture [Vanham & Bidoglio 2013], as shown in Figure 6. Similarly, the reported EUROSTAT water abstraction from agriculture is of 11 billion m^3 for 2015, while JRC estimates suggest that it is around 71 billion m^3 [Vanham & Bidoglio 2013]. It shall be stressed that in terms of water consumption, the agriculture sector is the main consumer of water resources.

As a result, employing the data available from EUROSTAT would lead to a significant underestimation of the impact of the EU energy system on freshwater resources, both in terms of EU energy system water use, and in terms of assessing the potential conflict of water resources with other sectors. This confirms similar assessments by the EEA:

> *Incomplete information about how energy and water interact at different scales means that policies (whether they be education campaigns, economic subsidies, stringent regulation, new infrastructure, etc.) designed*

Figure 6. Comparison of water abstraction and consumption for energy (JRC analysis [Medarac et al. 2018]), agriculture (JRC analysis, [Vanham & Bidoglio 2013]), public water supply ([Eurostat 2018]).



> *to increase efficiency in one sector may be creating additional demand in the other sector. With better data, utilities and governments can effectively strategize how they will plan to manage their energy and water use with minimal effect to their citizens. [Jacobsen 2014].*

Only 6 % of the water withdrawn by the energy system is consumed, with the remaining part returned to the hydrological system, for example water discharged from a cooling system at a higher temperature to downstream rivers or water turbined in hydropower plants. In comparison, the water abstracted for human consumption is treated and returned as treated wastewater to downstream water bodies.

In Figure 7, the water exploitation index of the energy sector is compared with the total water exploitation index of each EU country, showing that the Mediterranean appears as the primarily water stressed region. However, the WEI+ of the energy sector represents only a small fraction of the total. On the other hand, some countries such as Poland, Czechia, Bulgaria, Germany, France and Romania have a high energy-related index, suggesting that water requirements from the energy sector have a

Figure 7. Water Exploitation Indexes (for energy and total) based on reported data [Eurostat 2018]

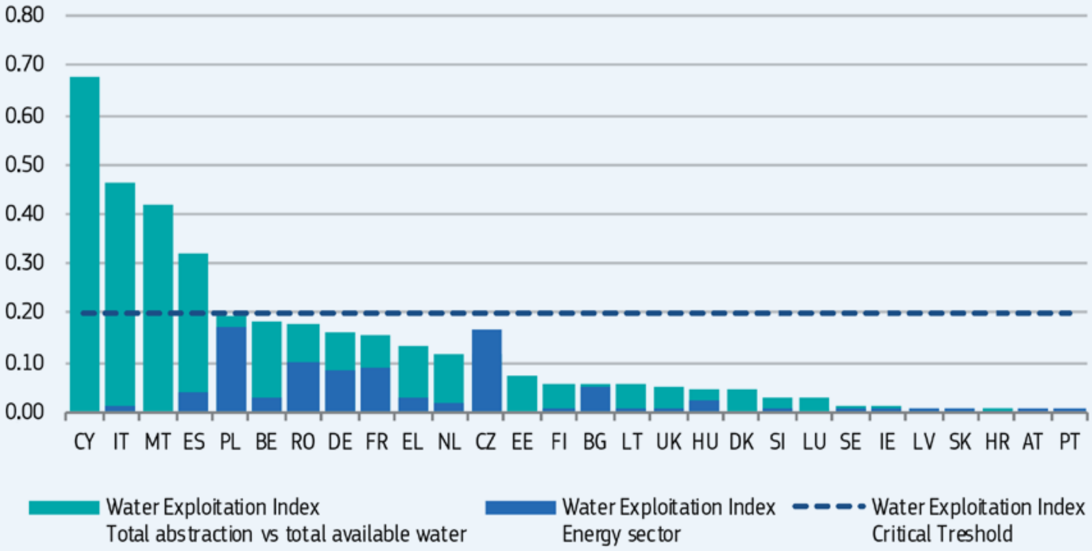
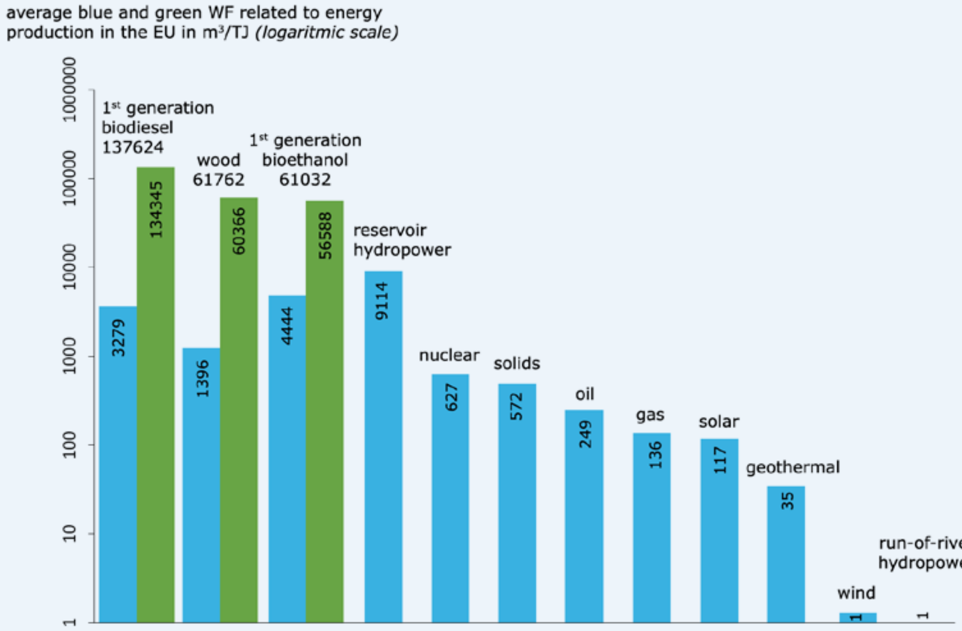


Figure 8. Average blue and green WF related to energy production in the EU (m³/TJ) for the three stages in the energy production chain (fuel supply or energy production; construction; and operation of power plants). Note the logarithmic scale.



Operation	0	547	0	9113	567	437	175	130	27	33	0.2	0
Construction	1	1	1	1	0.3	1	1	1	90	2	1	1
Fuel supply	3278 134345	848 60366	4443 56588	0	60	134	73	5	0	0	0	0

significant impact on the total WEI+, and that the energy sector may be particularly vulnerable to water scarcity.

2.4.1 The water footprint of the EU energy sector

The water footprint (WF) is an estimation of the amount of water consumed along a supply chain [Hoekstra & Mekonnen 2012], which is used to produce a more complete accounting of the water resources required to produce goods and services [Vanham 2018]. Employing the WF to assess the impact of the EU energy sector on water resources would allow a complete quantification of the water requirements, needs and consumption of all energy processes, including biofuels and hydropower.The WF includes a blue and green water component. Blue water refers to liquid water in rivers, lakes, wetlands and aquifers; whilst the green component refers to water held in the soil and available to plants.

The green WF quantifies evapotranspiration from plants from soil water. Irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), while rain-fed agriculture receives only green water. Energy resources that require both blue and green water include biofuels and wood [Schyns & Vanham 2019].

A differentiation needs to be made between the WF of EU energy production, which quantifies consumptive water use of domestic freshwater resources for energy produced in the EU, and the WF of EU energy consumption. The latter quantifies the consumptive water use of domestic and foreign freshwater resources for energy consumed in the EU. The use of foreign water resources comes from imported energy sources, for example oil, wood, biodiesel from palm, or imported solar panels. It can then be expected that the WF of consumption is larger than that of production, as more than half of the EU-28's gross inland energy consumption is supplied by net imports[28].

The average blue and green WF related to energy production in the EU differs substantially according to energy source. Figure 8 shows the average consumptive water amounts required in the EU for the three different

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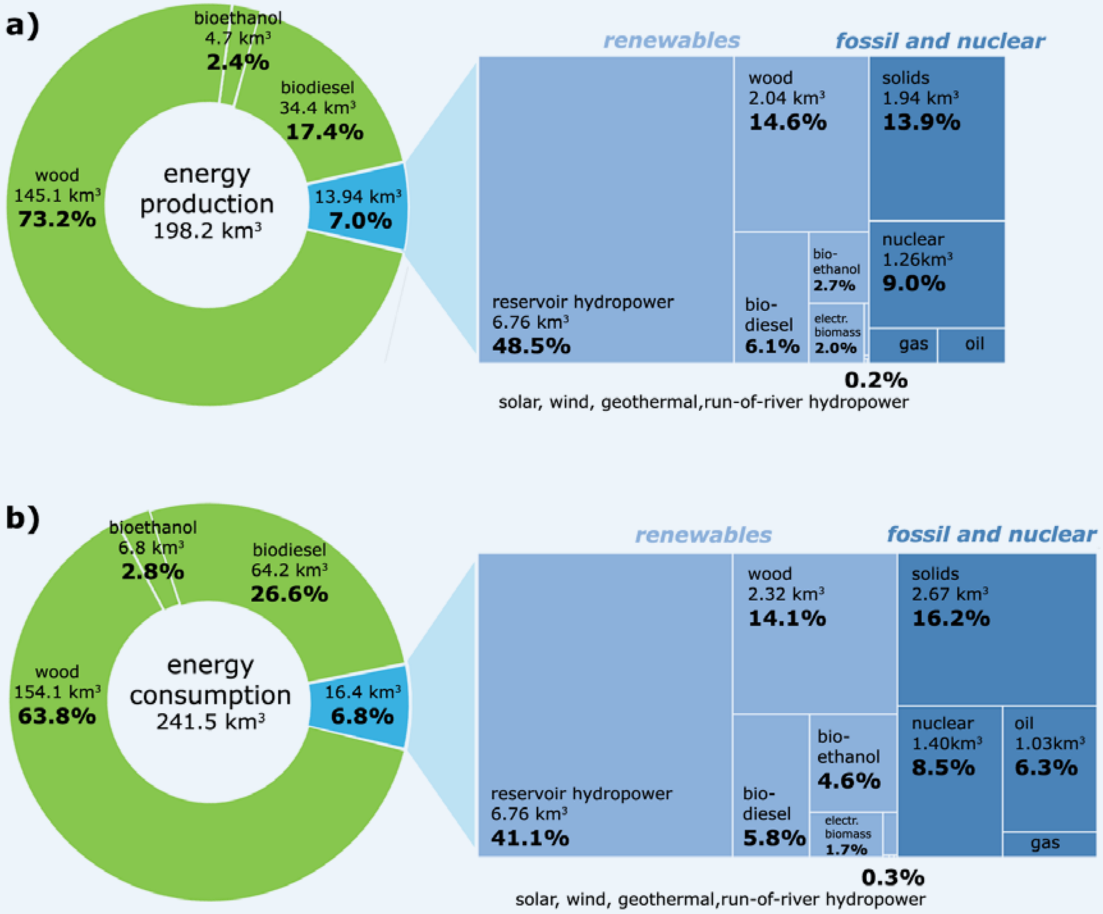
[28] https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_production_and_imports#More_than_half_of_EU-28_energy_needs_are_covered_by_imports

stages of the production chain expressed in m³/TJ [Vanham, Schyns et al. 2019]. The first stage is fuel supply or energy production (which in this analysis includes oil refining), the second stage is the construction, and the third stage is the operation of power plants. It can be observed that particular renewable energy sources are the most water-efficient in terms of water consumption: solar, geothermal, wind and run-of-river hydropower [Vanham 2016]. The least water efficient renewable energy sources are biofuels, wood and reservoir hydropower. The latter WF is high (average 9 113 m³/TJ) as much blue water evaporates from reservoirs during storage in the operation phase (6.8 billion m³/year, which is 9 % of the energy-related withdrawals in 2015).

The usual quantifications of the volume of water consumed by the energy sector, which is what drives the operational constraints, yield much lower values than the WF analysis. Whereas the amount of water consumed by the energy sector in 2015 estimated by [Medarac et al. 2018] amounted to 4 billion m³, Figure 9 shows that the total green plus blue WF of energy production in the EU (year 2015) amounts to 198.2 billion m³/year, 50 times more. The WF of energy consumption was 241.5 billion m³/year. For the whole EU population, those WF values are equivalent to 1 068 and 1 301 litres per person per day [Vanham, Schyns et al. 2019]. That is approximately four to five times the average municipal water requirements per capita. By far the largest part of these amounts is accountable to green water and a smaller part to blue water. Renewables make up a higher amount of the total blue WF as compared to fossil fuels and nuclear energy.

Estimating the WF resulting from scenarios of a more decarbonised EU energy system would provide a deeper assessment of the implications of the decarbonisation on water resources, enhancing policies for water conservation and management, and ensuring that a reduction in carbon footprint does not translate to an increased water footprint.

Figure 9. Green and blue WF of energy production (a) and WF of energy consumption (b) of the EU, in billion m³ (or km³) in the year 2015.



2.5 Energy needs of the water sector

Energy drives every element of the water cycle [Lazarova et al. 2012]. According to the IEA, the energy requirements of the water sector in Europe amounted to around 80 TWh in 2014 [International Energy Agency 2016], similar to the gross electricity generation of Belgium. This energy is used by the public water sector, which comprises the supply of drinking water, desalination for municipal use, and wastewater treatment. The EU public water sector requires about 2.6 % of EU electricity consumption, in line with other estimates [Jacobsen 2014, EURACTIV 2018] and the figures reported by the IEA [International Energy Agency 2016]. Energy (mostly electricity) consumption from the water sector in the US is at a similar level, 4 % of the total [Electric Power Research Institute 2002], though it has been indicated that through energy-saving measures the energy footprint of the water sector could be reduced to 2 % or less [Sowby 2016].

A breakdown of the energy needs of different domains of the water sector is presented in Table 1. Desalination accounts for 25.7 % of the electricity consumption from the water sector, but accounts for 2 % of the treated water volume.

Table 1. Breakdown of volume treated and energy requirements for each stage of the water sector in 2017. (Source: water volumes: [Eurostat 2018], [GWI 2018], analysis: JRC)

Domain	Volume (billion m³)	Energy (GWh)	Energy (share)	Share of EU electricity
Drinking water supply	49.5	35 000	43.5 %	1.13 %
Desalination for municipal use	2.1	20 695	25.7 %	0.67 %
Wastewater treatment	47.9	24 747	30.8 %	0.80 %
Total	99.5	80 442	100 %	2.60 %

Water treatments, for drinking and wastewater, account for a significant share of municipal energy bills (30-50 %) [International Energy Agency 2016]. Up to 25.7 TWh could be saved in the water sector through the implementation of energy efficiency measures, operational optimisation of treatment plants, and addressing leakages and losses in the water network, as shown in Figure 11. The implementation of these measures in the water sector could help the EU meet the energy efficiency targets set for 2020 and 2030.

A high-level analysis of the energy requirements of the various stages of the water sector is presented in sections 2.5.1, 2.5.2 and 2.5.3.

2.5.1 Drinking water supply

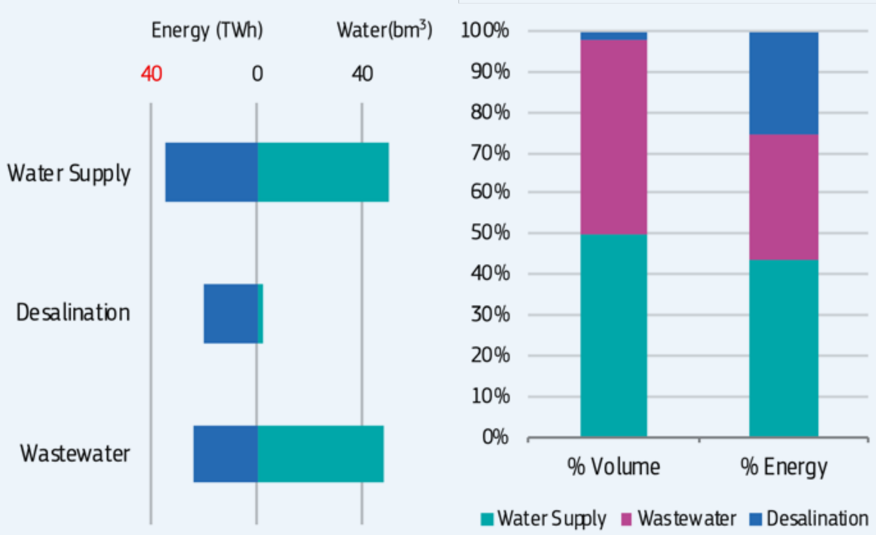
In the EU, each year 49 billion m^3 of freshwater are abstracted for public water supply [Eurostat 2018]. Distribution and treatment account for most of the energy consumed for supplying drinking water. Benchmarking of energy consumption from water utilities undertaken for selected regions in Europe shows that electricity consumption for water supply is in the range 0.5-0.7 kWh/m^3 in Germany, 0.2-0.6 kWh/m^3 in Denmark and 0.7-0.93 kWh/m^3 in Sweden, with a median value of 0.76 kWh/m^3 [Jacobsen 2014]. In order to provide 245 litre/day/person of water, the total electricity consumption for drinking water supply amounts to 35 000 GWh, which represents 1.13 % of the electricity currently produced in the EU, or approximately 70 kWh/year/person.

2.5.1.1 Energy-saving potential for drinking water supply

The transportation of water is one of the most energy-intensive processes within the water industry. Operation costs of water pumps are blamed for a large share of the electricity bill associated with running a water distribution system [Bagloee et al. 2018], with water distribution representing 60-80 % of public water supply energy consumption [Danfoss 2018]. In Europe, the cost of electricity for water supply ranges between EUR 2.9 and EUR 3.9 billion a year. In the city of Milan, Italy, the billing cost of pumping water to 50 000 customers was around EUR 16 million per year [Castro-Gama et al. 2017].

Estimates indicate that savings of 10–30 % are possible through combinations of operational and capital measures, which include addressing water

Figure 10. Energy needs for the different parts of the water sector in 2017 (source: JRC).



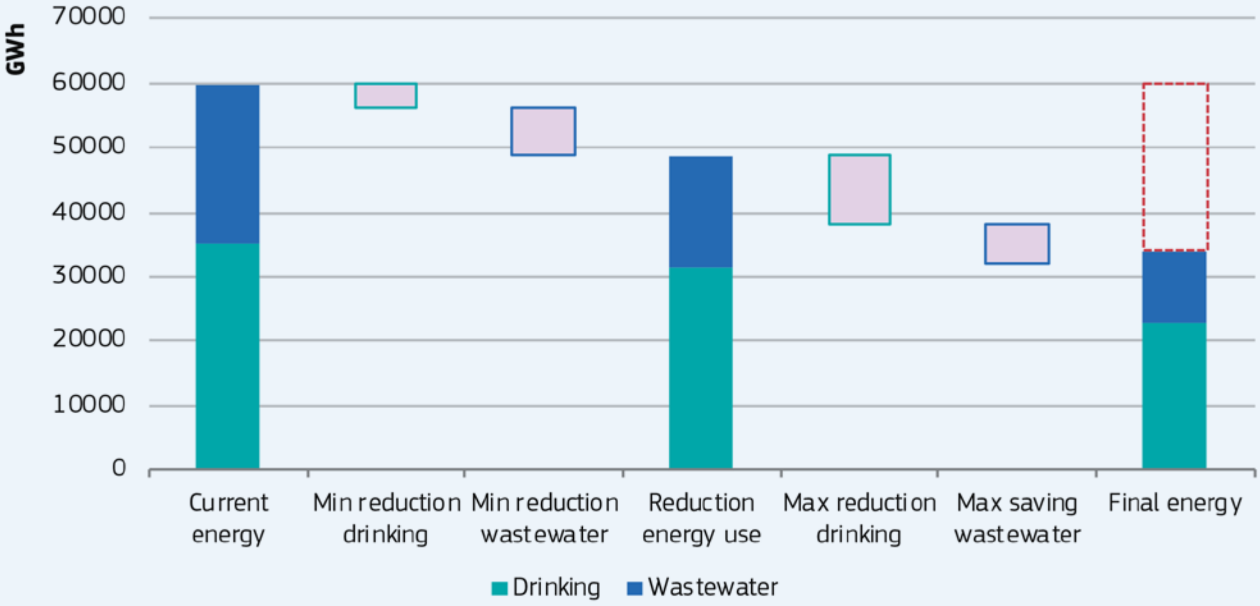
losses and leakages, implementing restrictions on water consumptions [European Environment Agency 2018], and improving pumps and pressure in distribution networks.

Water losses in Europe range between 25 % in Italy and 8 % in the Netherlands [PWC 2018]. Water leaks reduce the availability of clean water and increase the amount of energy needed to transport the water. An energy saving of 25-40 % can be achieved by boosting pumping stations [Danfoss 2018]. A 26 % reduction in the electricity consumption of the water supply system was achieved through optimisation of the operations of the pumps in the city of Milan [Castro-Gama et al. 2017].

2.5.2 Wastewater treatment

Wastewater treatment is an essential public service that has a major impact on energy use in the urban water cycle. A detailed analysis of the energy consumption in EU wastewater treatment plants (WWTPs) has been undertaken on the basis of the information reported by the EU Member States compliant with the Urban

Figure 11. Potential energy saving in water supply and wastewater treatment achievable through energy efficiency and operational measures.



Wastewater Treatment Directive 91/271/EC [Ganora et al. 2019]. The database contains information on 19 074 plants with actual load equal or greater than 2 000 Person Equivalent (PE) and a total capacity of about 569 million PE.

The overall WWTP energy use in Europe was estimated at 24 747 GWh per year [Ganora et al. 2019], which is about 0.8 % of the electricity generation in the EU in 2015 (Eurostat, 2017). Small plants (less than 50 000 PE) represent almost 90 % of the total number of plants, but they process only 31 % of the PE and absorb 42 % of electricity use. Mid- to very large-sized plants (more than 50 000 PE) process about 70 % of the PE with 58 % of the total electricity use.

2.5.2.1 Energy-saving potential for wastewater treatment plants

The main difference between water treatment plants and WWTPs, besides the type of treatment, is the potential of the WWTPs to generate at least the amount of energy they consume. The most easily exploitable source of energy in a WWTP is the biogas produced in the anaerobic digestion of sludge, yielding both thermal and electric energy [Gude 2015, Coats & Wilson 2017].

A benchmark study of the performance of wastewater treatment plants has identified savings of about 13 500 GWh/year for WWTPs [Ganora et al. 2019] through the implementation of stringent targets for efficiency improvements. This includes, for example, the use of more efficient equipment, such as upgraded blowers for the aeration of the biological stage. Operational improvements may be equally important.

Although several energy-neutral or energy-positive plants have been demonstrated at full scale of operation, they are not yet the norm. A large-scale transition in this direction requires significant investments, usually possible only for new plants or major overhauls (and primarily for plants larger than 50 000 PE), and should be placed in a broader context. Significant improvements in the energy neutrality of plants have been reported for Germany and Austria [DWA 2016], and more recently in Denmark (Aarhus Marselisborg Wastewater facility) [International Energy Agency 2016].

2.5.3 Desalination for municipal use

In the EU, a small fraction of freshwater is obtained through seawater desalination. EU facilities can supply up to 2.89 billion m^3 of desalted water a year (active capacity). Nevertheless, only 71 % of the water produced is used for public water supply (2 billion m^3, 4.2 % of total water employed in public supply). 17 % of the desalinated water produced is used for industrial applications, 4 % in power plants, and 8 % for irrigation.

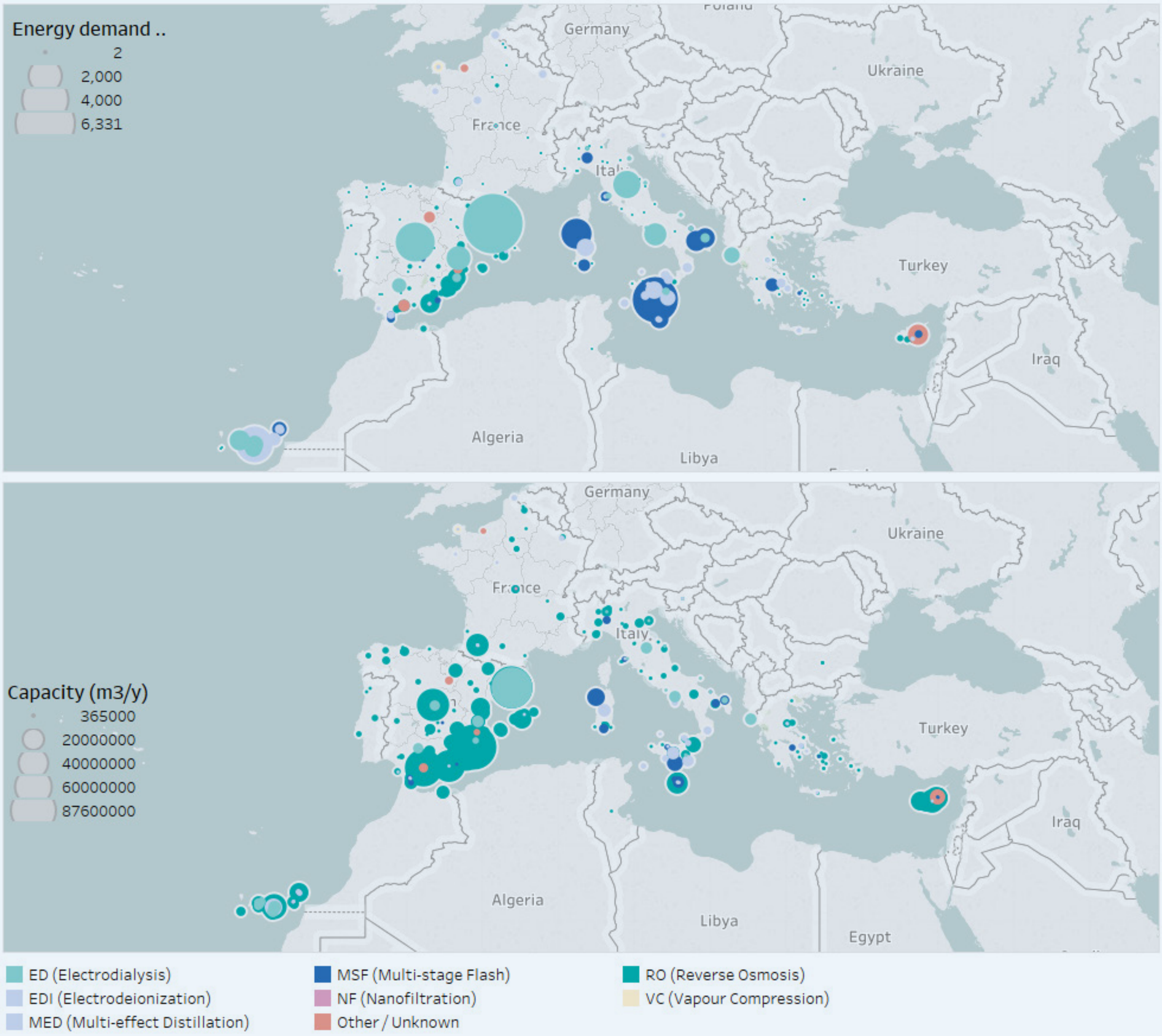
The electricity requirements of desalination technologies vary according to the desalination technology, the salinity of the source water, and the level of purity of the desalted water at the end of the treatment. In general, membrane desalination technologies such as Reverse Osmosis (RO) have lower energy requirements than thermal technologies such as Multi Stage Flash (MSF). MSF systems require roughly 83-84 kWh/m^3 of energy; while large scale RO systems require 3-5 kWh/m^3 for saline water and 0.5-2.6 kWh/m^3 for brackish water [Olsson 2012]. In Europe, 91 % of the operational desalination plants employ membrane technology [GWI 2018].

The electricity required by the desalination facilities providing water for public supply is 21 TWh (0.67 % of the total electricity consumed in the EU, 25.7 % of water sector electricity consumption).

There are 1 200 operating facilities located in EU Member States across the Mediterranean Sea (where most desalination plants are located and where it will mostly be needed in the future), with a capacity of 2.37 billion m^3 (82 % of total EU desalination capacity). In the Mediterranean region, desalination is a key technology for the provision of public water supply. Desalination facilities in the Mediterranean account for 95 % of the capacity employed for municipalities and tourist facilities (1.88 billion m^3/year) for a total electricity demand of 20 TWh (Figure 12).

System improvements and energy efficiency measures suggest that energy consumption of RO systems may be reduced to 1.5 kWh/m^3, thus reducing the energy demand of the desalination sector by about 55 %, without considering pre- and post-processing of desalted water [Olsson 2012].

Figure 12. Desalination facilities across EU Member States in the Mediterranean region expressed in terms of energy consumption (GWh/year – top) and freshwater production (m³/year – bottom)



2.5.3.1 *Future outlook of desalination in Europe*

Desalination may provide a viable solution to alleviate water scarcity in many European regions. The International Energy Agency has estimated that at global level, the energy consumption of desalination is expected to increase eight-fold by 2040, due to increased demand for freshwater [International Energy Agency 2016].

Most of the new desalination capacity is expected to be installed in the Middle East and Northern African regions. However, under the assumption that desalination demand will increase by a similar ratio in the EU, desalination capacity could reach 28 billion m³/year, equal to 150 litres of water per person per day. Nevertheless, this value may represent the ceiling in terms of new desalination capacity to be deployed in Europe. The implementation of restrictions on water consumption, environmental impacts related to desalination technologies and the energy requirements of desalination may contain new desalination demand in the future.

Investigating the use of renewable energy sources, in particular solar PV, for power desalination facilities in the Mediterranean would provide a valid alternative to the reduction of the energy requirements of the desalination sector. Examples of PV-powered desalination plants are the Ghantoot plant in Abu Dhabi [Tsagas 2017], and the Al Khafji plant in Saudi Arabia [Laursen 2018]. Technical and economic factors drive the uptake of renewable-driven desalination [Caldera et al. 2016]. The integration

Box 2. Desalination technologies

Desalination techniques can be divided into two main categories:

i) Thermal Desalination, which employs heat to separate salt from water, and

ii) Membrane Desalination, employing membrane to separate water and salt.

Thermal desalination comprises a number of different distillation techniques such as Multi Stage Flash (MSF), Multi Effect Distillation (MED) and Vapour Compression (VC). Membrane technologies include Reverse Osmosis (RO), Electro-dialysis (ED), Electro-deionisation (EDI) and Nanofiltration, which is normally applied to brackish water.

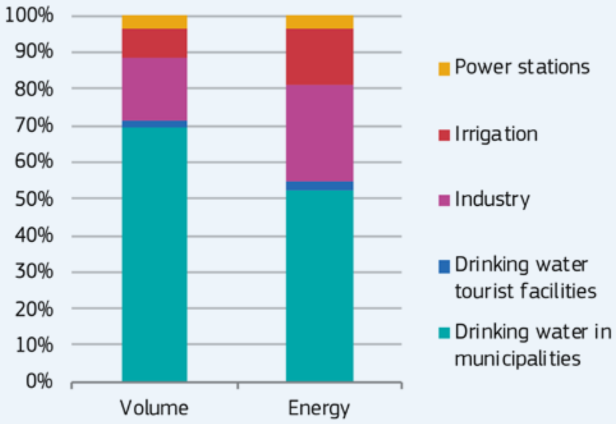
Energy requirements for thermal desalination are significantly higher than those of membrane systems (such as reverse osmosis, widely used in the EU). RO accounts for 91 % of EU desalination capacity and MSF for 7 %.

of renewable energy sources to supply up to 100 million citizens with water is investigated in section 4.3.

2.5.3.2 Desalination for industrial and irrigation purposes

In order to provide a complete overview of the total energy used by desalination facilities, it should be noted that desalination is not only restricted to the provision of public water supply. Desalination facilities are also employed to provide water for the operation of refineries, power plants and other industries, often as a process fluid. In water-scarce areas, desalination is used as a supplement to freshwater resources for irrigation (agriculture).

Figure 13. Impact of industrial and agricultural desalination facilities in Europe in terms of volume (left) and energy requirements (right).



Desalination facilities for industries and irrigation provide 0.82 billion m^3/year of desalinated water (30 % of the total EU desalination capacity) and require some 17 TWh a year of electricity (and thermal energy) to operate. The energy needs of agricultural and industrial desalination facilities are close to those of the public water supply (Figure 13).

This is related to the technologies employed and the higher requirements for process water (low saline concentration). Thermal desalination is mostly used for industrial uses, as well as in oil refineries and power plants, where waste heat may be recovered for these purposes.

3

THE SUSTAINABILITY OF THE EU WATER-ENERGY SYSTEM UP TO 2050

3.1 Long-term freshwater needs from the EU energy sector

Both water withdrawals and consumption are expected to decrease significantly during the period 2015-2050 [Medarac et al. 2018], due to the projected decarbonisation of the EU energy system and the announced closures of nuclear and coal-fired power plants and coal mines throughout Europe[29]. The estimated amount of water withdrawn by the energy sector (for primary energy production, oil refining, and cooling of thermal power plants) would decrease by 38 %, from 73.5 billion m^3 in 2015 to 46 billion m^3 in 2050. Water consumed by the whole energy sector is expected to decrease by 27 %, from 3.8 billion m^3 in 2015 to 2.7 billion m^3 in 2050. Hydropower relies on water passing through turbines to generate electricity, while also serving as a major source of global energy storage. Most of the water withdrawn by hydropower plants is returned to the water system. The water consumed by hydropower plants is site-specific and there is no agreement to estimate it [International Energy Agency 2016]. The water consumed by hydropower plants due to increase slightly to 6.9 billion m^3/year, since hydropower output from reservoirs is expected to increase slightly (less than 3 %) during the period 2015-2050 [Capros et al. 2016]. These figures are in line with other recent estimations available [International Energy Agency 2016, Larsen & Drews 2019].

Table 2. Projected water use from the EU energy sector (rounded figures, billion m^3) [Medarac et al. 2018]

Sector	**Withdrawals**		**Consumption**	
	2015	**2050**	**2015**	**2050**
Energy	74	46	4	3
Of which **Energy production**	**21**	**9**	**1**	**0**
Solid fuels	21	9	1	0
Oil	0	0	0	0
Gas	0	0	0	0
Of which **Energy transformation**	**52**	**37**	**3**	**2**
Oil refining	0	0	0	0
Power generation	52	36	3	2
Nuclear power plants	31	20	1	1
Solid-fired power plants	16	5	1	1
Oil-fired power plants	0	0	0	0
Gas-fired power plants	5	11	0	1
Biomass power plants	0	1	0	1
Geothermal power plants	0	0	0	0

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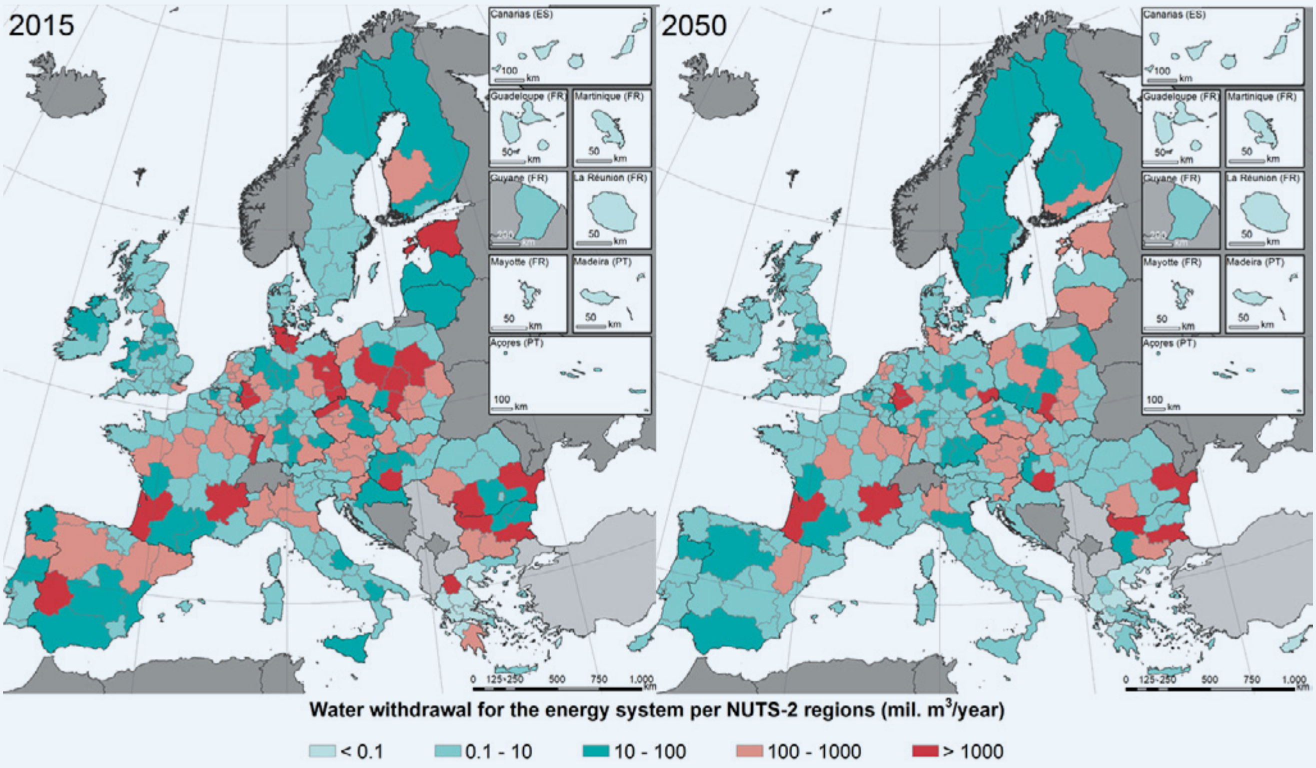
[29] The energy scenario used in this analysis expects that by 2050, more than half of solid-fuelled generation (approx. 66 %) will be produced from facilities with installed CCS technologies; but overall power generation from solids, including CCS, would only represent 5.1 % of total net generation in 2050. The share of biofuels in final energy demand would grow from 4 % in 2010 to 6 % in 2050.

However, the expected reductions will not eliminate all the criticalities at the regional level, as the estimated regional breakdown of the energy system freshwater withdrawals for 2015 (left) and 2050 (right) shows (Figure 14). An aspect of this analysis to be highlighted is that studies on water availability and policy implementation take place at hydrological units (water regions) whilst energy policies are implemented at national and regional level (NUTS2 administrative boundaries). Discrepancies in boundaries should be considered to ensure that criticalities in water availabilities are taken into account by both energy and water policies.

Figure 14. Regional energy-related freshwater withdrawal for 2015 and 2050.



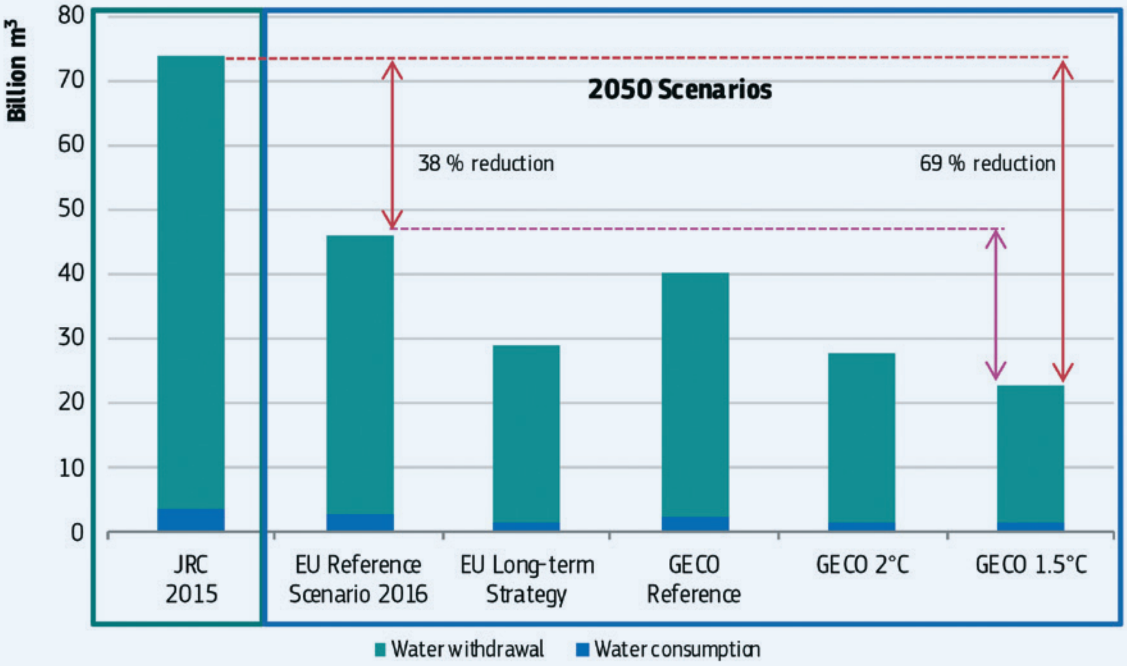
Moreover, the expected water requirements of the energy sector by 2050 would amount to the current freshwater demand for public water supply. Therefore, the energy sector will still be a major user of water resources.

In order to achieve a carbon neutral Europe by 2050 without jeopardising water resources, the switch to a low carbon energy system would have to be managed with care, taking into account the water needs of the different energy technologies, since some low-carbon options (e.g. nuclear or some bioenergy systems) could use water more intensively than the system they replace.

In this context, the trade-off between different technologies, in terms of water requirements and CO_2 emissions, should be taken in consideration. For example, the IPPC report on the impact of global warming [IPCC 2018] suggests that Carbon Capture and Sequestration (CCS) will be required in order to keep the global temperature rise below 1.5 °C. Yet, CCS technologies are associated with significant water requirements, which could lead to a doubling of freshwater demand for cooling of fossil fuel-based power plants coupled with CCS [Byers et al. 2015]. Another example is the crucial role that hydrogen may have in a decarbonised energy system. In the European Commission Long Term Strategy, hydrogen could account for up to 16-20 % of the total EU energy share, mostly in the residential and transport sectors, and could provide additional solutions for long-term energy storage. Supplying the equivalent of 1.6-2.3 TWh of hydrogen would consume 1.2-1.4 billion m^3 of freshwater, equal to a third of the total water consumed in the energy sector today [Moya et al. 2019].

Figure 15 shows that overshooting the 1.5 ºC limit (based on the JRC's Global Energy and Climate Outlook (GECO) [Keramidas et al. 2018]) will make climate-resilient

Figure 15. Alternative 2050 estimations of the projected water use by the EU energy system ([Capros et al. 2016, Keramidas et al. 2018, Medarac et al. 2018])

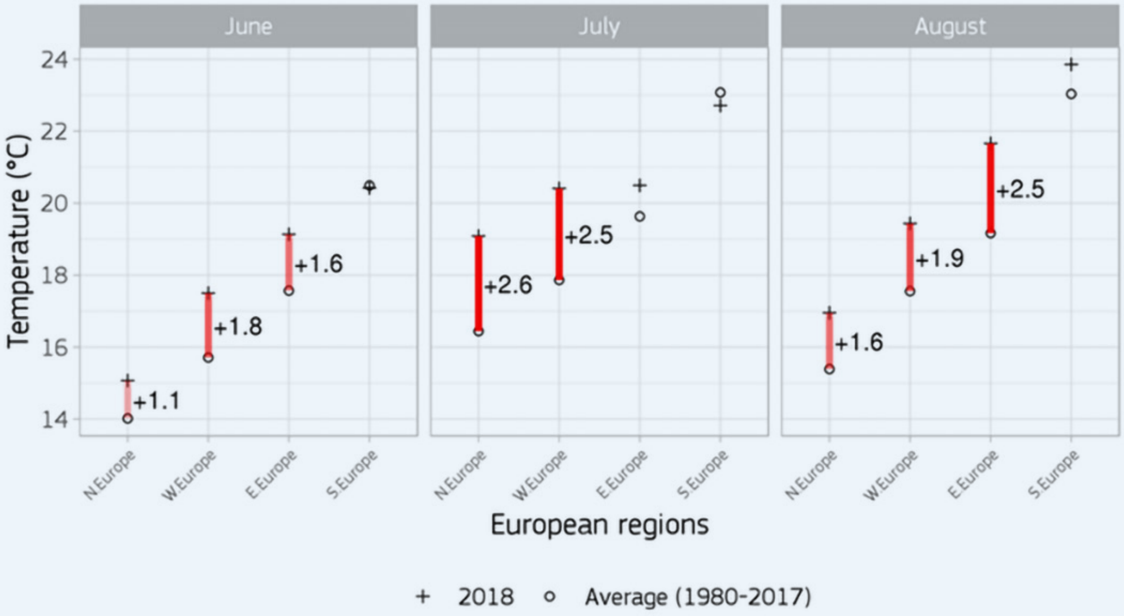


development pathways more elusive and impacts on water-energy-food-biodiversity links more difficult to manage. The GECO 1.5 ºC scenario is associated with a 69 % reduction of water needs from the energy sector by 2050 with respect to 2015, compared to the 38 % derived from the EU Reference Scenario 2016, which are in line with the requirements from the GECO reference scenario.

3.2 Generation adequacy in the EU power system

The events which occurred throughout Europe during the summer of 2018 are an example of the influence of water resources on generation adequacy in the power system; that is, the ability of the system to match supply and demand of electricity. From June to July 2018,

Figure 16. Average temperature in summer 2018 compared with long-term average (1980-2017)[30]



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[30] Data from E-OBS gridded dataset v17.0.

most European countries experienced a period of hot weather and lack of precipitation, particularly intense in northern and central Europe, as shown in Figure 16. The combination of drought and high temperature stressed power systems across Europe, affecting the operations of many power plants and transmission lines in several regions identified as having vulnerable to severe weather by the WEI+ analysis seen in section 2.4.

In France and Germany, many coal and nuclear plants could not operate normally due to the high temperature of the river water used for cooling. The flow of the Rhine and Rhone rivers decreased significantly (considering the time series from 1950), and many power plants along those rivers had to limit their generation to reduce the discharge of the warm after-cooling water. In July 2018, EDF was forced to reduce nuclear production[31], curtailing the output of reactors at Fessenheim 2, reducing the available capacity from 900 to 400 MW, and stopping Bugey 3 reactor (900 MW). In other cases, EDF extended the planned outages, including Bugey 2 (900 MW) and St. Alban 1 (1 300 MW). The same plants were also closed in the summer of 2015, showing an increasing vulnerability of energy plants to water scarcity and the temperature of cooling waters.

The impact of the high temperature of the Rhine also affected German plants: the Grohnde and Brokdorf nuclear reactors in the northern regions had to reduce their output, as did coal and gas plants. Similar issues also affected Switzerland, where output was reduced at the Beznau nuclear reactor because the river water temperature reached the maximum permitted by national regulations.

The impact of water was not limited to rivers; some nuclear reactors in Finland and Sweden, which use sea water for cooling, were also affected. Due to the warmth of the sea water, an event very unusual in this part of Europe, the Finnish Loviisa 2 reactor reduced its output and the Swedish Ringhals 2 900 MW unit was shut down.

The lack of water resources also affected hydro-power generation. For instance, according to the data from the ENTSO-E Transparency Platform, hydropower generation was 38 % lower in Sweden in July 2018 than in July 2017, while the energy stored in water reservoirs was 13 % lower.

Apart from the impacts on power generation, transmission and distribution, these weather-related water issues have an economic impact. For instance, during the heat wave that affected France in 2003 (with temperatures 20-30 % above average), electricity shortages were avoided, despite the shutting down or reduced output of 17 nuclear reactors due to lack of cooling. As a consequence, nuclear power output was reduced by 5.3 TWh over the course of the summer, and France halved the power exported to Switzerland, the United Kingdom, Italy, Belgium and Spain during peak hours [Aivalioti 2015, Añel et al. 2017], at an estimated cost of EUR 300 million [International Energy Agency 2012]. The annual damage produced by extreme climate events (heat waves, cold waves and droughts) on critical energy infrastructure is expected to increase from EUR 0.5 billion to EUR 1.8 billion per year by the 2020s, EUR 4.2 billion per year by the 2050s and EUR 8.2 billion per year during the 2080s [Forzieri et al. 2018].

According to the latest IPCC Assessment Report, water availability will be affected by climate change [Jiménez Cisneros et al. 2014] and land use and water consumption changes [Forzieri et al. 2017, Füssel et al. 2017, Bisselink et al. 2018] with a possible influence of global warming. Yet, future risks of weather-related hazards on human lives in view of climate and demographic changes have not been comprehensively investigated. Methods We assessed the risk of weather-related hazards to the European population in terms of annual numbers of deaths in 30 year intervals relative to the reference period (1981–2010. Changes in water quantities and temperature will have consequences on the energy sector, which will have to cope with impacts similar to those described above. The in-depth analysis in support of the communication from the European Commission, *A clean planet for all: a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy* [European Commission 2018a], warns that:

> *Thermoelectric generation will be under more pressure in Southern European regions where their water cooling needs may no longer be met: they may generate up to 20 % less under a 3 ºC scenario; 15 % less in a 2 ºC world. Thermal electricity generation may suffer most from water stress in the near term in the Mediterranean, France, Germany and Poland.*

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[31] https://www.reuters.com/article/france-nuclearpower-heatwave/french-nuclear-production-reduced-by-31-gw-due-to-heatwave-rte-idUSL5N-1UU5JG

While the magnitude of these impacts is not expected to jeopardise Europe's long-term decarbonisation path, it may entail higher costs and different regional energy mixes, unless adaptive measures are deployed, such as increased plant efficiencies, replacement of cooling systems and fuel switches. Private stakeholders in the energy system and EU and national policies should reinforce the right market framework to ensure that the climate impacts do not jeopardise the EU's stability and security of energy supply. Transitions in the electricity sector should encompass both mitigation and adaptation planning, if they are to sustain and secure a sustainable water–energy nexus in the next few decades.

The most recent assessments of the impacts of climate change on European freshwater resources, using JRC's LISFLOOD model [Bisselink et al. 2018], expect: i) a decrease in river flows in Southern and Eastern Europe (particularly in summer) and an increase in other regions (particularly in winter), ii) an increase in the reported number of flood events (mainly due to land use changes), iii) an increase in the frequency and intensity of droughts (particularly in Southern Europe), and iv) an increase in water temperature in rivers and lakes.

The projected future inflows into 835 major hydropower sites across Europe were examined. The European continent was divided into six regions, with an east-west division near Berlin, and north-mid-south divisions at Hamburg and Milan:

- SW – South West: Spain, Portugal, southern France, northern Italy
- MW – Mid West: France, Benelux, Germany
- NW – North West: United Kingdom, Ireland, Norway
- NE – North East: Sweden, Finland, Baltic States
- ME – Mid East: Poland, Czechia, Hungary, Austria
- SE – South East: Greece, Southern Italy, Croatia, Serbia, Romania, Bulgaria

According to the EURO-CORDEX initiative[32], temperatures are expected to increase as follows:

- For the period 2035-2064[33]: the average increase will be between 1.5 °C (RCP 4.5, mild emission scenario) and 1.9 °C (RCP 8.5, high emission scenario), with the highest expected increase in southern-eastern Europe.

- For the period 2071-2100: the mean annual temperature will range from 1.4 °C (the Atlantic region considering the RCP 4.5 emission scenario) to 6.2 °C (Northern Europe in the RCP 8.5) [Jacob et al. 2014].

In order to estimate the expected impacts of climate change on water availability for cooling thermal power plants, the projected inflows into 433 thermal power plants across Europe have been examined [Adamovic et al. 2018]. The method investigates the future projection of the 5th percentile streamflow (the 5 percent lowest discharges) as an indicator of sufficient freshwater for thermoelectric cooling, since, especially during low flow periods, there might be abstraction limitations to meet other constraints such as environmental flow and water temperatures.

Box 3. Description of climate scenarios

In order to evaluate the effects of climate change on Europe's water resources, 11 different EURO-CORDEX climate scenarios have been used as forcing within JRC's LISFLOOD water resources model. The results of three periods have been examined:

i) 1981-2010: representing the 'current' or reference climate.

ii) 2026-2055: a 30-year window centred on the year when the increase of global temperature reaches 2 °C above pre-industrial levels (on average the year 2040 for the high greenhouse gas scenario RCP 8.5). A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC for its fifth Assessment Report in 2014. With RCP 8.5, emissions continue to rise throughout the 21st century, reaching a radiative forcing value of 8.5 W/m^2 in 2100.

iii) 2070-2099: for a more extreme worst-case scenario and its effects, a further window, 2070-2099 under an RCP 8.5 emission scenario, was also investigated. This reflects a situation where the global temperature increase reaches 4.0-6.2 °C above pre-industrial levels.

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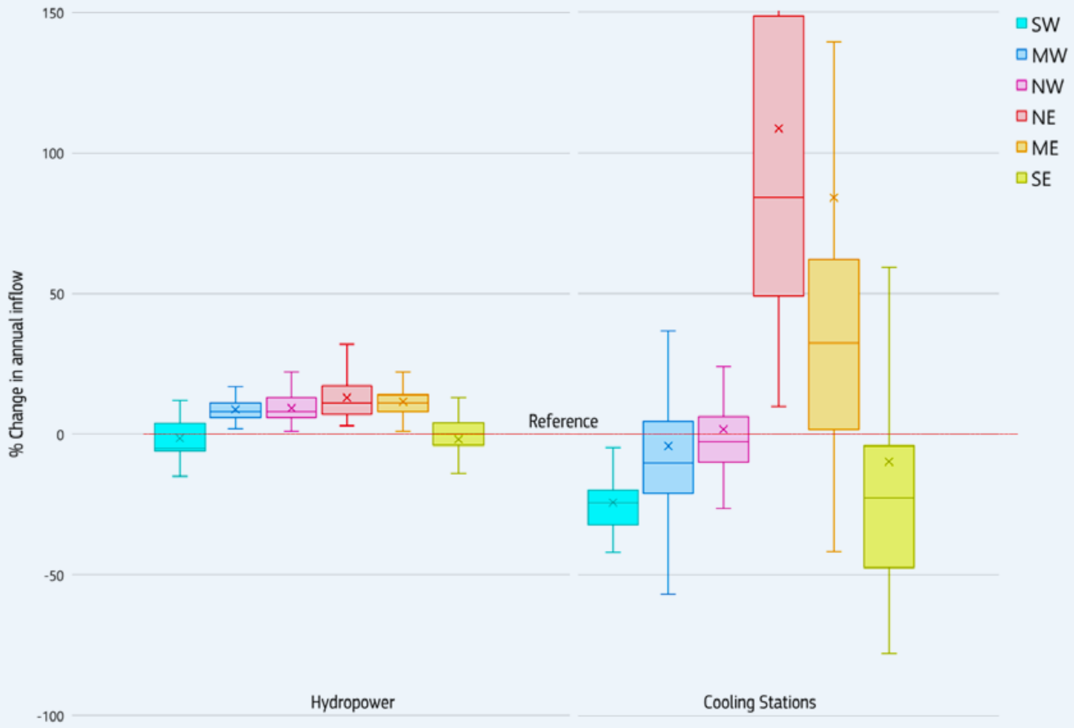
[32] EURO-CORDEX is one of the domains of the CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative, sponsored by the World Climate Research Programme (WCRP). CORDEX will produce ensemble climate simulations based on dynamical downscaling models forced by multiple global climate models.

[33] Data available on http://ecem.climate.copernicus.eu/demonstrator/.

In general, all the models expect a consistent increase in European air temperature over coming decades; this increase reaches 3 degrees for all months, and even more during summer, when we look at the worst-case emission scenario RCP 8.5 (high greenhouse gas scenario) [Riahi et al. 2011]. Those projections suggest that the disruption of some nuclear power plants in France and Germany observed during the summer of 2018 might become more common in future decades. Similar conclusions can be found in [Van Vliet et al. 2012, Van Vliet et al. 2013, Behrens et al. 2017].

Figure 17. The projected change in low-flow near hydropower (left) and thermo-electric (right) power stations, for the RCP 8.5 2070-2099 climate as compared to the current climate[29]



Overall, southern European countries are projected to face decreasing water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and northern European countries show increasing annual water availability. The extreme RCP 8.5 2070-2099 warming period displays the same spatial pattern as under the 2 °C warming period, but more drastic in the amounts of increasing and decreasing water availability.

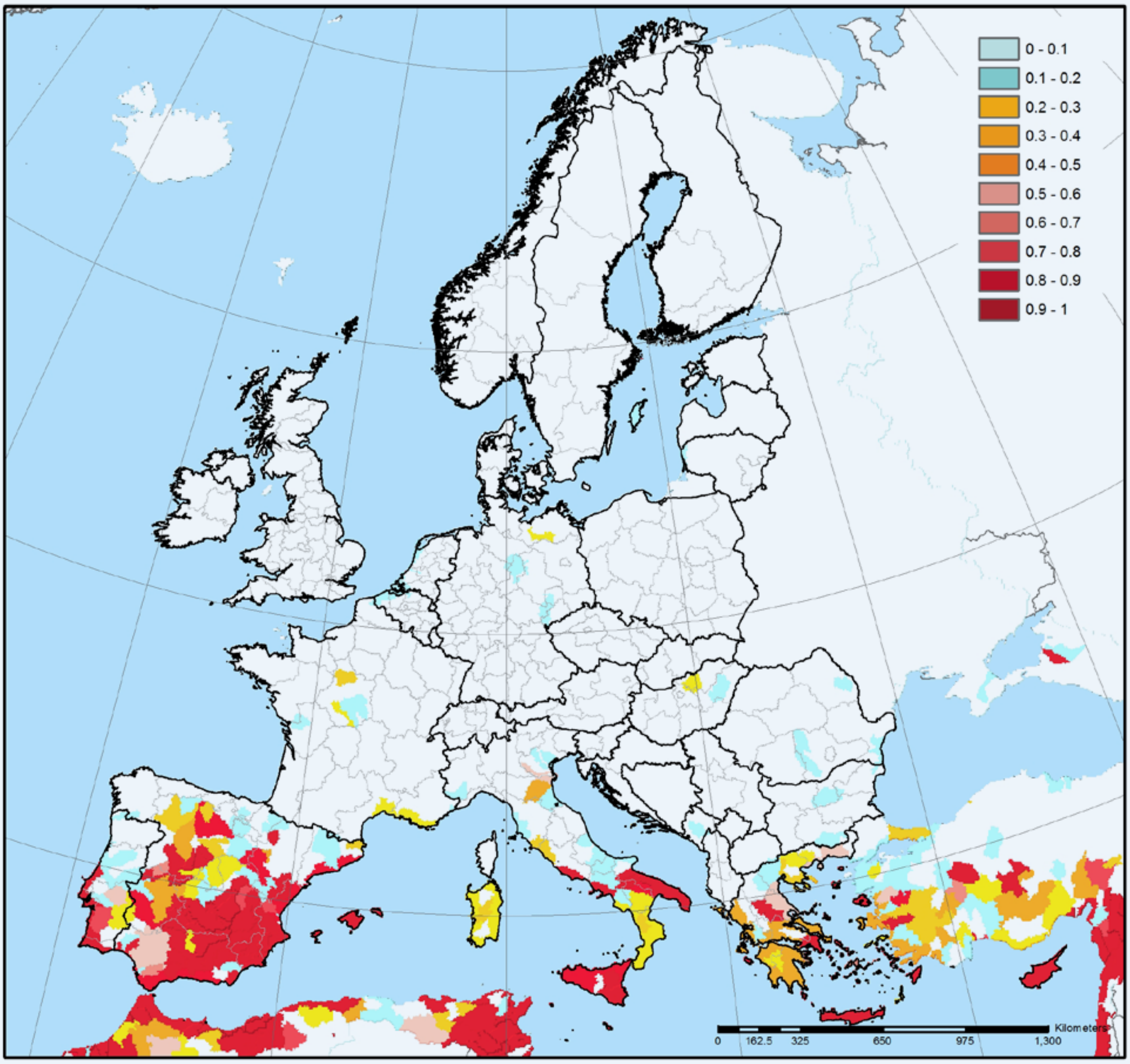
Seasonal analysis shows marked differences between summer and winter streamflow, especially in France, Belgium and the UK. These three countries are projected to experience wetter winters and drier summers, with increased water availability in winter, and decreased water availability over the summer months. The more severe warming scenario shows again the same spatial pattern as under the 2 °C warming period, but more extreme in the amounts of increasing and decreasing water availability.

Even in the present climate it is possible that there will be insufficient cooling water available during summer days, or that the temperature of the available surface water is too high to be used as cooling water. Figure 17 shows projected significant decreases of low flows of around 25 % in the SW and SE regions. For Scandinavian countries and eastern European countries the low flow numbers are increasing. For the end of the century RCP 8.5 climate scenario, a far more extreme picture is projected, with 12 % decreases in hydropower inflow in the SW region, and 10 % decreases in the SE region. For NE Europe, inflows would increase by around 28 %, potentially leading to widespread dam safety issues.

Figure 18 presents an overview of the average WEI+ in Europe for the 30-year period centred on 2050 under the RCP 8.5 scenario. It can be seen that critical levels of the WEI+ (>0.2) are likely to take place across the Mediterranean, but also in localised areas in France, Germany, Hungary, Northern Italy, Romania and Bulgaria. Coupling the results from LISFLOOD with analyses of the energy system would provide an initial overview of areas where water scarcity may increase the vulnerability of the energy system.

Furthermore, under the 2°C warming period it is projected that about 90 million people will be affected by water scarcity for at least one month per year, mainly in the Mediterranean countries [Bisselink et al. 2018].

Figure 18. Mapping of the average WEI+ for 2050 (2036-2065) under the RCP 8.5 emission scenario [Bisselink et al. 2018].



4 POSSIBLE OPTIONS FOR SOLVING WATER-ENERGY ISSUES IN THE EU

4.1 Technology options for reducing the water needs of the EU energy system

Whilst it is expected that by 2050 water use will reduce, the water needs of the energy sector will still be considerable, amounting to the current freshwater demand for public water supply, as seen in section 3. Taking into account how climate change may affect adversely water availability, and how water scarcity could lead to more frequent generation adequacy problems, it is advisable that technological options are investigated to reduce the water needs of the EU Energy system. These options could consist of:

- ***Increasing the shift from coal/nuclear to renewable power generation***. The decarbonisation of the energy system is expected to drive a significant reduction of water use by 2050 [Medarac et al. 2018]. Yet, active coal and nuclear power plants would account for 50 % of projected water use in 2050, based on the assumptions of the latest EU Energy Reference scenario [Capros et al. 2016]. Increasing the shift from coal and nuclear power plants to renewable energy sources would further reduce the water requirements of the EU energy system.

- ***Finding the proper trade-offs between open-loop and closed-loop cooling systems***. Closed-loop cooling systems withdraw less water, but consume more, than open-loop ones, and can thus reduce the water needs of the energy system [International Atomic Energy Agency 2012]. However the choice of a cooling system for a power plant depends on the availability of water resources in the vicinity throughout the year, on the temporal pattern of water and ambient temperatures, and on the local regulations defining the amounts of warm water that may be discharged, and its maximum temperature. The choice of closed-loop systems should be studied for new power plants, since the implementation of mandatory retrofits from open to closed-loop systems would not always be possible due to unsuitable locations, excessive capital costs, or the reductions in the net output (due to losses in efficiency and the need to run additional equipment) that would alter the economic performance of the power plant [US Department of Energy 2008].

- ***Use of dry cooling (air-based) and advanced cooling systems (with alternative cooling agents)***. Dry cooling systems use air instead of water as a cooling agent, eliminating the need for withdrawing and consuming water [World Nuclear Association]. Advanced cooling systems using new materials, improved airflow design and water recovery, additives (often phosphonates), or alternative cooling agents (such as brackish groundwater, liquefied petroleum gas, wastewater, or supercritical carbon dioxide) have lower water requirements and may represent a viable alternative in areas subject to water scarcity [Bushart & Shi]. However, capital requirements of dry cooling systems more than double those of water-based systems and reduce the overall efficiency of the power plants by approximately 5 % (that is, 1–2 % point reduction in overall plant efficiency) [Zhai & Rubin 2010].

- ***Waste heat recovery as a means of reducing cooling needs***. An option to reduce water withdrawal or consumption in cooling systems is to increase the use of waste heat for thermal applications such as district heating, heat for industrial applications, thermal desalination, and aquaculture [International Atomic Energy Agency 2012]. The use of new materials could enhance the conversion of heat to power in supercritical cycles, heat exchangers, anti-corrosion and anti-fouling pipes [US Department of Energy 2014], thus diminishing cooling needs.

- ***Smart water metering for data collection and process optimisation; improved data surveys***. The use of smart meters would help develop a more optimised power plant and water management system, reduce waste and leaks, and improve the information to be collected [Stewart et al. 2018]. This can also allow for the implementation of variable-speed cooling pumps for cooling systems. Improved data collection from different energy subsectors through periodic surveys would improve the gathering of information often needed for long-term planning [Beal & Flynn 2015].

- ***Use of alternative drilling and fracking agents instead of water***. Water needs could be reduced by recycling extracted groundwater, using wastewater and other alternatives such as carbon dioxide or liquid natural gas [Middleton et al. 2014, Scheyder 2014].

4.2 Technology options for saving energy in the EU water system

The current energy consumption of the water system is small, accounting for 2.6 % of the total electricity produced in the EU. Energy consumption, and the associated costs, may increase significantly in the future if the availability of water resources is reduced due to climate change, since the imbalances would be compensated by more desalination, wastewater treatment and water transfers (Figure 3) [International Energy Agency 2016].

Increasing electricity prices and energy efficiency targets are prompting investigations into ways to reduce the energy consumption of water supply, treatment and distribution systems. The water system could be powered by renewable energy sources, but there are other viable technological options that can be employed to reduce the energy needs of the water system. Potential and theoretical energy efficiency savings for water utilities have been studied extensively, and most estimates indicate that savings of 10-30 % are possible through combinations of operational improvements and investments [Sowby 2016]; whilst energy savings of up to 50 % can be identified in wastewater treatment plants [Ganora et al. 2019]:

- ***Addressing water losses and leakages***. In Europe, water losses range between 25 % in Italy to 8 % in the Netherlands [PWC 2018]. The use of old, poor infrastructures and dated technology result in significant amounts of water lost through leaks, reducing the availability of clean water, affecting pressure in pipes and increasing the amount of energy needed to transport the water, and the amount of water that needs to be distributed to meet demand.

- ***Implementation of voluntary or mandatory restrictions on water consumption***. Lower water demands would lead to lower energy demands. Measures to reduce demand could include the use of economic instruments; water loss controls; water reuse and recycling; increased efficiency of domestic, agricultural and industrial water use; and water-saving campaigns supported by public education programmes [European Environment Agency 2018].

- ***Improving pumps and pressures in the distribution networks***. Adapting the pressure by developing pressure zones and boosting pumping stations can achieve energy savings of 25-40 % [Danfoss 2018]. In 2015, Milan reduced the electricity consumption of the water supply system by 26 %, through optimisation of the operations of the pumps [Castro-Gama et al. 2017] which is supplied entirely by 26 pumping stations. The system currently supplies its 50 000 customers with 103 pumps which are actively operated during the day [3]. In previous years a pump scheduling algorithm has been proposed to the utility for a Pressure Management Zone (PMZ).

- ***Optimisation of Wastewater Treatment Plants operations***. If all plants that use more than the current EU average were shifted to the average value through optimised operation, the saving would be slightly more than 5 500 GWh/year [Ganora et al. 2019]. With highly stringent targets of efficiency improvement, savings of about 13 500 GWh/year could be expected [Ganora et al. 2019]. Energy may also be saved by using more efficient equipment, such as upgraded blowers for aeration of the biological stage. The impact of energy savings on wastewater treatment costs is difficult to evaluate due to variable energy prices. However, adopting the average cost of electricity of 0.11 EUR/kWh (EU average price for non-household consumer reported by EUROSTAT for 2017, as in the case of water supply), EUR 0.66-1.62 billion could be saved under the different scenarios evaluated in the study. Although several energy-neutral or energy-positive plants have been demonstrated operating at full scale, they are not yet the norm. A large-scale transition in this direction requires significant investments, usually possible only for new plants or for major overhauls (and primarily for plants larger than 50 000 PE), and should be placed in a broader context [Ganora et al. 2019].

- ***Employing Energy Efficiency indicators in the Water Sector.*** There are currently no prescriptions from the Energy Efficiency Directive for the water sector. Some associations and governments have undertaken initiatives to include water-related efficiency targets, asking water sector operators to meet these targets. [Jacobsen 2014]. Energy efficiency indicators for water treatment could be employed for benchmarking the performance of water and wastewater treatments facilities and increasing energy efficiency levels in the water sector.

4.3 The potential of desalination plants to integrate renewable power generation

Desalination may become an increasingly viable option for water supply, due to reduced availability of freshwater resources induced by climate change. This would be especially relevant in the Mediterranean region, where 3 800 facilities currently supply about 4.37 billion m^3 of desalted water per year, which corresponds to the needs of 70-80 million people. These desalination plants require 52 TWh/year of energy, of which over 20 TWh/year are necessary to power EU facilities. Energy requirements for thermal desalination are significantly higher than those of membrane system (such as reverse osmosis, widely used in the EU). Investigating the use of renewable energy sources, in particular photovoltaic (PV), would provide a valid alternative to the reduction of energy requirements by the desalination sector. However, although proven as technically feasible, solar-assisted desalination is still regarded as less cost-effective than, for example, hybrid solar/fossil fuel desalination [Li et al. 2013]. Yet, experience increasingly points to both PV and wind as promising energy sources for cost-effective desalination in spite of intermittency [Ma & Lu 2011, Shatat et al. 2013, Lienhard et al. 2016].

Due to the intermittency of PV, quasi-continuous operation of a PV-RO plant requires solar energy to be stored during daytime for use during the night. The most obvious way to store energy is to exchange it with the electric grid. When the radiation is sufficient, RO is on gear with PV production; when there is excess radiation, this is fed in to the grid and taken back during periods of insufficient radiation. Assuming that PV energy can be exchanged with the grid at negligible cost, the cost of desalinated water at the plant's gate would lie in the range 0.5-1 EUR/m^3 [Pistocchi et al. 2018]. However, some desalination plants are not connected to the power grid (e.g. many EU islands in the Mediterranean) or the grid is unable to supply the required power, thus on-site energy storage may be used. A water reservoir placed upstream, with some potential energy with respect to the desalination plant, is in principle a convenient option for energy storage, because it enables the use of excess energy to 'pre-pressurise' the RO feed directly, with minimal energy losses, limiting the demand of energy from the grid to the needs of the additional pressure required for the membrane treatment. The effectiveness of this option depends on the availability and elevation of suitable water storage areas around the site of the plant and of the required reservoir volume.

The dependence of the desalination plant on the power grid could be reduced by: (a) an electric battery on site; (b) a water reservoir upstream of the desalination plant, or (c) a combination of both [Ganora et al. 2018]. A battery not exceeding 1.1 kWh/m^3 per day combined with a reservoir not exceeding 5 m^3, could in most cases enable autonomous operation at practically all sites for 60-80 % of the time, whereas batteries or reservoirs alone would require higher exchanges with (and enable less autonomy from) the grid. The on-site energy storage would reduce peak power fed to the grid from 350 to 160 W/(m^{3}day^{-1}), and peak power drawn from the grid from 130 to 100 W/(m^{3}day^{-1}).

Around 100 million people could receive desalinated water from PV-powered RO desalination plants in the Mediterranean region with levelised costs up to 2 EUR/m^3

(without energy storage) and 3.5 EUR/m^3 (with energy storage), taking into consideration investment and operation costs and the requirements of water transport from desalination plants to inland users [Pistocchi et al. 2018], and under the assumption that PV electricity is generated onsite at negligible cost. However, that would generate approximately 5 km^3/year of brine with a concentration twice as high as seawater. While brine is a potential source of minerals, its exploitation as such is not yet economically feasible [Pistocchi et al. 2019] and its disposal has negative environmental impacts. The ecological sensitivity of the location of the desalination plant would need to be considered.

4.4 Water allocation between and within WEFE sectors

Competition for water resources has led to blue (liquid water in rivers, lakes, wetlands and aquifers) and green (water held in the soil) water scarcity throughout the EU and outside its borders [Mekonnen & Hoekstra 2016, Schyns et al. 2019]. Therefore, trade-offs in water allocation between these sectors, but also within these sectors, needs to be accounted for.

The water footprint assessment of the EU energy sector (section 2.4.1) has shown that for renewable energy sources there is essentially a differentiation between two groups:

- Reservoir hydropower, wood and 1st generation biodiesel and bioethanol have very large unit WF amounts, and are responsible for the largest fraction in the total WF of production and consumption of the EU energy sector.
- Solar, wind, geothermal and run-of-river hydropower have small unit WF amounts, and are responsible for a small fraction in the total WF of production and consumption of the EU energy sector.

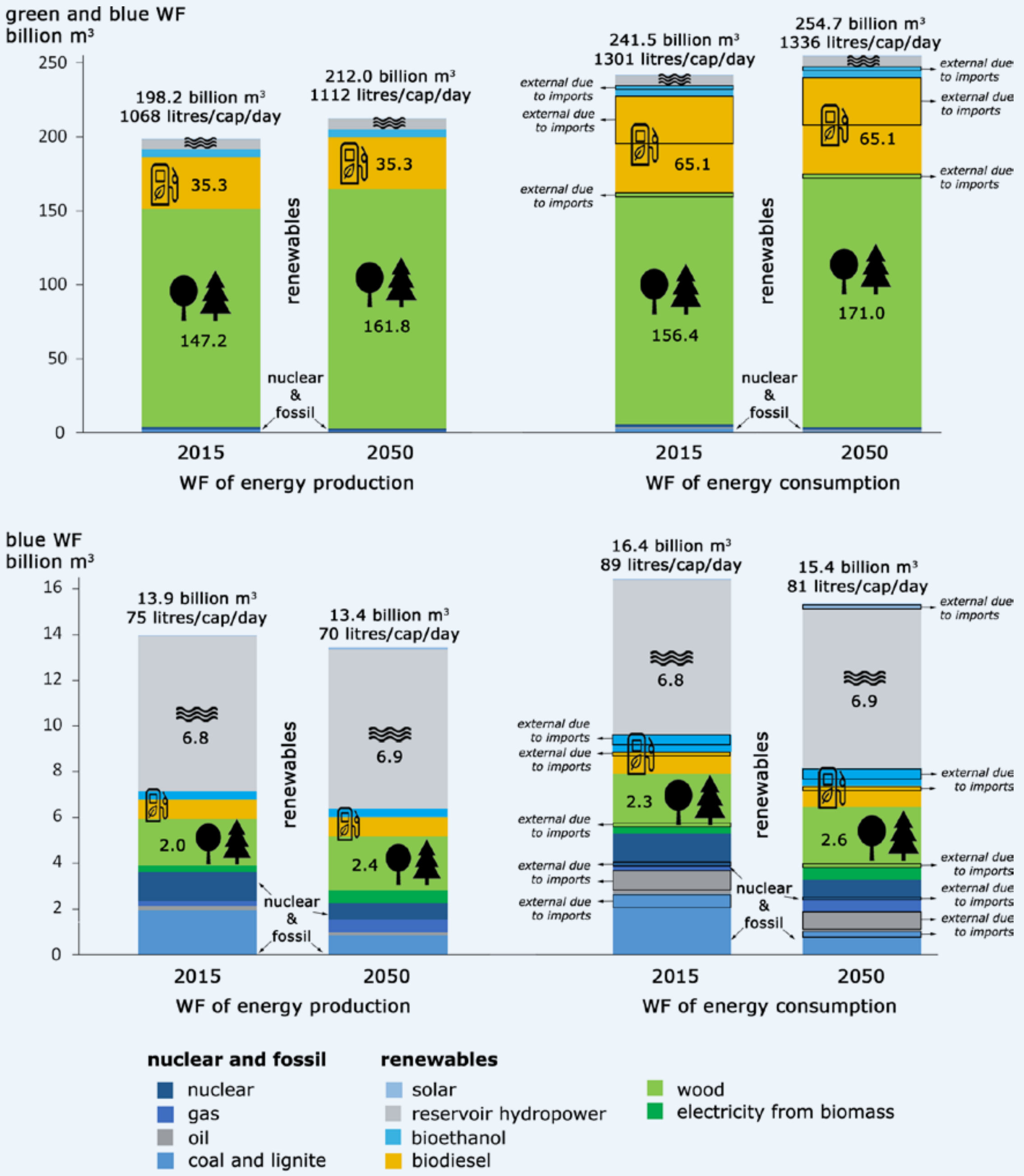
Therefore, in order to decarbonise the EU energy sector while reducing the impact on water resources, the policy instruments used to support renewable energy sources should take into account the water footprint of the various technologies, in Europe and beyond. For example, first generation biofuels are grown with water resources on fertile agricultural land, which go into direct competition with water resources for agricultural (food) needs and forest growth. They are often produced on deforested land with resulting losses in biodiversity and increased greenhouse gas emissions.

As the extra potential for energy wood production in the EU for 2050 is limited, most of the increase in energy from biomass (currently 132 600 ktoe to 183 700 ktoe), will come from waste (from 56 400 ktoe to 100 800 ktoe), for which the WF amount can be assumed to be zero. Nevertheless, the slight increase in energy wood production increases its green plus blue WF from 147.2 to 161.8 billion m^3, representing the bulk of the total WF of production in 2015 and 2050 (Figure 19). The WF of energy wood consumption is slightly higher (156.4 and 171.0 billion m^3 in 2015 and 2050 respectively), as part of energy wood is imported to the EU. An extra increase in wood imports in the coming decades would increase the total WF of energy consumption substantially.

When only assessing the blue WF (Figure 19 bottom), the observed decrease in the combined WF of energy production of nuclear and fossil fuels, as well as electricity from biomass and geothermal energy, from 3.9 billion m^3 in 2015 to 2.8 billion m^3 in 2050 (decrease of 28 %), is in line with the results presented in Table 2. However, an increase in the blue WF of wood (from 2.0 to 2.4 billion m^3) as well as from reservoir hydropower (from 6.8 to 6.9 billion m^3) reduces the total blue WF of 13.9 billion m^3 by only 4 %. The blue WF of energy consumption for the group nuclear and fossil fuels, as well as electricity from biomass and geothermal energy, would decrease from 5.6 to 3.8 billion m^3 (decrease of 32 %). However, an increased future WF for wood and reservoir hydropower would result in a total blue WF of energy consumption reduction by only 7 % (from 16.4 to 15.4 billion m^3). A comprehensive assessment of the total blue WF thereby shows only small reductions by 2050, which could shift to an increase in the WF of consumption when the decision is made to import extra wood biomass or biofuels.

For 2050, the production and consumption of 1st generation biofuels are assumed constant in this specific scenario, in order to show the impacts on water resources. An increase in production and/or import would result in a substantial increase in the EU WF. This assumption does not take into account that the Commission has already indicated that biofuels, bioliquids and biomass fuels produced from food and feed crops should be phased out gradually and replaced with advanced biofuels, including, notably, cellulosic ethanol and diesel and algal fuels, as well as renewable electricity-based fuels, as highlighted in the recent directive COM(2018)2001[34]. The water intensity of these advanced biofuels should, however, also be accounted for. As an example, algae show substantial unit WF amounts [Yang et al. 2011], which depend on factors such as technology (open pond, closed photobioreactors), water source used (freshwater, brackish, saline water), operation with and without recycling or algal species.

Figure 19: The water footprint of energy production (left) and consumption (right) for green and blue water (top) and only blue water (bottom), for the years 2015 and 2050. Note that the amount of 1st generation biofuels is kept constant.



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[34] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

4.5 Joint management of water and energy resources

The water system is one of the major sources of operational flexibility for the European power system [Eurelectric & VGB-Powertech 2018a]. Systems with hydropower capacity can better integrate electricity produced from intermittent non-dispatchable sources (such as wind and solar), since they can start or adjust operation within seconds in response to fluctuations in the production or demand of electricity. Hydropower systems can also provide short- and long-term storage [Huertas-Hernando et al. 2017]. EU water reservoirs are currently able to store approximately 360 TWh/year, roughly the gross inland consumption of energy in Romania. Nearly all the large-scale dispatchable energy storage capacity in the EU consists of pumped hydro storage units (47 GW), and this storage capacity helps to reduce the need for the curtailment of wind and solar power during periods of low electricity demand [Eurelectric & VGB-Powertech 2018b]. With a very low carbon footprint, hydropower technologies provide other energy-related services to the power system as a source of:

- backup, operating reserve, and quick-start capacity,
- voltage stability,
- re-dispatch capacity and peak load control,
- regulation and frequency response.

Hydropower also renders other services besides the generation of renewable electricity, such as ecosystem services (e.g. low GHG emissions, flow and flood control), energy security, water storage for irrigation and public supply, navigation, and recreational [Eurelectric & VGB-Powertech 2018b].

Different hydropower technologies offer differing levels of flexibility, depending on energy storage capacity and other operational constraints related to the availability of water and the reservoir levels [Huertas-Hernando et al. 2017]:

- Impoundment hydropower plants are large water reservoirs that receive a natural inflow, providing greater flexibility and long-term storage capabilities.
- Run-of-river plants do not have significant storage capacity and offer very limited flexibility since their output depends on the water stream, which may be controlled by an upstream reservoir.
- Pumped hydro storage units are able to store water from a downstream source, which can be used later to generate power, offering short-term flexibility and storage capability.

Transmission capacity and interconnections linking the hydro-dominated parts of a power system with those requiring operational flexibility are key to taking advantage of all the flexibility that may be offered by hydropower technologies [Huertas-Hernando et al. 2017], allowing a more efficient use of power generation assets over broader areas [Charmasson et al. 2018].

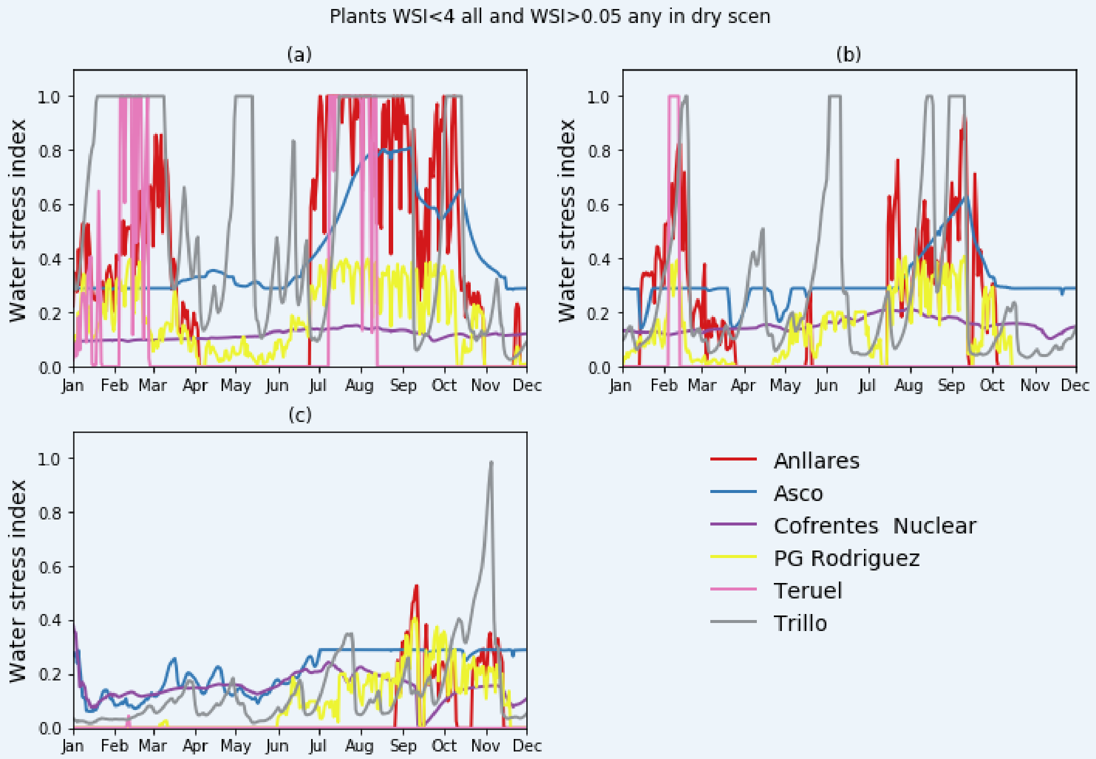
Despite the importance of hydropower for current and future energy systems, most of the power system models used today neglect water-related constraints and represent the availability and variability of hydrological resources in a simplified way that does not adequately reflect real-world decision-making conditions. Current expansion models and production models used by system planners should be tested for such factors as scale, measured variables, assumptions, data availability and viability over expanded time horizons.

Current models often ignore the importance of water resource adequacy in design modelling. Hydrological-related ‘boundary conditions’ (e.g. catchments, flows, irrigation uses) determine hydropower operations throughout the year, which can in turn affect the operation of thermal power plants due to large-scale water withdrawals for cooling purposes. In addition, water overflows might present a risk for the smooth operation of power plants. Several recent studies have raised awareness about the relevance of the water-energy nexus and its analysis as an integrated system [Huertas-Hernando et al. 2017, Sanchez Perez 2017, Stoll et al. 2017].

The WEFE project provides some examples of integrated water and energy modelling that could be used for supporting policy design and assessment [Fernández-Blanco Carramolino et al. 2016, Fernández-Blanco Carramolino, Kavvadias & Hidalgo González 2017, Fernández-Blanco Carramolino, Kavvadias, Adamovic et al. 2017, Fernández-Blanco et al. 2017]. These analyses use the JRC LISFLOOD and Dispa-SET models to assess, in depth, the impact of the water availability on power system economics and operations and the consequences of power system operations on water availability, to quantify the vulnerability of individual power plants to water scarcity, and the effect of water stress- and cooling-related constraints from a policy perspective, under different hydrological scenarios (Figure 20).

Reservoirs are often simulated using assumed relations between reservoir water volume and reservoir water outflow, often lacking the link with energy production. Another example of integrated water and energy modelling addressing this problem with the LISFLOOD model is presented in [Adamovic et al. 2018]. Two models, LISFLOOD and LISENGY are coupled to assess the hydropower potential of the Iberian Peninsula.

Figure 20. Daily water stress index of selected coal power plants in Spain, under (a) dry, (b) average and (c) wet scenarios [Fernández-Blanco Carramolino, Kavvadias, Adamovic et al. 2017]



Box 4. Assumptions used by LISFLOOD and LISENGY

The new hydro-power model simulates water levels and power production at a daily time step and fine spatial resolution (5x5 km grid) based on the volume-depth relationship, and enhances our scientific understanding of reservoir management operations in hydrology. An Iberian Peninsula case study is used to experiment with integrated water and power system modelling between 2007 and 2016.

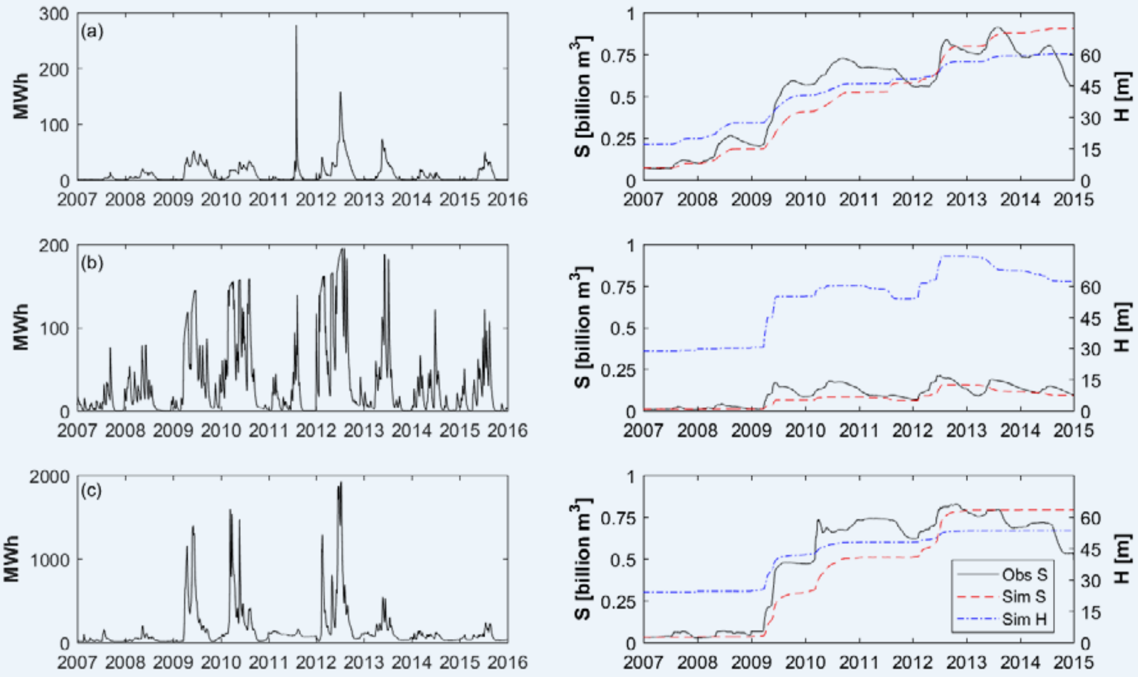
The model is applied to 168 reservoirs categorised as convex, conical and concave, using the water extent from the Global Water Surface data set [Pekel et al. 2016] and reservoir morphometry methodology. The reservoir classification is based on the reservoir bathymetric capacity to store water, which drives the expected power output of the reservoir.

The proposed methodology allows the hydro-power model simulations to be carried out to evaluate the impact of various hydrological and operational limitations in relation to the water-energy nexus capacity of the Iberian Peninsula.

Results of the simplified integrated hydropower modelling driven by energy production and power market show that it is possible to connect the LISFLOOD and LISENGY models, and that the timing and magnitude of simulated storage matches observations (Figure 21). It represents a first step towards integrated hydro-dynamical pan-European water-energy modelling. The integrated system simulates the trends of increasing and decreasing reservoir depth that do seem to follow observed storage trajectories.

The frequency of drought and low-flow events is expected to increase in the Mediterranean and particularly over the Iberian Peninsula. The model allows the identification of the reservoirs with the highest energy production potentials and their generation levels under different scenarios, providing insights on joint management of water and energy resources. This approach could be extended to other European areas and include more details on both the water and the power systems.

Figure 21. Energy daily generation in MWh (left) and comparison between simulated (*Sim S)* and observed storage (*Obs S)* with level fluctuations (*Sim H)* for selected reservoirs in the Iberian Peninsula (a: Alarcon; b: Fuensanta; c: La Breña)



5

CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1 Conclusions

Although the interdependencies between water and energy are well known, and are attracting increasing attention from the scientific and policy communities, the development and implementation of water and energy policies remain largely disconnected at EU and national levels. The studies presented in this work show that there is a complementarity between water and energy modelling, allowing the identification of criticalities and vulnerabilities under different policy and climate scenarios.

The availability of electricity is fundamental for water supply and processing, but it does not limit the operations of the water sector. On the other hand, water availability can be a key constraint, affecting energy sector operability and the generation of electricity essential to most human activities.

Ongoing consultations on the Fitness Check of policies such as the Water Framework Directive, 2030 climate strategies in the EU National Energy and Climate Plans, and the Energy Efficiency Directive, give scope for addressing the water-energy nexus in a broader policy context. A more cohesive policy approach would ensure that specific energy- and water-related policy targets are met. In particular, recognising the role that the energy sector plays in terms of water abstraction would help to develop better water management and preservation instruments in the Water Framework Directive, whilst increasing the stability and security of the energy system as one of the key pillars of the Energy Union. There is also scope to increase the links between the Water Framework and the Urban Wastewater Treatment Directives with the Energy Efficiency Directive, to stimulate and drive energy saving in the water sector.

Recent extreme weather events such as the heat wave of 2018 have shown that the energy system is becoming more vulnerable to reduced water availability and increased water temperatures, thus resulting in temporary shutdowns of energy facilities. Understanding the water demand of the energy system and its future evolution provides valuable information on its potential impact on water resources. Assessing the availability of future water resources helps to identify areas at risk, and informs the design of policies to tackle water-energy problems.

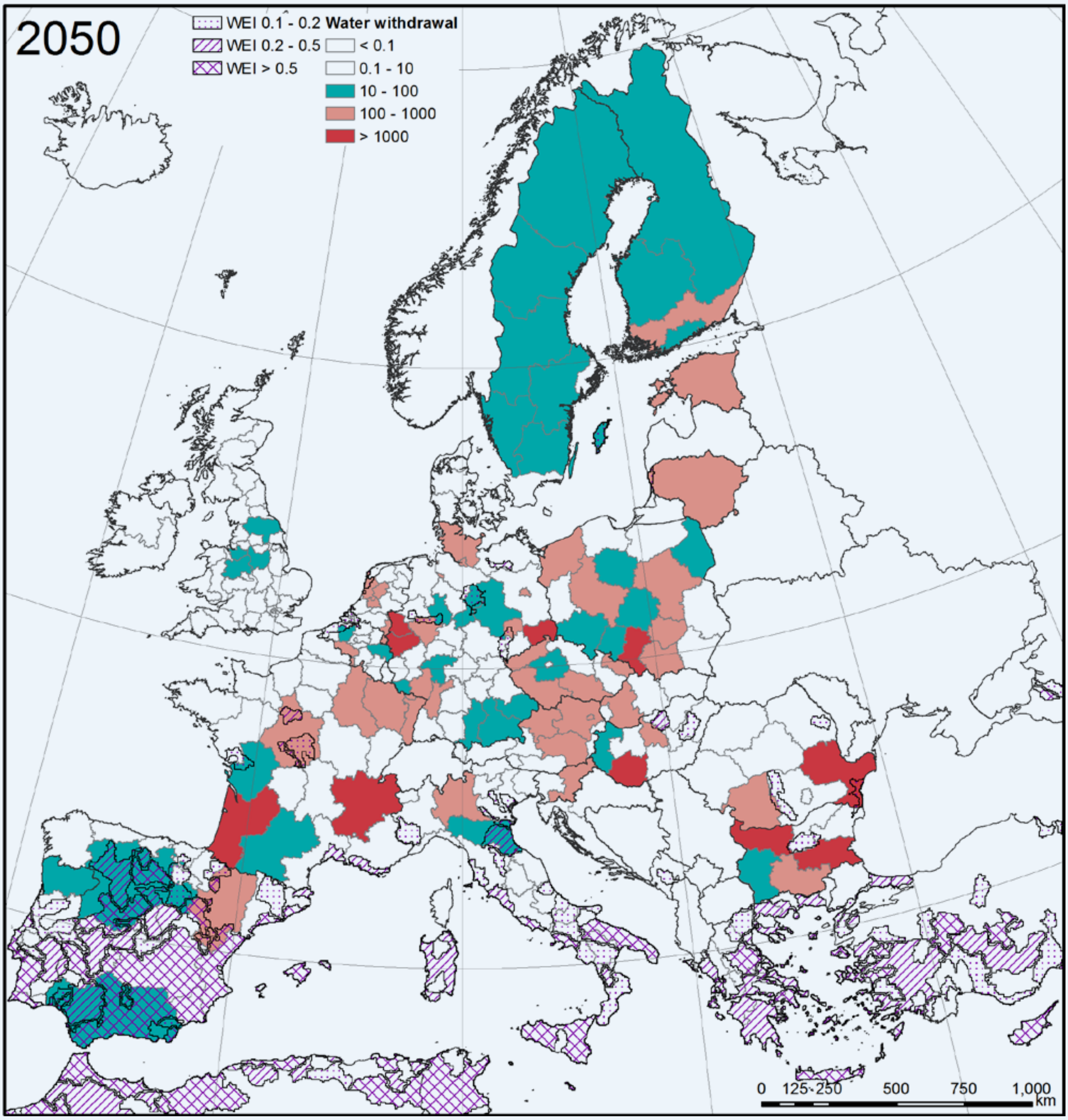
The transition to a more decarbonised energy system, based on the implementation of the 2030 Strategy and the recent Clean Energy for All Europeans agreement, can reduce the impact of the energy sector on freshwater resources. However, different decarbonisation scenarios are slated to have different impacts on water resources. In particular, a considerable increase of biomass may lead to a higher water footprint for the energy system. This takes into account the amount of water that is required by crops and wood. The current European Commission biofuel sustainability criteria define thresholds for the production of biofuels based on their carbon intensities, but they do not include information with regard to the water intensity of biofuels crop and their impact on water resources.

As water becomes scarcer, the policy instruments used to support renewable energy sources should take into account the water footprint of the various technologies, as well as the trade-offs of water allocation to the different WEFE sectors. The unit water footprint of solar, geothermal, wind and run-of-river hydropower is low, whereas it is higher for biofuels, wood and reservoir hydropower. Policies that promote further externalisation of energy sources through imported biofuels or wood, often produced under water scarcity conditions, could result in higher energy insecurity.

The long-term outlook of the EU energy system indicates that, thanks to decarbonisation policies, water withdrawal by the EU energy system is expected to decrease to 46 billion m^3 in 2050 (a 38 % reduction with respect to 2015 levels). This means that the impact of the energy system on water resources would be in line with current levels of abstraction for public water supply.

The overall reduction in water needs from the energy system does not reduce criticalities at regional level, in particular for those regions where nuclear power, coal-fired power plants and coal mines will be still operational

Figure 22. Comparison of projected water withdrawal in 2050 at NUTS2 Level [Medarac et al. 2018] vs forecasted WEI+ under the 2 °C degree scenario modelled by LISFLOOD [Bisselink et al. 2018]



by 2050. These criticalities may become more acute in 2050, under increased water stress scenarios, despite the expected decarbonisation of the energy system, since some low-carbon energy systems could use water more intensively than the systems they replace.

Figure 22 provides a comparison of projected future water withdrawal from the energy system along with the Water Exploitation Index derived from the LISFLOOD model under the 2 °C scenario for the year 2050. Mediterranean regions, especially those in Portugal, Spain, Italy, Malta, Greece, and Cyprus, will likely experience increased water scarcity. At the same time, regions likely to expect high freshwater withdrawal for the operation of the energy system and critical water scarcity can be found in France, Hungary, Bulgaria, and Romania.

Desalination may reduce water scarcity problems; however, any increase in desalination capacity would then translate into a significant increase in energy demand by the water sector. Powering desalination plants with renewable energy would be another option to absorb more wind and solar power generation, especially in areas around the Mediterranean. Nevertheless, the impact of renewable-driven desalination on the energy system should be addressed; as well as other possible environmental impacts in the broader WEFE context.

The report also highlights concrete actions that could have an immediate and significant impact on the water and energy domains. The EU water sector accounts for 80 TWh (2.6 % of the EU electricity consumption or approximately the amount of electricity generated in Belgium). Solutions have already been identified to reduce the energy requirements of drinking and wastewater treatment processes, thus making possible the implementation of energy efficiency targets for the water sector. There is, therefore, scope to integrate the EU climate, environment and energy policies and objectives in the revision or updates of the Water Framework, Urban Waste Water Treatment, and Energy Efficiency directives.

5.2 Policy recommendations

This report summarises key focus areas identified by WEFE Nexus analyses, where a more holistic policy approach would improve the impact of energy and water policies, avoiding the potential conflicts at the heart of the WEFE nexus. The policy recommendations stemming from this work are classified as strategic (long-term, may require a paradigm shift in policy design), and operational (based on existing technological solutions whose impact could be immediate).

The long-term strategic recommendations are:

- **The introduction of water-related criteria into long-term energy policies.** Decarbonisation will reduce the amount of water used by the energy industry overall, but certain alternative processes such as biomass and hydropower will increase its water footprint. Including water-related criteria in long-term energy policies will allow for a careful balance of decarbonisation goals with water sustainability.

- **The integrated management of water and energy resources to support the energy system without affecting agriculture and water supply.** Energy-related criticalities are expected across several parts of the EU. The integration of water and energy modelling allows for regions to be identified which are at risk of water shortages and associated energy production problems. Hydropower resources can also bring greater flexibility to the energy system by balancing and storing renewable energy.

- **Exploring the role of desalination, powered by renewable energy, as a viable source of freshwater.** Desalination has the potential to play a key role in public water supply, given the impact of climate change on available resources. Desalination techniques are, however, highly energy intensive, and renewable-powered desalination plants should be explored as a viable alternative.

Short-term operational actions to be taken include:

- **The development and adoption of energy efficiency indicators and targets for the water sector.** Viable technologies already exist which can reduce losses and leakages in water networks and optimise wastewater treatments. The adoption of such energy- and water-saving measures could be stimulated by the inclusion of energy efficiency indicators and targets in water policies.

- **R&D in water- and energy-saving technologies**. Energy- and water-saving technologies (e.g. air-based and advanced cooling systems, advanced materials for improved waste-heat recovery and smart meters) are currently too expensive in terms of power plant efficiency and design. In order to make these technologies more feasible, both technically and economically, further research and development is needed.
- **Improved data collection across water uses.** The scientific evidence on which this report is based shows the importance of complete, accurate data from different water uses in order to understand the interdependencies which make up the WEFE nexus.

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LIST OF BOXES

- Box 1. Indicators of water use 18
- Box 2. Desalination technologies 27
- Box 3. Description of climate scenarios 33
- Box 4. Assumptions used by LISFLOOD and LISENGY 43

LIST OF TABLES

Table 1. Breakdown of volume treated and energy requirements for each stage of the water sector in 2017. (Source: water volumes: [Eurostat 2018], [GWI 2018], analysis: JRC) 23

Table 2. Projected water use from the EU energy sector (rounded figures, billion m^3) [Medarac et al. 2018] 29

LIST OF FIGURES

Figure 1. The water-energy nexus among the energy issues from 2010 to 2018 (red arrows) [World Energy Council 2019b] 10

Figure 2. EU energy flow diagram in 2016, with estimated freshwater requirements of the most water-intensive energy sectors in 2015. Source: JRC, based on EUROSTAT 2018 15

Figure 3. Electricity consumption in the water sector by process. Source [International Energy Agency 2016] 16

Figure 4. a) Planetary boundaries [Steffen et al. 2015] and b) DPSIR (Driver-Pressure-State-Impact-Response) framework [OECD 2013] and its relationship with pressure and impact indicators [Vanham, Leip et al. 2019]. 17

Figure 5. Historical water abstraction for energy (cooling), agriculture, public water supply, manufacturing industry, and mining reported [Eurostat 2018]. The number of MS reporting information on freshwater for energy cooling abstraction is provided for each year. 19

Figure 6. Comparison of water abstraction and consumption for energy (JRC analysis [Medarac et al. 2018]), agriculture (JRC analysis, [Vanham & Bidoglio 2013]), public water supply ([Eurostat 2018]). 20

Figure 7. Water Exploitation Indexes (for energy and total) based on reported data [Eurostat 2018] 20

Figure 8. Average blue and green WF related to energy production in the EU (m^3/TJ) for the three stages in the energy production chain (fuel supply or energy production; construction; and operation of power plants). Note the logarithmic scale. 21

Figure 9. Green and blue WF of energy production (a) and WF of energy consumption (b) of the EU, in billion m^3 (or km^3) in the year 2015. 22

Figure 10. Energy needs for the different parts of the water sector in 2017 (source: JRC). 24

Figure 11. Potential energy saving in water supply and wastewater treatment achievable through energy efficiency and operational measures. 24

Figure 12. Desalination facilities across EU Member States in the Mediterranean region expressed in terms of energy consumption (GWh/year – top) and freshwater production (m^3/year – bottom) 26

Figure 13. Impact of industrial and agricultural desalination facilities in Europe in terms of volume (left) and energy requirements (right). 27

Figure 14. Regional energy-related freshwater withdrawal for 2015 and 2050. 30

Figure 15. Alternative 2050 estimations of the projected water use by the EU energy system ([Capros et al. 2016, Keramidas et al. 2018, Medarac et al. 2018]) 31

Figure 16. Average temperature in summer 2018 compared with long-term average (1980-2017) 31

Figure 17. The projected change in low-flow near hydropower (left) and thermo-electric (right) power stations, for the RCP 8.5 2070-2099 climate as compared to the current climate 34

Figure 18. Mapping of the average WEI+ for 2050 (2036-2065) under the RCP 8.5 emission scenario [Bisselink et al. 2018]. 35

Figure 19: The water footprint of energy production (left) and consumption (right) for green and blue water (top) and only blue water (bottom), for the years 2015 and 2050. Note that the amount of 1st generation biofuels is kept constant. 41

Figure 20. Daily water stress index of selected coal power plants in Spain, under (a) dry, (b) average and (c) wet scenarios [Fernández-Blanco Carramolino, Kavvadias, Adamovic et al. 2017] 43

Figure 21. Energy daily generation in MWh (left) and comparison between simulated (Sim S) and observed storage (Obs S) with level fluctuations (Sim H) for selected reservoirs in the Iberian Peninsula (a: Alarcon; b: Fuensanta; c: La Breña) 44

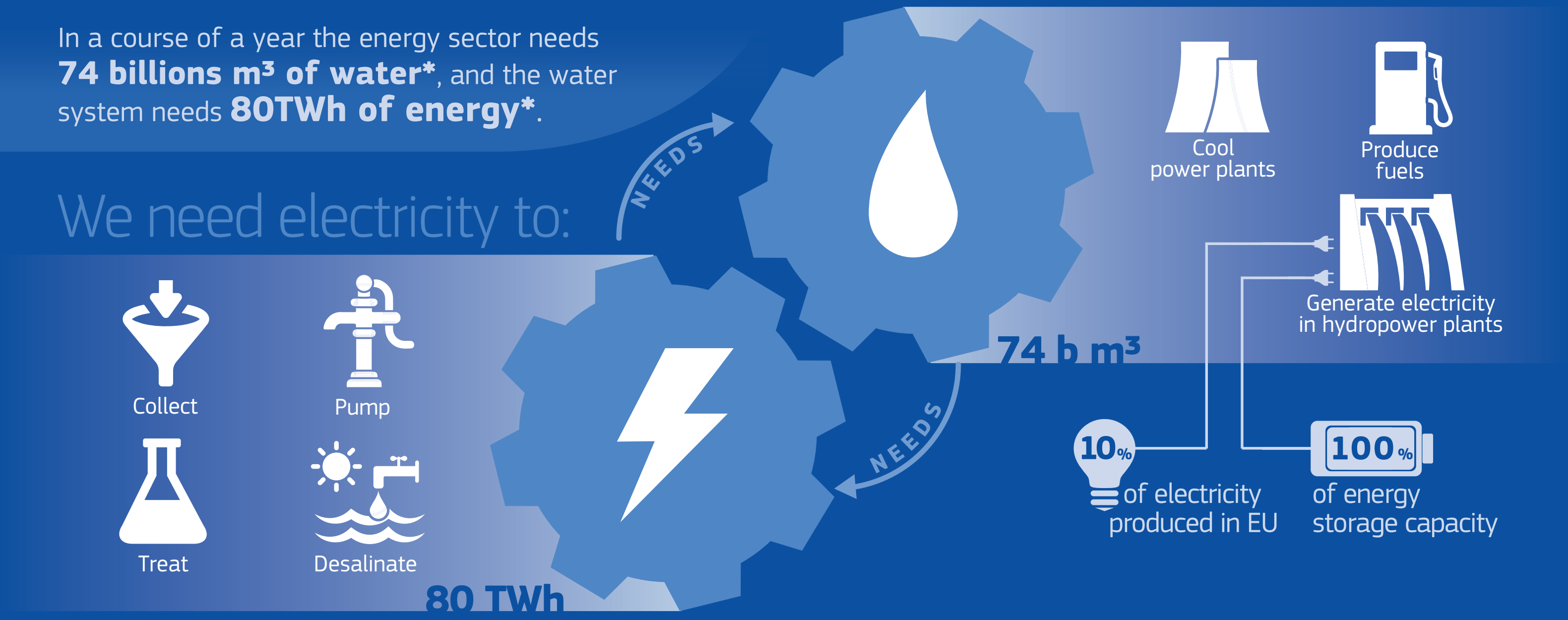
Figure 22. Comparison of projected water withdrawal in 2050 at NUTS2 Level [Medarac et al. 2018] vs forecasted WEI+ under the 2 °C degree scenario modelled by LISFLOOD [Bisselink et al. 2018] 48

European Commission

WATER - ENERGY NEXUS IN EUROPE

The EU has ambitious decarbonisation goals for the future which may rely on water intensive technologies...

In a course of a year the energy sector needs **74 billions m^3 of water***, and the water system needs **80TWh of energy***.



We need water to:

- Cool power plants
- Produce fuels
- Generate electricity in hydropower plants

We need electricity to:

- Collect
- Pump
- Treat
- Desalinate

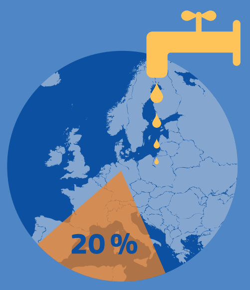
...but these goals must be reached in a way that guarantees the sustainability of water resources.

***74 b m^3** = 30 million olympic swimming pools
***80 TWh** = 1 year of electricity produced in Belgium

challenges

Energy can be renewable, however the available water is limited.

20 % of European population will be affected by water scarcity by 2050 (under the 2°C warming scenario).



Currently, the use and management of water and energy are not jointly addressed.

Joint Research Centre

WEFE Nexus can help...

The WEFE Nexus project aims to develop a holistic understanding of the interactions between Water, Energy, Food and Ecosystem, treating them collectively.

- Support the implementation of several sectoral EU policies
- Analyse the most significant interdependencies
- Evaluate the value of water in transitioning towards a climate neutral economy
- Deliver country and regional scale reports
- Develop practical guidance to allow the identification of a portfolio of measures

...taking action!

strategic actions

INTRODUCING

water-related criteria in long-term energy policies

to find a proper trade-off between decarbonisation goals and water sustainability

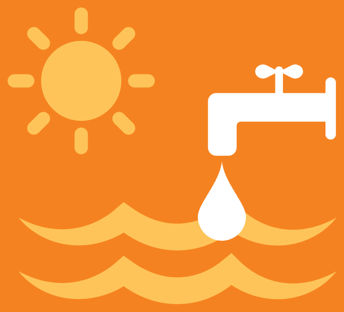
DEVELOPING

integrated management of water and energy resources

to ensure the functioning of the energy system without affecting agriculture and water supply

UNDERSTANDING

the role of renewable-powered desalination as a viable source of freshwater



and how it may impact the functioning of the energy system

operational actions

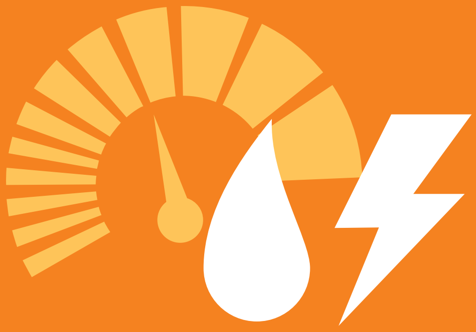
INCLUDING

energy efficiency indicators and targets for the water sector

to reduce losses and leakages in water networks and optimise wastewater treatments

RESEARCHING

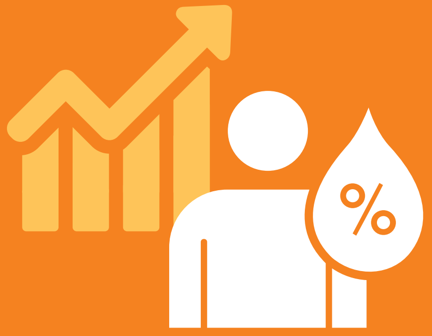
on water and energy saving technologies



to improve the technical and economic feasibility of these technologies

IMPROVING

the gathering of data from different water uses



to understand the extent of water-energy interactions, and other interdependencies in the WEFE nexus

Find the JRC report on Water-energy nexus in Europe at: ***https://europa.eu/!VM38Vw***

KJ-NA-29743-EN-N

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Publications Office

ISBN 978-92-76-03385-1
doi:10.2760/968197