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Water-energy nexus: Evaluation of future scenarios of water treatments and their energetic sustainability

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Guidelines and parameters employed taken from the literature and from organizations are always cited.

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Andrea

1. Introduction

Primary goods are the one needed unavoidably by a person. They can be distinguished in social and natural goods[1]. The formers are generally non-material and linked to the ethical, cultural, religious, freedom purposes glued to the social context of living. The last ones are more related with physiological aspects like diet, rest, protection etc. Water and energy have a relevant position in the latter category.

Water is fundamental for life: the major percentage of this element in the constitution of human body is a perfect metaphor of the vital needs by humans not just for surviving, but also to drive all the activities that are relevant for ensuring a good quality of living. To stress the relevance of this topic it must be kept in mind that, nowadays, still 844 million people[2] in the World lack access to safe potable water, but it would be a limitation to think about this issue only in terms of potable water. Obviously, the repartition of use is not equal worldwide, but it is also related to cultural and socio-economic features. Nevertheless, it is possible to identify some high water-demand sectors: thermoelectric power, irrigation (not just for crops, but also for public or private facilities), public supply, industrial activities, aquaculture, mining, domestic and recreational use.

Energy can now be considered as crucial as water in the definition of the elements necessary to guarantee human health. Any product and service needs energy to be extracted, transformed, transported, and disposed hence, also primary goods are energy dependent. Large water use is related to two energy-related sectors: thermoelectric power and mining. The connection is not directed one way, but mutual. In fact, the availability of water, in any form and feature is achieved after water is processed (e.g., purified) with a specific source of energy. Both resources show an increasing trend looking forward as revealed in figure 1 and figure 2.

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[1] https://it.wikiversity.org/wiki/Bisogni_e_beni

[2] https://water.org/our-impact/water-crisis/

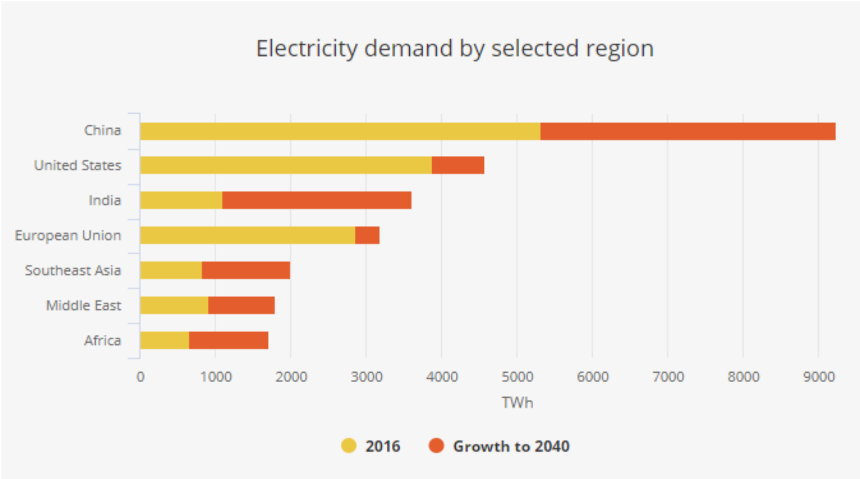

Figure 1 Comparison of electricity demand in 2016-2040[3]

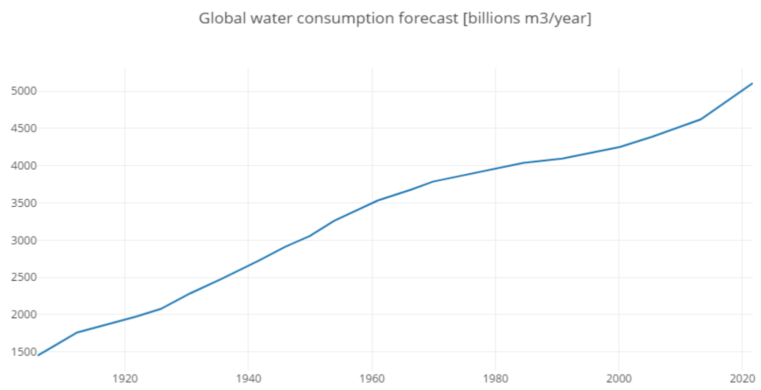

Figure 2 *Water demand scenario from 1900 to 2025*[4]

Figure 1 reveals the overall increasing demand for electricity in some of the World regions. In detail, the countries that will experience the most significant growth in demand are China (which is supposed to need in 2040 about 4,000 TWh more than in 2016) and India, in which electricity needs by customers will more than double with respect to today. The rising trend is true worldwide, but it is less severe for developed countries like The European Union and The United States of America, in line with the standards adopted and in phase of development.

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[3] https://www.iea.org/weo2017/#section-1-1

[4] http://12.000.scripts.mit.edu/mission2017/social-solutions-to-energy-and-water-problems/

Figure 2 shows an increasing trend of water demand in the range of time within 1900 and 2020: the varying steepness of the trend line can be attributed to several parameters, but it is notable that the prediction for the 20's of the 21st century is similar to the period across the two World Wars, in which a very strong technological development occurred.

1.1 Factors associated to water-energy demand

Since the availability of both resources, water and energy, will dramatically change in the future, it is interesting to analyse some of the factors that are affecting or being affected by this evolution in the trend:

- Climate;
- Gross domestic product (GDP);
- Social aspects.

Climate is affecting energy and water in a recursive way. Globally, the use of energy represents by far the largest source of greenhouse gas emissions from human activities[5], thus one of the most significant actors in climate change, but at the same time the energy world is adapting to the shocks provided by these changings. Regarding climatic impact in the water and energy context, the following effects can be listed[6]: both air and water temperature will rise, together with the sea level, some areas will be severely affected by water scarcity and in other areas the occurrence of catastrophic events like floods and severe storms will increase. These events will lead to the loss of a significant part of freshwater stored, making the water supply less reliable. Moreover, the water cycle will be compromised because the rising of sea level will add salinity to both surface and groundwater, while heat waves will drastically modify the evapotranspiration phenomenon.

Gross Domestic Product (GDP) is defined as "the monetary value of all the finished goods and services produced within a country's borders in a specific time period"[7] but, more generally speaking, it is used as an index for standard of living, productivity and economic growth of a

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[5] https://www.eea.europa.eu/signals/signals-2017/articles/energy-and-climate-change

[6] Water and energy, threats and opportunities; G. Olssen

[7] https://www.investopedia.com/terms/g/gdp.asp

country. As previously stated, the increasing chance of water scarcity would significantly influence the values in GDP calculations. Water-GDP connection is well shown in figure 3.

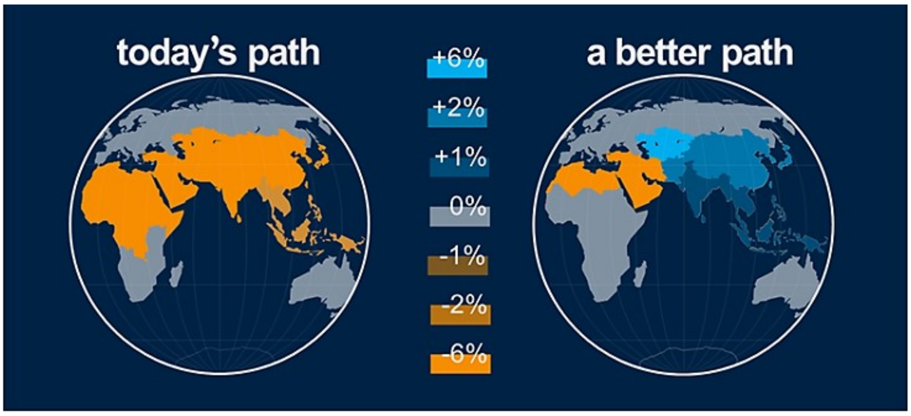

Figure 3 The impact of water scarcity on GDP[8]

The picture provides an estimation of GDP in 2050 according to two scenarios. The left-hand side reveals the momentous effect on the economic parameter in case that no counter-measures will be taken to fight water scarcity led by climate change. The more sensible areas would be the MENA (Middle East North Africa) as well as China, in which a reduction of 6 points per cent is estimated. On the opposite side, a policy regime including a wiser water management (reduction of water losses, recycling and reuse, water storage, etc...) would result in a different situation. The drastic reduction of GDP will unavoidably hit MENA, but rising countries like China and India will be able to grow, as well as Kazakhstan. The matter is more complex when it is related to energy. In fact, the connection exists, but the discrepancy between studies is so relevant that researchers have reached no clear consensus about whether energy use will lead to economic growth, or not[9].

[8] http://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy

[9] Energetic Limits to Economic Growth; James H. Brown, William R. Burnside, Ana D. Davidson, John P. DeLong, William C. Dunn, Marcus J. Hamilton, Norman Mercado-Silva, Jeffrey C. Nekola, Jordan G. Okie, William H. Woodruff, and Wenyun Zuo

Social matters are also crucially related to water and energy: issues, such as equity, security and justice. In the energy field, these concepts can be combined in the so-called energy trilemma, whose pillars are provided in figure 4.

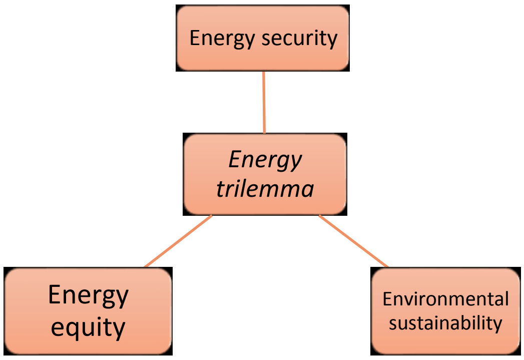

Figure 4 *Composition of energy trilemma*[10]

In this specific application the trilemma, the choice is between three options, in which the co-existence of only two of them is acceptable. Energy security is defined by the International Energy Agency[11] as the "uninterrupted availability of energy sources at an affordable price". The idea is not so simple: it involves the assurance from the energy providers of meeting the future demand-offer match, reliability of the infrastructures in both the short- (sudden adaptation of energy demand) and the long- (timely investment to reach some economical or environmental goals) terms. Energy equity is the accessibility and affordability of energy supply across the population. Finally, environmental sustainability concerns the satisfaction of the demand by using renewable, low-carbon and efficient energy sources.

Water does not have an analogous trilemma, but it has its corresponsive of security and equity. The former is defined as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political

[10] https://www.worldenergy.org/news-and-media/news/12243/

[11] https://www.iea.org/topics/energysecurity/

stability"[12]. The latter is measured through indicators showing the proportion of a population having access to 'improved water sources'[13](i.e., sources that in theory may provide access to safe water like piped water into dwelling or yard, public tap or standpipe, protected dug well or spring and rainwater). However, the boundaries of inclusion of these two concepts are not well defined. Indeed, the ideas are limited to potable water, hiding a world of intermediate water quality that is outside the interest of these definitions, but not negligible.

1.2 Outlook of conventions and their goals

The relevance of energy use, its change and effect on the environment has been discussed in many conferences, such as The Earth's Summit (Rio de Janeiro,1992), Energy Charter Treaty (Lisbon,1994), Kyoto Protocol (Kyoto, 1997), Europe 2020 (2010), Paris Agreement (Paris, 2015), International Energy Charter (Netherlands, 2015), Agenda 2030 (2015). During these summits, very notable tasks have been set often to respond to issues like the depletion of fossil fuels, reduction of environmental impact, and the limitation of temperature rise. The relevance of the subject was such that Rio's conference was the first in which the heads of 172 (over 196 recognized) countries of the World met to discuss topics like environment and agriculture, transportation, industry and energy security. Boosted by the spirit of the Earth's Summit, the World Water Day was instituted in 1992, whose goal is to generate public awareness about access of potable water and sustainability of aquatic habitats[14]. In spite of this rising interest about water resources, no international dialogs have been initiated about it until the statement of Agenda 2030, as provided in figure 5.

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[12] http://www.unwater.org/publications/water-security-infographic/

[13] What is water equity? The unfortunate consequences of a global focus on 'drinking water'; Matthew Goff, Ben Crow

[14] http://worldwaterday.org/

Figure 5 *Summary of Agenda 2030's goals*[15]

The figure summarizes the sustainability targets to be ideally reached within 2030 by the UN participants. The common denominator of the list is to reach shared advantages in economic, social and ecological settings. Water issues emerge directly in point 6 (clean water and sanitation access) and 14 (life below water, guaranteeing a not polluted living environment), while energy in point 7 (affordable and clean energy) directly and 13 indirectly (climate action). The establishment of worldwide standards is impossible: according to the development and cultural perspective of each country, different legal bindings are in force. A simple example is the definition of parameters and limits for potable water distribution or wastewater discharge and reuse. Limits can vary widely, not just among continents, but also across different regions belonging to the same country. The challenge of these international conferences is to establish joint results to be achieved, conscious of the different chances and opportunity of each population, in the name of global welfare.

1.3 Topics to be developed

Once the main questions related with energy and water have been discussed, the introduction of the water-energy nexus can be provided. The definition of the link between these two resources is not well specified, but it can be properly summarized as the interdependence between energy and water, by considering the water required in all the stages of energy

[15] https://www.unric.org/it/agenda-2030

generation as well as the energy required for water supply and treatment[16]. The aim of this study is to analyse both qualitatively and quantitatively this nexus, by investigating the withdrawal and consumption of water for the main technologies used to produce electricity and the amount of energy needed to obtain high-quality water, considering both traditional and unconventional water sources. To guarantee an adequate panorama, this analysis is performed in three different locations, each with a different energetic and water mix. A short- and long-term quantification of the energy mixes are considered, and three quantities are evaluated: the energy required to obtain one cubic meter of high-quality water, the water to generate one energy unit, and the hidden quantity of water needed for the purification of water considering the energy needs of water treatment and supply. Next, in line with the rising request of water, a focus on unconventional sources is provided. The goal is to weigh the impact of the expansion of these alternatives in potential scenarios: this analysis is done to understand in what measure a radical change in the exploitation of different water sources would impact these resources. Considering an increment of non-conventional water exploitation, a case study is proposed involving the restoration of domestic greywater to lower the urban water footprint. After the identification of a proper treatment train, based on the quality standards to be achieved, an evaluation is carried out in terms of specific energy, water savings, and economics, compared to the current scenario.

[16] Energy-water nexus: potential energy savings and implications for sustainable integrated water management in urban areas from rainwater harvesting and grey-water reuse; P. A. Malinowski, P.E. Ashlynn S. Stillwell, J. S. Wu, P. M. Schwarz

2. Water: Classification, sources, and needs for energy production

About 71% of the planet Earth is covered by water, the main part of which is composed by the oceans as shown in figure 6.

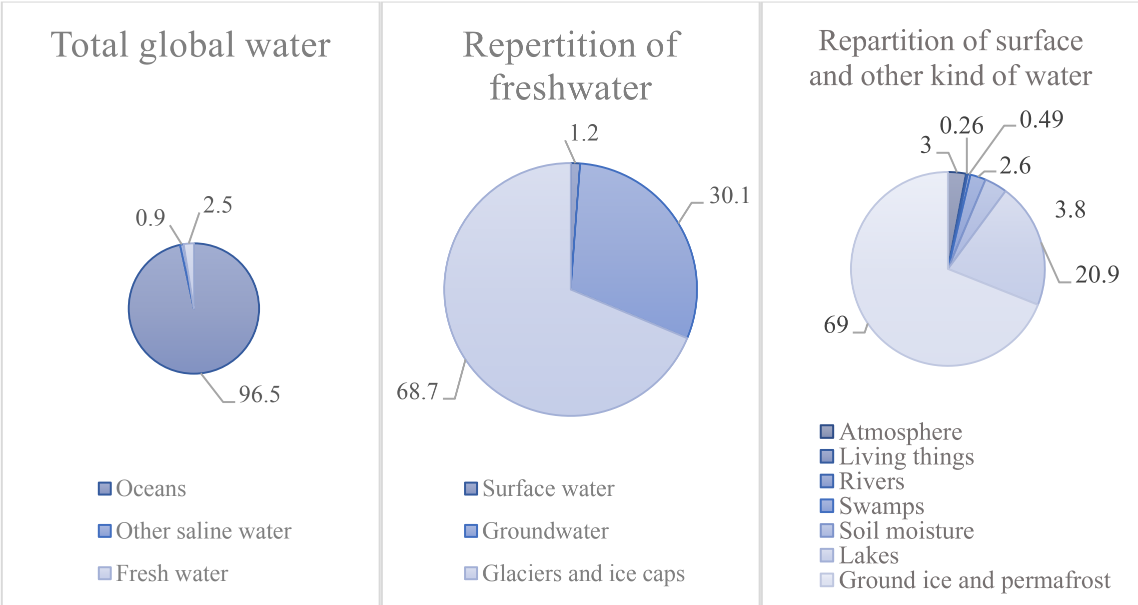

Figure 6 Repartition of water on Earth[17]

Freshwater comprises glaciers and ice caps (68.7%), groundwater (30.1%) and surface or other kind of freshwater (1.2%). Surface water is the most exploited portion, but abstraction of groundwater, then treated and applied for several purposes, is not negligible, while the water in the solid phase is inaccessible. To talk about water and its application in human activities is fundamental to understand the water cycle and the differentiation in its classification. Consequently, an overview of the sectorial consumption of water is provided, with a specific exploration of water employment in the different energy technologies.

2.1 Water classification

One of the most trivial distinctions of water quality can be made according with the salt content expresses as electrical conductivity, in table 1.

[17] https://water.usgs.gov/edu/earthwherewater.html

Table 1 Water classification according to its electrical conductivity[18]

Classification:	Electrical conductivity (EC) [S/m]
Ultra pure water	$5.5\times\times10^{-6}$
Drinkable water	0.005-0.05
Seawater	5

Conductivity is related to the total dissolved solids (TDS), a term which describes all species that are dissolved in the aqueous solution[19] (mainly inorganics, such as calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulphates and a small fraction of organics[20]), as reported in table 2.

Table 2 Water classification according to its TDS[21]

Classification:	Total Dissolved Solids (TDS) [ppm]
Fresh water	< 100
Agriculturale irrigation water	2,000
Brackish water (midly-highly)	1,000-35,000
Seawater	35,000-50,000
Brine	>50,000

Apart from the classification based on salinity, a sort of "chromatic" definition of water is available: blue, green, grey and black water belong to this classification and all of them, beside the last one, are part of the concept of virtual water. Virtual water (VW) refers to the amount of

[18] https://www.lenntech.it/applicazioni/ultrapura/conduttivita/conduttivita-acqua.htm

[19] https://www.lenntech.com/calculators/tds/tds-ec_engels.htm

[20] https://www.water-research.net/index.php/water-treatment/tools/total-dissolved-solids

[21] https://www.engineeringtoolbox.com/water-salinity-d_1251.html

water embodied in the production of natural and manufactured goods[22]. This parameter was set to reveal the hidden quantity of water not used directly, but as a vector for the production of goods (e.g., food, luxury products). The definition of VW includes an ambiguity which was discussed by Hoekstra et al. about the differentiation of real and theoretical virtual water. The distinction was related to the awareness that water, as well as the products manufactured through its employment, is subject of trade, thus imported or exported. Consequently, the real virtual water is that required in situ for production, while the theoretical share is associated to the saving of the water resource obtainable in case the goods are imported instead of being produced. The allocation of water in transportation is excluded from the latter concept. Differently, the water footprint (WF) is defined as "the total volume of freshwater used to produce the goods and services consumed by the individual or community or produced by the business. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and/or polluted per unit of time"[23]

To define the composition of virtual water is necessary to determine the previously mentioned green, blue and grey water[24]. Green water is the soil moisture gained from precipitation and used by plants via transpiration; blue water, instead, is the freshwater (surface and groundwater) stored in lakes, streams groundwater, glaciers and snow. Finally, the grey water is the product water of domestic activities: bathing, laundry and dishwashing or polluted water due to pesticides in agriculture and nutrients from fertilizers. Due to its interactions it is a polluted one, as the black water which is not a virtual water and, differently from the grey one, is in contact with faecal matter containing harmful bacteria and disease-causing pathogens.

About VW, a study performed by Carr and colleagues, was devoted to track its trade in some reference areas in a period between 1985 and 2010. It covered mainly four sectors of interest: plants, luxury, animals and others. The choice is emblematic since, as easily imagined, irrigation is still the first user of water in terms of quantity, luxury goods production requires high level of purity, and finally animal farming necessitates water mostly for washing purpose (pollution into the water caused by this activity is strong and difficult to be removed). Globally

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[22] Virtual water embodied in international energy trade of China; Cuncun Duana, Bin Chena

[23] https://waterfootprint.org/en/water-footprint/glossary/#WF

[24] https://thewaternetwork.com/question-0-y/what-is-blue-green-and-grey-water-6uuv13bt8lVovKyD7Andyw

speaking, it is possible to state that, apart from the significant rise of water flows (it more than doubled in the considered time, from 1.1 to 2.7 Tm^3), the proportion of employment of virtual water among the sectors remained almost constant (plants: 52.1-56.2%, luxury: 27.2-27.3%, animals: 11.6-9.7% and other: 9.1-6.7%). Consequently, the study provided a breakdown of both import and export of virtual water in the 25 years of observation across some European (Germany, Hungary, Italy, Poland, Romania), Asian (China, Japan), American (U.S.A., Brazil) countries, India and Australia. A constant trend for both import/export was maintained by Australia, Bulgaria, Italy and Japan, while a dramatic increase of export (mainly for agricultural purpose) was experienced by Brazil, U.S.A. and Romania (just over the last quinquennium). countries whose spectrum of both import and export of virtual water grew with a sharp slope were Poland (where exportation overcame the importation, due to a massive delivery of luxury VW), India and Hungary (mainly in the last years).

To determine the water footprint, two approaches have been analysed by authors (Velázquez, Hoekstra and Chapagain, Galan-del-Castillo): the bottom up and the top-down approaches. The first one considers the consumption attributed to the generation of a product while the last one includes the analysis of commercial trades and is obtained by multiplying the commercial flows with the quantity of water required by each sector. Due to the lack or unavailability of data required by the bottom-up methodology, the top-down is the most widely adopted.

Feng and Chen introduced a linked indicator named grey water footprint[25]. This is the amount of freshwater required by a polluted (grey) feed to reach the minimum concentration required by the local standards to be reused. The amount of water needed for the dilution of the undesired compound (GWFR) is provided by equation 1.

Equation 1 *Grey water footprint reduction formula*

$$GWFR = \left(\frac{c_{pre} - c_{post}}{c_{pre}}\right) * V$$

Where c_{pre} is the concentration of pollutant before the treatment, c_{post} the concentration of pollutant after treatment and V the influent wastewater in the treatment system (WWTS). Parameters commonly used are chemical oxygen demand (COD), biochemical oxygen demand

[25] Energy-water nexus of wastewater treatment system: conceptual model and framework; L. Feng, B. Chen

(BOD) and total nitrogen (TN). GWFR numbers are not equal worldwide due to the different standards in force; however they can be important in the evaluation of the options to be considered when the application of an integrated water management (IWM) occurs. This practice involves coordination and effective management of several water sources into the urban water cycle26. IWM has several tasks, such as the reduction of potable water demand, the proper location of centralized and decentralised wastewater treatments, the increase of maintenance, the replacement of the damaged infrastructure and pipelines to avoid leakage, the reuse of grey water and recycling of the green one. The correlation between the involved sources (potable, waste and storm water) for the implementation of an IWM is listed in figure 7 with letter A, B and C.

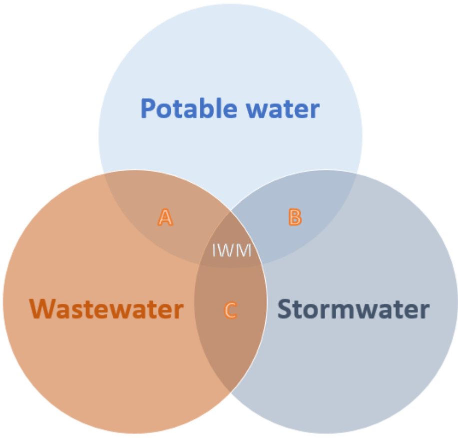

Figure 7 *Venn scheme of integrated water management*[27]

Firstly, A, aims to recycle grey water for potable water applications. Option B is the match between a sustainable supply options of drinkable water and the improvement of storm water quality: it can be obtained operating a rain and storm water reuse. To conclude, C choice intersects the application of wastewater treatment with the improvement of collected rains and

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[26] Energy-Water Nexus: Potential Energy Savings and Implications for Sustainable Integrated Water

Management in Urban Areas from Rainwater Harvesting and Grey-Water Reuse; P. A. Malinowski, A. S. Stillwell, J. S. Wu, P. M. Schwarz

[27] WSUD resilience to Climate Change; A. Hoban, T.H.F. Wong

to propose a reduced sewer overflows. Together, they constitute the integrated water management to be applied in urban context, to optimize the use of the resources within its cycle.

2.2 Water employments

The most relevant global water statistics are collected by AQUASTAT, which contains a database for the Food and Agriculture Organization (FAO) of United Nations, about land and water divisions. According to this source, the use of water worldwide is divided as reported in figure 8.

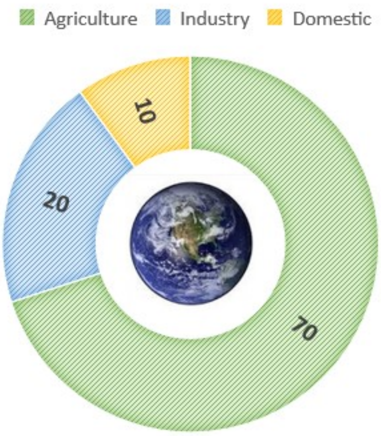

Figure 8 *Repartition of water withdrawal within the major sectors*[28]

As previously mentioned, the largest amount of water is required for agricultural purposes, followed by the industry (within it a substantial part is associated to power plants), while just a 10 % is devoted to domestic use. Across the World, the volume withdrawn changes significantly as provided by figures 9-11. The evidence shows that the more relevant consumers on Earth are China and U.S.A. Additionally, the countries which overcome the threshold of 50 Gm^3/year for agricultural purposes are Mexico, Iran, Philippines, Thailand, Uzbekistan, Vietnam, despite the notable lower demand for other applications.

[28] http://www.fao.org/nr/water/aquastat/main/index.stm

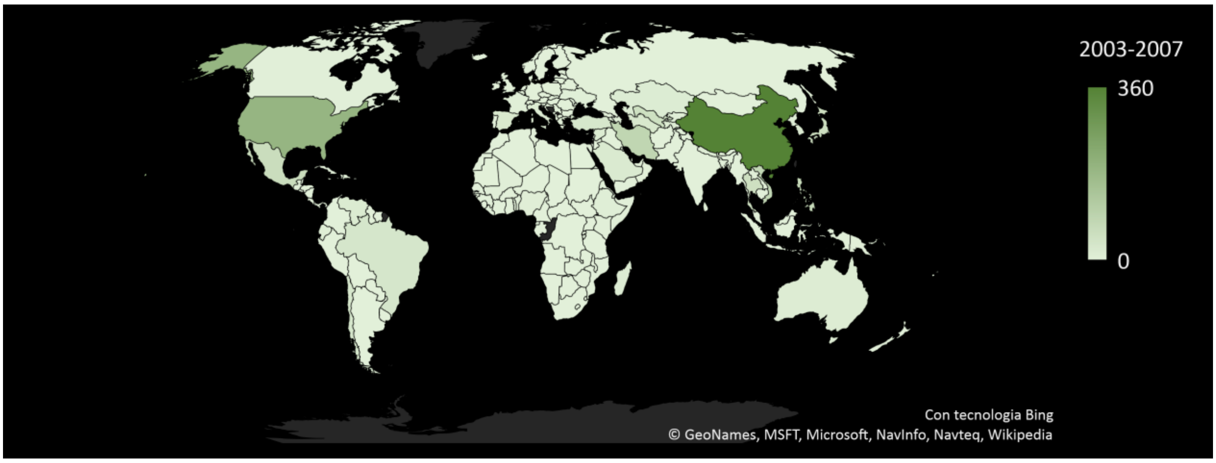

Figure 9 *Global agricultural withdrawal in billion m3/year*

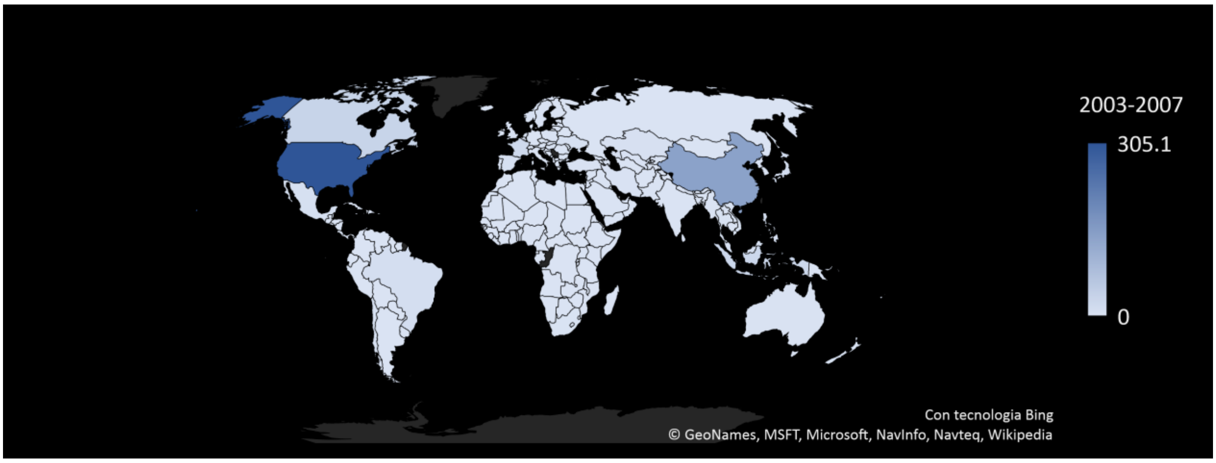

Figure 10 *Global industrial withdrawal in billion m3/year*

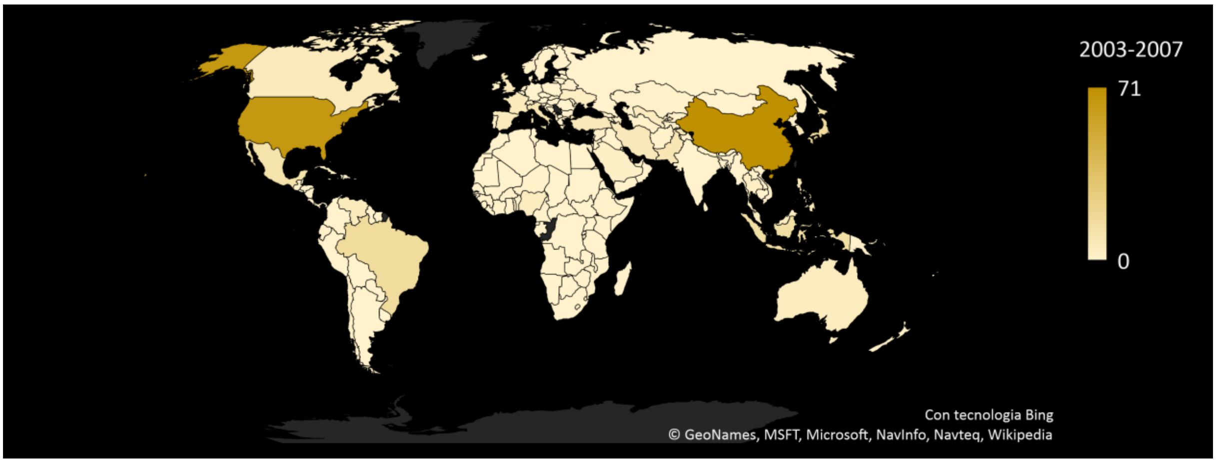

Figure 11 *Global municipal withdrawal in billion m3/year*

The evaluation of the average consumption per continent in the investigated sectors is reported in table 3.

Table 3 *Average water withdrawn per continents in 2003-2007 in yearly billion cubic meter*

	Agriculture	Industry	Municipal
Africa	2.03	0.14	0.31
Americas	18.59	15.97	5.35
Asia	26.24	4.67	3.35
Europe	1.79	1.56	1.04
Oceania	5.04	1.09	1.79

From these data, it is evident that agricultural applications are the most used worldwide, but Americas, Europe and Oceania do not follow the average breakdown showed in figure 8. In fact, for Americas, the percentages are 47, 40 and 13% (agriculture, industrial and municipal uses, respectively). For Europe, the distribution is more homogeneous. The data are incomplete since not all the countries are included and the quality of the data is affected by the method used to collect them. The figures, indeed, are obtained by external sources (other international agencies), estimated through models or obtained by aggregation when several sources were available. To visualize the variability of the data according to the four years of reference, figure 12 is provided.

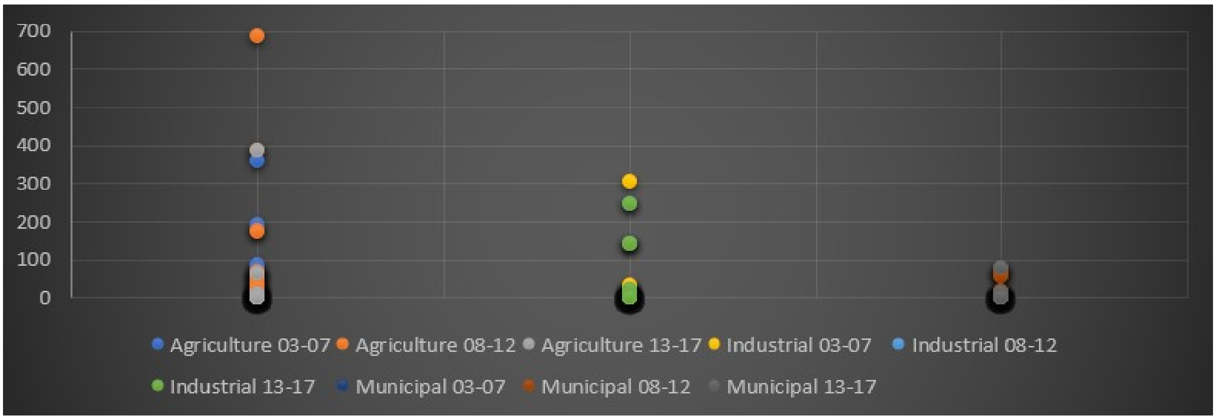

Figure 12 *Distribution of data per sector over the period 2003-2017*

Figures 9-11 are related to the withdrawal of water, concept that must be separated from consumption. The first idea is defined as the water removed from an original source to obtain a certain service, while the consumption account for the portion of the water removed from a source and that has evaporated, has been embodied into a product, or transferred to another sector or environmental matrix, like percolation into the ground[29]. The main difference lies in the return of the water into the original source.

2.3 Water needs for electricity production

In first instance, the needs of water in energy applications could be attributed to its direct use in hydroelectrically or steam-driven power plants. Additionally, a more comprehensive study of a power cycle would highlight its necessity for cooling applications. About cooling, it is interesting to split this field into the principal solutions adopted for this purpose: open loop, or once-through, and closed loop, where the most common technique involves cooling towers. The open loop is the least preferred one because it is associated with several environmental impacts[30]. Firstly, thermal pollution: water is collected from a river and after its employment as refrigerant is turned back to its source at higher temperature, thus affecting aquatic life. Secondly, both impingement and entrainment can occur during the phase of abstraction, where organisms can be trapped into pumps and pipelines of the cooling system.

Water is also used in the upstream processes (obtainment of the energy source) of energy production. To generalize water needs, the following categories can be distinguished[31]:

- Water for the fuel cycle (including all the processes like extraction, refining, mining etc.);
- Water for transportation (including the water associable to the fuel required by the form of transport);
- Water for generation (mainly electricity);
- Water for transmission (generally this degree of accuracy is not considered).

Following, a short description of water needs for each of the major energy sources is provided.

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[29] Sustainability of public policy: example from the energy–water nexus; A. S. Stillwell

[30] Integrating water resources and power generation: The energy–water nexus in Illinois; T.A. DeNooyer, J. M. Peschel, Z. Zhang, A. S. Stillwell

[31] Gaining perspective on the water-energy nexus at the community scale; D. Perrone, J. Murphy, G. M. Hornberger

2.3.1 Coal

Water is mostly needed in mining and in the conversion stages. The cooling technologies applied to coal-fuelled power plant are cooling towers, once through and ponds. The last solution requires the building of an artificial water body, nearby the power plant, where the refrigerant is discharged after its application. The energy dissipated by the condenser and provided to the coolant is then discharged to the pond, where it is released to the environment via evaporation. It is possible to distinguish water consumption within the coal-powered facilities since at least four kinds are available: besides the generic pulverized coal thermoelectric power plants, subcritical, supercritical and integrated gasification combined cycle (IGCC) exist. While the difference between sub and supercritical plants is in the physical state of steam generated by the coal, the IGCC is a technology which allows the generation of syngas from coal, hence its application for the Brayton cycle, and simultaneous recovery of primary combustion heat for driving a Rankine cycle. Coal is very polluting, and the major target of this negative behaviour is atmosphere. To deal with this unavoidable downside, systems of carbon capture and sequestration (CCS) are necessary: even considering the shifting to renewables, coal will play a significant part in the share of feedstock for electricity production for the closer future. The increase of water footprint associable to CCS calculated by Gerdes and Nichols[32] is about 87% for IGCC plants. Oxy-combustion is just one of the possibilities after which the capture and storage of carbon dioxide may be easier (just 56% more of water per MWh produced would be requested), but the application of membranes and solid adsorbents to be used in the future are even more promising.

2.3.2 Oil

The macro categories of water requirement in the oil sector are production and refining. In these areas, the phases of water use are: extraction and production of oil, refinery (in traditional way or with reforming and hydrogenation) and recovery, steam injection, water flood and other plant operations. The access and processing of both oil and natural gas have common steps such as drilling and seismic or geophysical exploration, but the most water demanding process is hydraulic fracking. This practice is largely used to promote the propagation of natural

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[32] https://www.globalccsinstitute.com/insights/authors/guidomagneschi/2015/01/02/how-does-carbon-capture-affect-water-consumption

underground fractures into hydrocarbons basins by using a pressurized fluid, which is composed mostly by water. The technique may cause the pollution of aquifers[33]: a study[34] done by Montcoudiol and colleagues revealed that despite a change in aquifer features like conductivity and ions presence due to fracking, no short-term contamination was detected in the Polish case study, while the Americans detected both heavy metals as well as odorous substances[35] and flammable methane[36] leakage into the tap water deriving from aquifer polluted by fracking. Downstream side (i.e., refinery to get by-products, cooling, steam production and process water) of the oil production together with operational step are the most water demanding. Additionally, minor applications are imputable to extraction (both off-shore and on-shore) and transportation[37] of oil.

2.3.3 Gas

As mentioned the supply chain of gas is significantly close to the oil one, so that the requirement and application of water are almost the same.

2.3.4 Nuclear energy

The attention on this technology has been focused just on uranium. The water use for enrichment plays the most relevant part in the withdrawal of water related to nuclear energy. Nuclear energy raises worries for its hazardous features and release of water polluted. In particular, boiling water reactors (BWR) are most likely to be noxious since the steam generated through the contact with the fissile material is directly run by the turbine and this happens outside the containment building, thus a potential leakage would release contaminant water.

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[33] https://www.usgs.gov/faqs/how-hydraulic-fracturing-related-earthquakes-and-tremors?qt-news_science_products=0#qt-news_science_products

[34] Shale gas impacts on groundwater resources: Understanding the behaviour of a shallow aquifer around a fracking site in Poland; N. Montcoudiol, C. Isherwood, A. Gunning, T. Kelly, P. L. Younger

[35] The Fracturing of Pennsylvania; E. Griswold

[36] Study: High-Tech Gas Drilling Is Fouling Drinking Water; R.A. Kerr

[37] https://corporate.exxonmobil.com/en/current-issues/water/water-and-energy/water-use-in-oil-and-gas-industry

The situation is different for pressurized water reactors (PWR), where the contaminated water is used, inside the containment structure, as thermal vector to produce steam in the steam generator and several barriers are included for a potential release. Pools in which exhausted fuel is stored for no less than 15 years have to be considered as belonging to the water chain for nuclear application; this wastewater has to be treated extensively due to the high contamination caused by the contact with the products of fission reaction.

2.3.5 Biopower

Biomass, bio-fuels, biogas etc. are merged in this category. Biofuels will play a crucial role in the transition from fossil to renewable energy. In spite of their reduced impact on climate change, the three sources have a serious matter of concern, one of which is related to water use. The water requested in the production of biopower is very high: figure 13 reports the amounts of water demand per feedstock to get a gallon of ethanol.

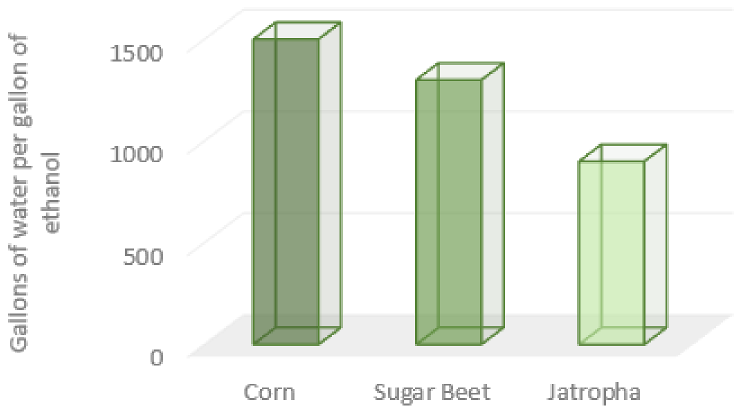

Figure 13 *Water withdrawn to produce one gallon of ethanol*[38]

Wood ligneous or agriculture waste or even other kind of biomasses can be employed to produce syngas or directly burned to run boilers in the power cycle. For these applications, the water withdrawal is the same of previously analysed fossil fuel and it concerns the refrigeration phase of the cycle.

[38] http://biofuel.org.uk/water.html

2.3.6 Geothermal

Heat in the subsoil can be exploit both directly and indirectly to produce power. Geothermal energy exploits water both as coolant and working fluid. It is a common practice to apply geothermal fluid rather than freshwater for cooling requirement[39]. For the good operation of the plant, other activities which could be water-demanding are dust suppression, drilling fluid and reservoir stimulation as well as to clean the equipment.

2.3.7 Hydroelectric

In the direct conversion of the energy associated to the motion of water into mechanical energy the typical water flow rate is large, and directly related to the power to be generated. The hydroelectric technology can be fed by a river or by artificial reservoirs, which can in turn be multipurpose or dedicated.[40] Water is usually withdrawn and used for its potential content and next discharged into an outflow basin or into a river. The main cause of water consumption in hydroelectric power production is evaporation while, during phase of construction of the plants, it is primary due to evapotranspiration of the vegetation surrounding the water body. However, as the size of hydropower plants can vary significantly, so does the amount of water withdrawn to run these systems, for this reason when a range of water use for this kind of application is provided, the difference between maximum and minimum is extremely large.

2.3.8 Solar

Solar technologies can be distinguished in solar thermal and electric ones. Photovoltaic systems use little quantities of water: this technology is not fed by water nor cooled, thus the only instance of water use is related to the cleaning of the receiving surface, in order to maintain the performance of the panels high. On the other hand, concentrated solar power processes have the same features of a traditional power plant (use of water for steam generation and cooling

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[39] NREL - A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generation Technologies

[40] Analysis of Water Consumption Associated with Hydroelectric Power Generation in the United
States; D. J. Lampert, U. Lee, H. Cai, A. Elgowainy

purpose), no matter if the technology is a Fresnel, parabolic trough, Stirling, or concentrated tower.

2.3.9 Wind

Strictly speaking, wind turbines, are another medium of power production at near zero-water cost. In fact, if the water necessity for the manufacturing of the wind park is excluded, water has no applications during the operation of this technology.

3. Energy: classification, sources, and needs for water supply

Human activities have always been energy dependent. Nowadays, the most popular forms of energy are electrical and thermal[41]. The main sources of energy for electrical power generation have been dealt with in the previous chapter. Global energy statistical yearbook provides a picture of energy breakdown[42] in 2017, as shown in figure 14.

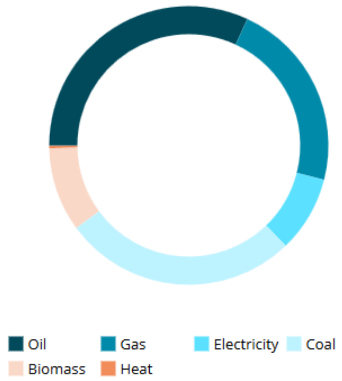

Figure 14 *World's energy repartition in 2017*

The share of fossil fuel is 59% of the total energy and it is associated to oil (32%) and coal (27%). The energy mix is naturally dissimilar in different regions, but the distribution in the major world's consumer for this last year (China with 3,105 Mtoe and U.S.A. 2,201 Mtoe) exceeded half of the total amount. The most relevant consumers of energy belong also to the list of the major water consumers.

A distinction between energy sources is provided, describing briefly how each of them is generated or available. Later, an outline of energy use in the world is available, accompanied by an investigation of energy requirements in the water field.

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41 https://physics.info/energy/

42 https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html

3.1 Energy classifications and sources

The most widely known distinction in the energy field is between renewables and non-renewables, where the principal members of the latter category are fossil fuels. An energy source can be defined as renewable in case it can be restored in a relatively short timescale compared to human life expectation[43]. Once this definition is set, it is possible to differentiate two classes:

- Renewables: solar, wind, hydropower, biomass, oceanic energy;
- Non-renewables: coal, oil, natural gas.

Some sources, like nuclear and biofuels[44], are actually in a grey zone and their definition is still cause for debate. Concerning nuclear, mineral fuels like uranium are used to run the fission reaction. Even if the mass energy content of nuclear sources is remarkably high compared to the other fuels, as shown in table 4, the required fuel, enriched uranium, is not so easy to get.

Table 4 Mass energy density of the main energy technologies

Energy technology	Energy density [MJ/kg]
Fuel cell	1.6
Coal	30
Oil	41.8
Biodiesel	42.2
Propane	49.6
Butane	49.1
Natural gas	55.6
Hydrogen	143
Enriched uranium	3,456,000

[43] Renewable energy resources: current status, future prospects and their enabling technology; E. Omar, A. Haitham, B. Frede

[44] https://www.nationalgeographic.org/encyclopedia/non-renewable-energy/

The definition of nuclear as renewable lies into the association of renewable energy sources with those that are low carbon emitting. Strictly speaking, this feature is better associable with a sustainable energy source rather than a renewable one and in this sense nuclear power is sustainable but not renewable. Biofuels are also object of debate: sustainability is due to the fact that the carbon emitted by a burned biomass equals that absorbed during the photosynthesis process. But the environmental benefit exists only if the consumption of this fuel occurs close to the production location, otherwise its transportation would generate an imbalance in the carbon stability. One more "time-dependent" definition of energy sources can be highlighted, related to the possibility to forecast the availability of an energy source as schedulable or fluctuating. The non-continuous availability of sources like wind or sunlight, make wind turbines and solar technologies (both thermal and electric), to be inconstant (without a storage). Also for this reason, the traditional thermoelectric power plants fed by coal, natural gas and oil, and the nuclear plants are the most widely used to cover the base load, since their application can be scheduled, while the previously mentioned sources are involved into the coverage of the peak loads.

Apart from the refined products and the enriched uranium, a significant part of the rest of the other feedstock used for energy generation is originated from the action of the Sun. Except from its direct use in thermal solar collector, photovoltaic panels and concentrated solar power, the Sun is also responsible for the generation of winds, waves, tides, biomass and is a relevant part of the water cycle.

3.2 Energy use

According to the international energy agency (IEA), in 2015[46] the share of final energy consumption in the World recorded 36.6 % for the "other" sector and 31.7% and 31.6%, respectively, for industry and transportations. Belonging to the first category are several sectors

[46] https://www.iea.org/statistics/?country=WORLD&year=2015&category=Key%20indicators&indicator=TFCShareBySector&mode=chart&categoryBrowse=false&dataTable=BALANCES&showDataTable=true

like residential, commercial and public services, agricultural, fishing and chemical or petrochemical, as visible in detail in figure 15.

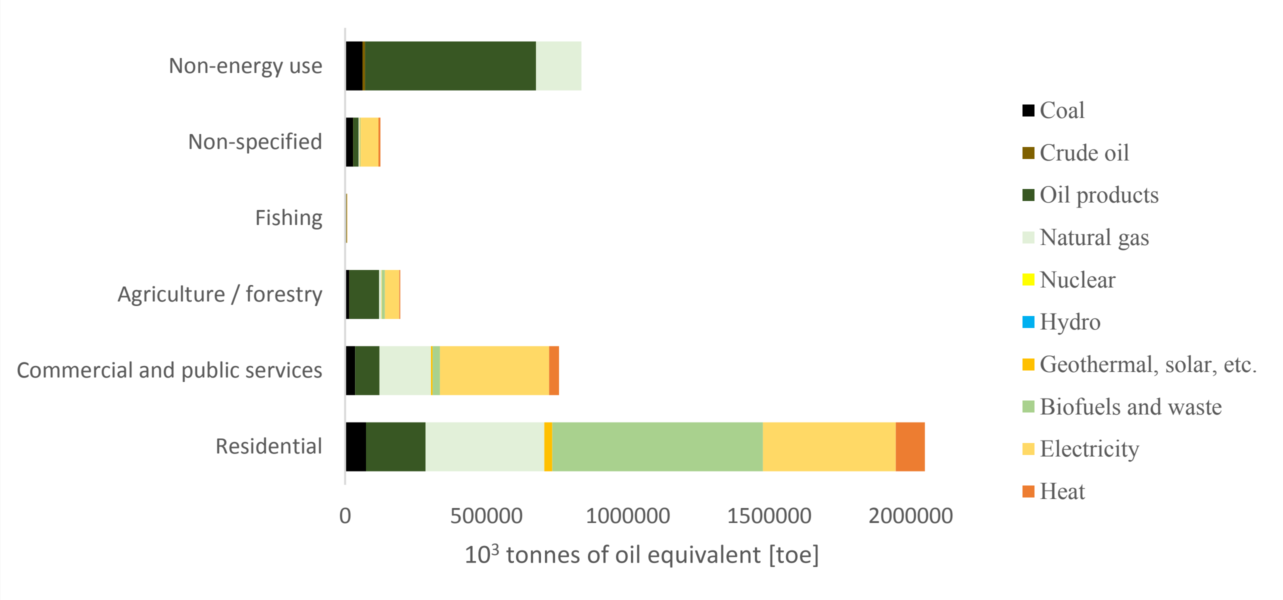

Figure 15 Final energy requested by "other" in the World in 2015 (IEA)

The residential sector is the most energy-demanding worldwide, and its request of final energy accounts for 65% of the "other" slice. The amount requested for residential purposes (2,050,573 ktoe) is comparable with the industrial (2,712,374 ktoe) and transportation (2,703,003 ktoe) sectors, while all the other sectors in figure 15 are below the value of one billion of toe.

To have a complete view of the highest final energy consumers, IEA proposed the following list of industries:

- Food;
- Pulp and paper;
- Chemicals;
- Refinery;
- Iron and steel;
- Non-ferrous metals;
- Non-metallic minerals.

In this overview, the use of energy for water purposes is not mentioned. However, in another document, IEA provided the data of electricity consumption for water purposes. Electricity (apart from thermal energy for desalination purposes) is basically the only kind of energy used for water treatment and distribution. In 2014, electricity allocated for water was 800 TWh[47], thus about 68 million of toe. If these data are compared with the electricity consumption of the three-main global sectors of 2015, water is 38-45 times less demanding than the main energy-consuming sector in the World. In the worldwide energy consumption for water, the applications involved are, in descending order: reuse, desalination, transfer, distribution, water treatment and supply. The projection provided to 2040 reveals a growth of global energy demand of 81% with respect to the reference year (2014). Apart from distribution and supply that will be kept at the same level of energy demand, the classes which will experience a notable increase are transfer, water treatment and desalination. Future concerns are related, as highlighted, to water scarcity and increased availability of drinkable water using alternative water sources.

3.3 Energy needs for water supply

The employment of energy for water supply is defined as the energy required to ensure that water reaches the appropriate quality for a specific purpose or before its discharge into the environment, plus its distribution or discharge[48]. The main energy required for water treatment and distribution is electricity.

3.3.1 Drinking Water Treatment and Supply

The conventional provision of drinking water is characterized by pumping systems, wells, purification, and distribution networks. The abstraction of groundwater is certainly more energy demanding than that of surface water, due to the resistance of the soil: it was reported that about 30%[49] less electricity is necessary for this step dealing with surface water. Conversely, the energy needed by treatments to be applied for surface water is generally than that needed to treat groundwater, due to the higher contamination of surface waters.

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[47]https://www.iea.org/newsroom/energysnapshots/electricity-consumption-in-the-water-sector-by-process.html

[48] Evaluation of Spain's Water-Energy Nexus; L. Hardy, A. Garrido, L. Juana

[49] http://www.un.org/waterforlifedecade/water_and_energy.shtml

3.3.2 Desalination

The application of this technique is actually applied mainly by the countries that have a lack of fresh water and becomes particularly attractive for populations living close to the sea and oceans. It is estimated that desalination matches the need of 75 million people in the World (the majority of which is located in MENA), using both seawater and brackish waters as influent[50]. This specific task can be reached through several technologies and electricity is not the unique energy form to be applied. Multi stage flash (MSF) or multi-effect (MED) distillation processes are a possible way to reach the goal of removals of ionic species by using thermal energy. Other technologies include reverse osmosis (RO), electrodialysis (ED) and vapour compression (VC). The list of possible applicable technologies is not over, but these are the more interesting ones for their maturity and implementation.

In RO, the driving force is the pressure gradient to win the osmotic pressure of the salty feed solution. The typical pressures are shown in figure 16, as well as the main elements retained.

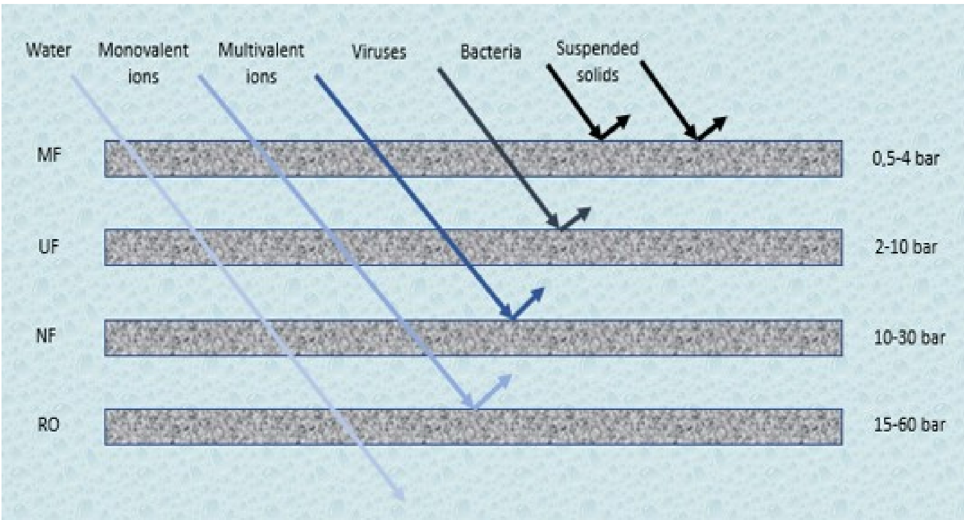

Figure 16 *Membranes classification and pressure range needed for the removals of the presented species*

The consumption of energy associated to the membrane technologies is mainly devoted to the pumps used to reach appropriate pressure. Other phenomenon increasing the energy demand of membrane-based desalination is fouling, the accumulation of substances on the surface of the

[50] Life-cycle uses of water in U.S. electricity generation; V. Fthenakis, H. C. Kim

membrane, leading to a progressive reduction of the performance of the system. A range of energy requirement between 1.5 and 2.5 kWh/m^3 is reported for RO desalination, but also in this case the influent nature is relevant: for brackish water, due to a lower TDS content, the pressure may be reduced and thus the requirement can be about 1.5 kWh/m^3 [51]. Additionally, the integration of energy recovery systems can lead to a further reduction of the energy needed by introducing into the layout a hydraulic turbine.

After membrane-based technology, the most diffused technology is the thermal distillation. To be precise, the MSF technology needs thermal energy in the form of both low and medium pressure steam, but also a quote of electricity. The working principle is the following: salty water is preheated and subsequently passed through the stages of the desalination unit. The pressure level decreases with respect to the proceeding stage, hence a partial flash of vapour is obtained, vapour is then condensed as fresh water, while the remaining brine is sent to the following chamber. The electricity is simply required for the pumping of the fluid, while the thermal energy is used to increase the brine temperature in the brine heater before it enters the flashing section. To reach the first operating temperature (90-110 °C), an external thermal source is necessary. However, the latent heat of the flashed steam can be recovered during condensation and recycled. The combination of these two forms of energy amounts to about 10-15 kWh/m^3 [52], of which 3.5-4 kWh/m^3 is the share of electrical energy.

Electrodialysis uses an electrical gradient as driving force to separate the species according to their charge. The only energy requirement is electricity: direct current can be applied on anodes and cathodes, while alternate or direct current can be used for pumping purposes. The energy requirement is directly connected to the salinity of the inflow thus, medium salty brackish water needs 0.7-2.5 kWh/m^3 while the requirement is in the range 2.6-5.5 kWh/m^3 for seawater.

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[51] Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes; A. Al-Karaghouli, L. L. Kazmerski

[52] Conventional Thermal Processes; H. Ettouney

Vapour compression (VC) can be either thermally- (TVC) and mechanically- (MVC) driven. The common step is the generation of vapour in a heat exchanger before compression. After that, the interaction with both nebulized seawater and recirculated brine makes the freshwater condensate. The energy requirement can vary significantly for this process: MVC needs only electricity in a range 7-12 kWh/m3, while TVC necessitates 1.6-1.8 kWh/m3 of electricity and an electrical to thermal equivalent amount of 14.5 kWh/m3.

3.3.3 Wastewater Treatment

Standards for wastewater discharge or reuse can vary worldwide and, for different sectors and applications, treatment can be classified as primary, secondary and tertiary or according to the predominant features involved, hence physical, chemical and biological. Concerning the first compilation of treatments, they can be distinguished according to their purpose as listed in table 5.

***Table 5** Main water treatments according to their scope*

Primary treatments:	Gravity separation, flotation, filtration
Task:	Sedimentation of solids, removals of heavy solids and floating materials
Secondary treatments:	Activated sludge, trickling filters, rotating biological contactor, membrane bioreactors
Task:	Oxidation processes
Tertiary treatments:	Adsorption, ion exchange, other oxidative treatments
Task:	Removals of undesired species like nitrates, phosphates, micropollutants, nutrients and disinfection

Moreover, the second classification groups the treatments according to the principal feature that characterizes the process. Physical treatments are based on the application of physical forces in a non-destructive way and generally they are the cheapest and the first to be applied in most of the wastewater treatment systems (table 6).

Table 6 List of the main physical processes and their energy request[53]

Physical process:	Energy use:
Mechanical separation	Generation of compressed air for the process
Sedimentation	Feeding of mechanical sludge removals on the bottom
Filtration	Keep the vessel pressurized for closed pressure filter, mechanical equipment needed by rotary vacuum filter
Adsorption*	Regeneration of the adsorbent
Ion exchange*	Keep the vertical cylinder pressurized in which lays the resin bed and restore it

*They are physic-chemical processes

Besides the pumping system, the consumption of energy can be associated to other mechanical devices, necessary for the operations of each process. Unfortunately, specific data about the energy consumption of these techniques are not easily available: as an example, primary physical filtration needs roughly 0.0016 kWh/m^3 to overcome a head loss of 0.6 m[54]. Chemical treatments are destructive as the removal of the pollutants is due to their reaction with chemicals. Examples include coagulation and flocculation for the removal of colloidal elements, precipitation to eliminate suspended solids, redox reactions to remove grease, ammonia, BOD, COD and to adjust the odour, disinfection to inactivate pathogens. Since the main feature of these processes is the application of chemicals to the influent to be treated, the main significant consumption of energy is associated to the pumps and the stirring devices needed to guarantee a sufficient turbulence in the fluid or feeding of the reactors.

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[53] Best Available Techniques (BAT) Reference document for common waste water and waste gas treatment/management systems in the chemical sector; T. Brinkmann, G. G. Santonja, H. Yükseler, S. Roudier, L. D. Sancho

[54] Principles of water treatment; K. J. Howe

The last category to be dealt with is biological treatment, which is denoted by the employment of microorganisms to degrade the organic compounds and uptake nutrients. Table 7 reports the main biological processes.

Table 7 List of the main biological processes and their energy request

Biological process:	Energy use:
Anaerobic treatment	Thermal energy to keep the optimal condition required by the bacteria (mesophilic or thermophilic)
Aerobic treatment	Mechanical aeration
Nitrification/denitrification	Aeration, mixing
Activated sludge processes	Aeration, mixing
Membrane bioreactor	Mixing, aeration, pumping the influent as required by the membrane

A relevant benchmark to be introduced dealing with biological treatment is the amount of energy consumed per unit of mass of degraded chemical oxygen demand (COD). The COD is a quantity indicative of the amount of oxygen required to oxidize both organic and inorganic substances using a chemically oxidizing agent[55]. In line with this purpose, the best available techniques reference document (BREF) for wastewater treatment, shows that the activated sludge process (ASP) is, in most of the cases listed, the process with the lower energy demand, while membrane bioreactors are more energy-intensive (six or ten times the energy needed in the average ASP), while the coupling of the two technologies has intermediate consumptions.

[55] http://goldbook.iupac.org/html/C/C01031.html

4. The water-energy nexus: Estimation of resource interlinked needs

The previous chapters have been devoted to the qualitative analysis of interrelation between the two resources, water and energy. This chapter aims to answer the following questions:

- What is the water withdrawn by a country to produce energy according to its energy mix?
- What is the electricity withdrawn by a country to supply water according to its water mix?
- What is the resulting hidden quantity of water required to purify one volumetric unit of water based on the energy needs for water supply?

To perform these analyses, three representative countries are selected, and their electricity and water mix analysed. Once the profile of each country is defined, a weighted allocation of energy consumption for water supply and a water use for energy request is obtained. By evaluating the change in the energy mix (in short and long-terms scenarios) the sensitivity of the quantities under investigation is computed with respect to the energy roadmap. An evaluation of the effect of a change in water mix is also applied, to quantify the "water for water" needs. The same methodology is applied to estimate the corresponding consumed quantities, so that the water consumed for energy generation is provided.

4.1 Water and energy mixes for each country

Three reference cases were chosen to guarantee an adequate variety of the analysed profiles: specifically, a large, medium and low energy and water users were considered. From a water point of view, figures 9-11 already provided that the most relevant global actors in this sector are China and U.S.A., while the lowest are not easy to define. To overcome the inadequacy of this parameter for the selection of appropriate countries, a water stress parameter can be a proper methodology. One possible and simple way is the evaluation of the Falkenmark indicator (FI):

Equation 2 Falkenmark indicator for water stress evaluation

$$FI = \frac{SR}{P}$$

Where SR is the surface runoff (generally the mean annual value is used) evaluated in m3/y and P the population expressed in number of inhabitants. According to this statement is possible to distinguish four[56] classes of countries as shown in table 8.

Table 8 Classification of water stress of a country according to Falkenmark index

Falkenmark Indicator [m^3/y-p]:	Stress level:
>1,700	No stress
1,000-1,700	Stress
500-1,000	Scarcity
<500	Absolute scarcity

This indicator revealed that notwithstanding the large withdrawals in China, its FI in 2015[57] was 425 m^3/y-p, associated with an "absolute scarcity" in this country. On the contrary, U.S.A. is on the edge of the "no stress" category (1,543 m^3/y-p in 2010) and it was selected as the country with large water needs. The intermediate band was covered by Italy, which was selected since its FI sits between the "scarcity" and the "stress" categories (899 m^3/y-p in 2008). Finally, the "absolute scarcity" country was Morocco, with an FI of 316 m^3/y-p reported in 2010.

The water mix contains the following classes of source:

- Surface water;
- Groundwater;
- Wastewater;
- High-salinity water.

[56] Mapping of water stress indicators; P. Ruess

[57] http://www.fao.org/nr/water/aquastat/data/query/results.html

The electricity mix is composed by:

- Natural gas;
- Coal;
- Oil;
- Nuclear;
- Geothermal;
- Biomass;
- Solar electric (PV);
- Solar thermal (CSP);
- Wind (offshore and onshore).

The energy mix of 2015 is used as reference case, for two reasons: firstly, due to the consistency of the data source (IEA for each country), secondly to address the change of a past recent configuration compared to a current (2017) and a future one (2040). The water mix data were taken from AQUASTAT database, while the energy related quantities were obtained by consulting documents published by the I.E.A., E.I.A., N.R.E.L., B.P., G.S.E., Terna, WindEurope, or Ministero dello Sviluppo Economico. The energetic and water mix of these three countries is thus provided.

4.1.1 U.S.A.

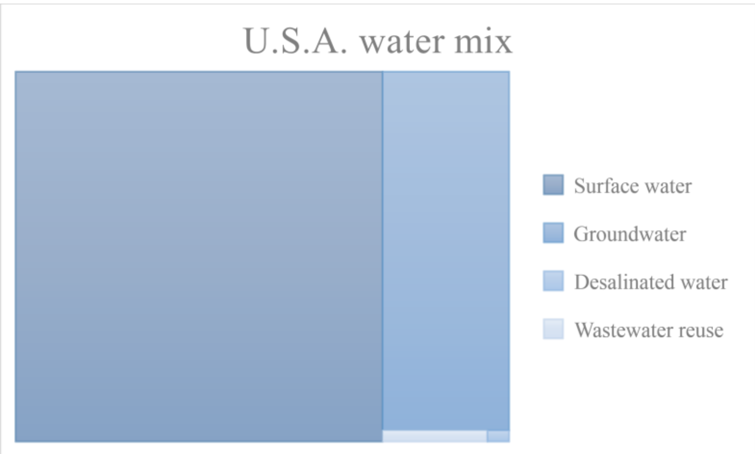

Figure 17 *Repartition of water in U.S.A.*

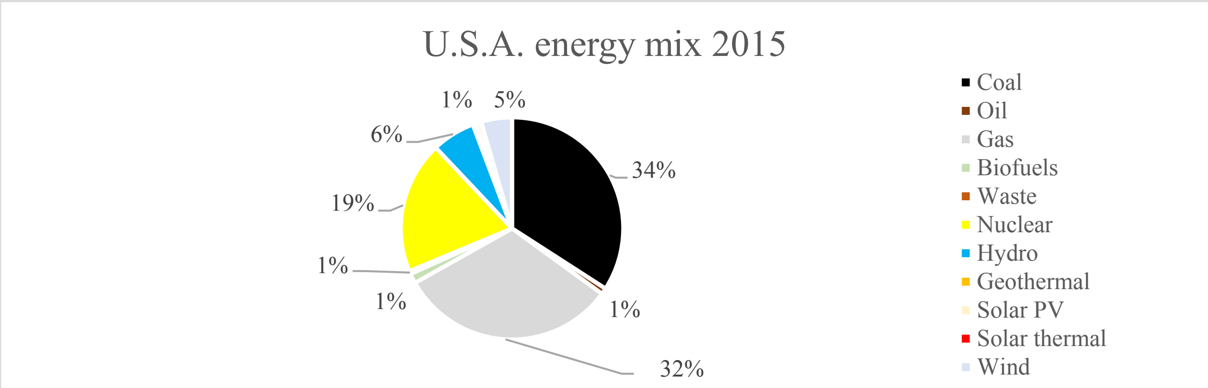

Figure 18 Electricity generation breakdown by fuels in U.S.A.

Figure 17 provides a qualitative repartition of water sources in the United States. Surface water dominates (74.3%), followed by groundwater (24.8%), while a very negligible share is associated with salty water (0.13%) and wastewater (0.65%).

By the observation of the energy mix, it is evident that fossil fuels dominated the generation of energy (about 67% of the total was covered by coal, oil and natural gas) in 2015, with another significant actor being nuclear power (19%). Within the renewables, the largest contribution was from hydro power (6%), while the other renewable sources did not contribute significantly (about 6% of the share). Figure 19 provides the electricity generation mix for the two different years investigated.

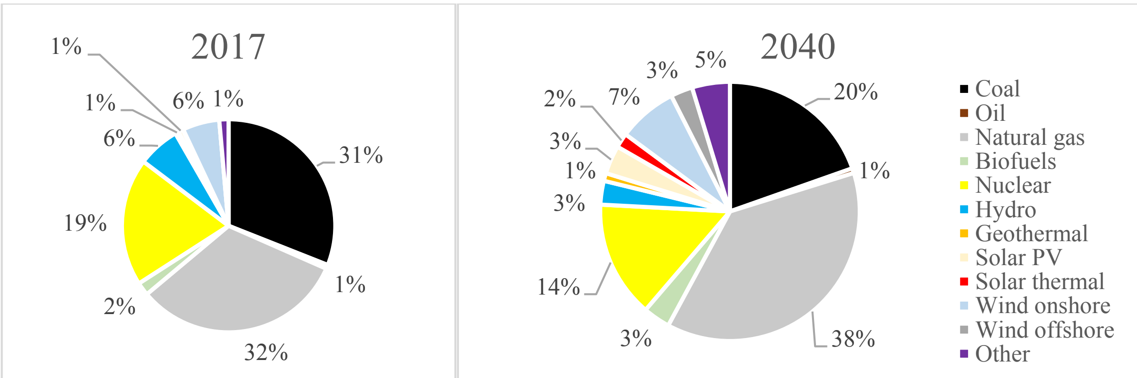

Figure 19 American energy mixes for 2017 and 2040

4.1.2 Italy

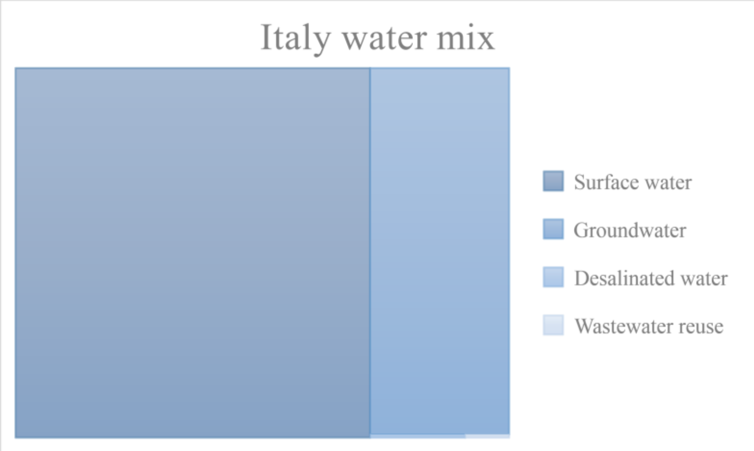

Figure 20 *Repartition of water in Italy*

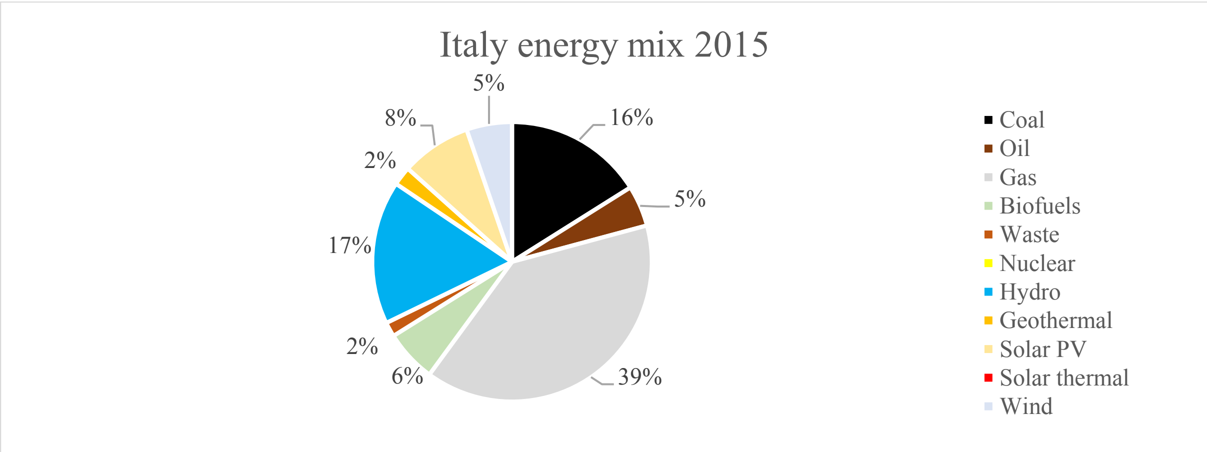

Figure 21 *Electricity generation breakdown by fuels in Italy*

The water mix in Italy reveals a repartition not so different from that of the United States of America: surface water represents 71.8%, groundwater 27.9%, and desalinated and wastewater, respectively, 0.18% and 0.08% of the total amount of water allocated for high-end uses.

The energy mix of 2015 reveals a significant use of fossil fuels (mainly natural gas, accounting for 39% of the chart), but in the Italian case, fission-fed power is substituted with hydro power, solar electric and wind (respectively 17, 8, 5 %). The energy mixes for the additional years are provided in figure 22.

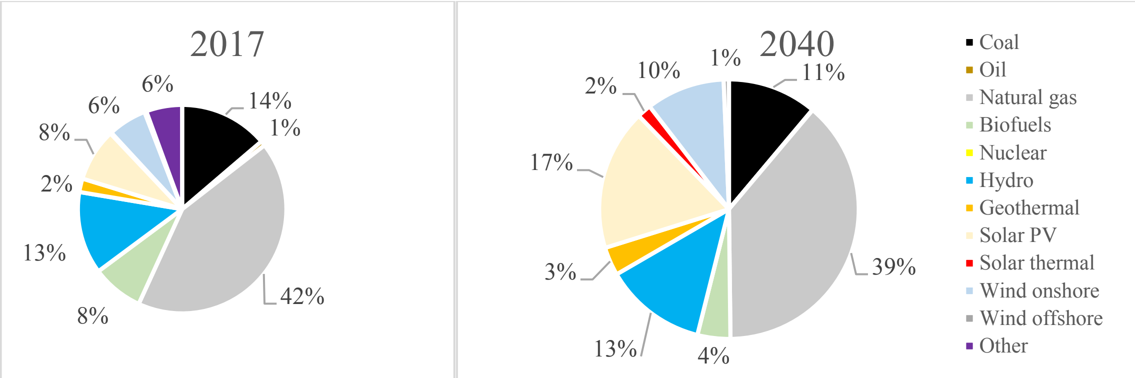

Figure 22 *Italian energy mixes for 2017 and 2040*

4.1.3 Morocco

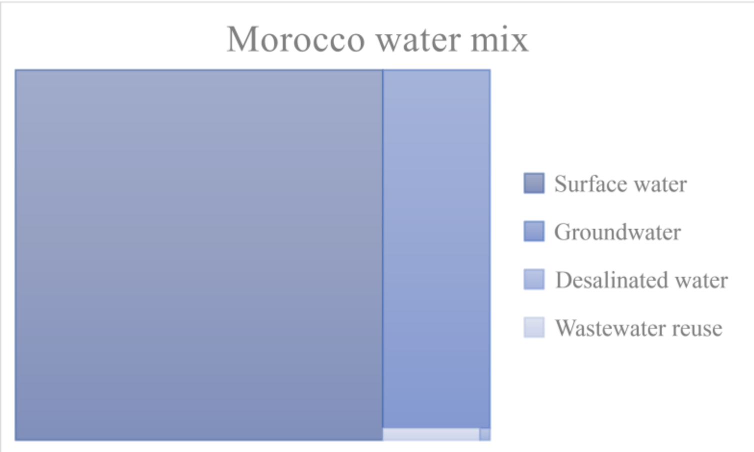

Figure 23 *Repartition of water in Morocco*

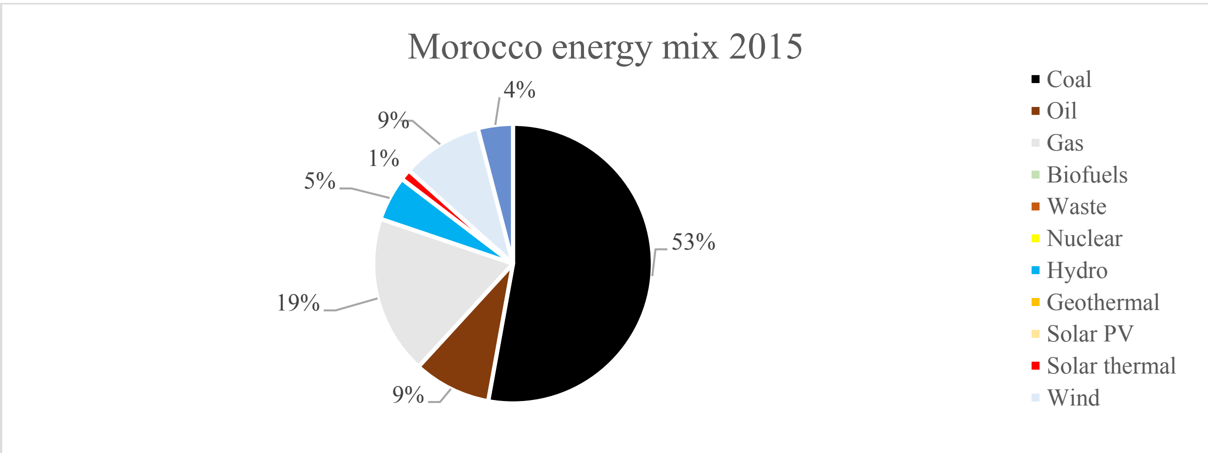

Figure 24 *Electricity generation breakdown by fuels in Italy*

The split of water mix for Morocco is very similar to the other previously shown cases: 77.4% is the quote of water coming from surface freshwater, 21.8% from groundwater and the remaining percentage is shared by desalination (0.06%) and reused wastewater (0.6%).

The electricity generated by Moroccan power plants is mainly from fossil fuels, accounting for 81% of the production considering coal (alone weighting for 53%), oil (whose contribution is a non- negligible 9%) and gas (19%). Current and predicted energy mixes are provided in figure 25.

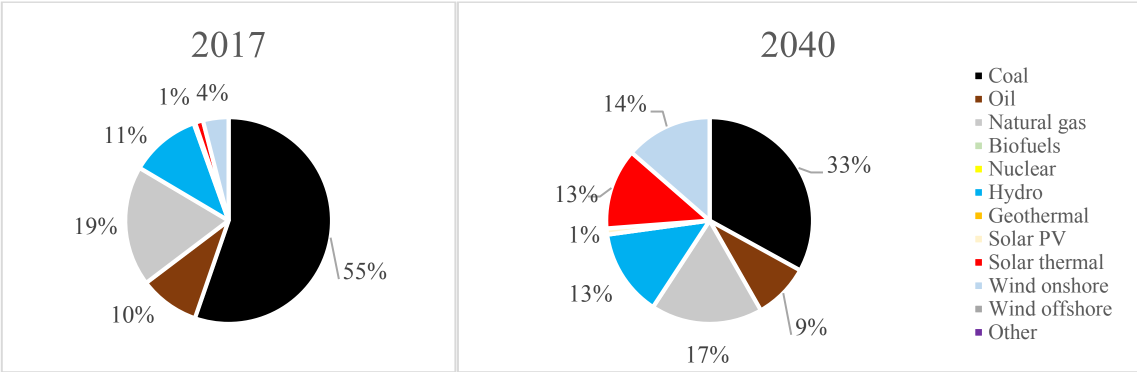

***Figure 25** Moroccan energy mixes for 2017 and 2040*

4.2 Primary data assessment

The electricity needed to supply water in each category was extracted by previous studies and results are shown in table 9. Before providing the results, the main assumptions are highlighted:

- Desalination value includes both brackish water and seawater;
- A single value instead of an interval was available for groundwater treatment energy requirements;
- For seawater desalination, only membrane-based systems were considered (i.e., RO systems);
- The values refer to the entire treatment train (i.e., values for desalination also include pre- and post-treatment).

Table 9 Energy needed to purify each water source[58,59]

Kind of water	Electric consumption [kWh/m^3]	
	Min	Max
Surface water	0.2	0.4
Groundwater	0.48	0.48
Wastewater reuse	1	2.5
Seawater desalination	2.6	8.5

The reported values are provided as ranges, due to their variability according to the features of the influent to be treated as well as the location of their application. Groundwater needs more energy for its treatment than surface water. Generally, groundwater is less polluted due to the direct interaction of surface water with human activities and additionally because the ground acts as a natural filter to clear the liquid stored below the ground level. Therefore, groundwater needs mostly a filtration, ionic exchange and disinfection steps before its supply, while things are more complex for surface water, which could require screening, flocculation and several levels of filtration before being disinfected and supplied. However, the pumping operations to pump groundwater from an aquifer affect the overall energy demand to purify this source. To have a clear overview of the variables affecting the energy required for groundwater pumping it would be necessary to account for the distance from which it has to be lifted, the friction losses (dependent on the kind of soil), the flow rate to be pumped and obviously the pressure to be applied[60]. It must be highlight that the figures provided in table 9 are not accounting for the distribution of purified water, but only the energy requirements for the quality enhancement of the listed water sources. The impact of the distribution step will be discussed later.

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[58] Creating low carbon cities; S. Dhakal, M. Ruth

[59] Water-energy interactions in water reuse; V. Lazarova, K.Ho Choo, P. Cornel

[60] Energy requirements for water production, treatment, end use, reclamation and disposal; A.K. Plappally, J.H. Lienhard

Concerning the water withdrawn to produce electricity, the focus was on the quantities related to fuel cycle, power plant, and operation. However, for obvious reasons, this classification could not have been applied to all the energy technologies: dealing with water requirement in the operation stage, the water withdrawal is mainly related to refrigeration, except for technologies like photovoltaic and wind, for which water is used for cleaning, or maintenance. Data are affected by the area in which these technological activities are performed. To simplify the evaluation, an interval of data has been used as provided by Meldrum[61] et al. which harmonized the values belonging to the state of the art. The validity of the data, available in table 10, is confirmed from their comparison with those provided by the World Energy Outlook by the IEA (2016).

Table 10 *Water withdrawn for energetic applications*

	Subcategory	Phase [m^3/kWh]	Min	Max
Oil	Fuel cycle	Mining	1.50×10^{-5}	2.58×10^{-5}
		In situ	5.83×10^{-6}	7.00×10^{-5}
	Power plant	Upstream and downstream	3.79×10^{-6}	3.79×10^{-6}
	Operation	CC: cooling tower	5.68×10^{-4}	2.88×10^{-3}
		CC: open loop cooling	2.73×10^{-2}	7.95×10^{-2}
		CC: pond cooling	2.27×10^{-2}	2.27×10^{-2}
Coal	Fuel cycle	Surface mining	2.27×10^{-5}	2.27×10^{-4}
		Underground mining	6.44×10^{-5}	8.71×10^{-4}
		Extraction (surface)	4.92×10^{-5}	4.92×10^{-5}
		Extraction (underground)	6.81×10^{-4}	6.81×10^{-4}
		Processing	3.79×10^{-3}	3.79×10^{-3}
	Power plant	Upstream and downstream	3.79×10^{-6}	4.54×10^{-5}
	Operation	PC: cooling tower	4.54×10^{-3}	4.54×10^{-3}
		PC C CCS: cooling tower	5.30×10^{-3}	5.30×10^{-3}
		PC: open loop cooling	2.16×10^{-1}	2.16×10^{-1}
		PC: pond cooling	9.84×10^{-2}	9.84×10^{-2}

[61] Life cycle water use for electricity generation: a review and harmonization of literature estimates; J. Meldrum, S. Nettles-Anderson, G. Heath, J. Macknick

Natural gas	Fuel cycle	Conventional natural gas	1.51×10^{-5}	1.29×10^{-4}
		Shale gas	1.89×10^{-5}	8.33×10^{-4}
		Drilling	3.79×10^{-6}	7.19×10^{-5}
		Fracturing (shale gas)	3.79×10^{-6}	7.04×10^{-4}
		Processing	3.79×10^{-6}	3.79×10^{-6}
	Power plant	Upstream and downstream	3.79×10^{-6}	3.79×10^{-6}
	Operation	CC: cooling tower	5.68×10^{-4}	2.88×10^{-3}
		CC C CCS: cooling tower	1.85×10^{-3}	1.93×10^{-3}
		CC: open loop cooling	2.73×10^{-2}	7.95×10^{-2}
		CC: pond cooling	2.27×10^{-2}	2.27×10^{-2}
Nuclear	Fuel cycle	Centrifugal enrichment	4.92×10^{-5}	1.14×10^{-3}
		Diffusion enrichment	2.35×10^{-4}	1.55×10^{-3}
		Extraction (surface)	1.89×10^{-5}	3.48×10^{-4}
		Extraction (underground)	3.79×10^{-6}	9.08×10^{-4}
		Processing (centrifugal enrichment)	1.14×10^{-5}	2.27×10^{-5}
		Processing (diffusion enrichment)	1.93×10^{-4}	4.54×10^{-4}
		Processing (fuel fabrication)	3.79×10^{-6}	1.14×10^{-5}
		End-of-life (storage and disposal)	3.79×10^{-6}	1.89×10^{-5}
		End-of-life (reprocessing spent fuel)	2.73×10^{-3}	2.73×10^{-3}
	Power plant	Upstream and downstream	3.79×10^{-6}	3.79×10^{-6}
	Operation	Cooling tower	3.03×10^{-3}	9.84×10^{-3}
		Open loop cooling	8.71×10^{-2}	2.27×10^{-1}
		Pond cooling	1.89×10^{-3}	4.92×10^{-2}
Biomass	Operation	Cooling tower: biogas	1.82×10^{-3}	3.65×10^{-3}
		Cooling tower: steam	8.90×10^{-4}	8.90×10^{-4}
		Open loop	7.60×10^{-2}	1.90×10^{-1}
		Pond	1.10×10^{-3}	2.30×10^{-3}
Hydropower	Operation	In-stream and reservoir	4.00×10^{-5}	2.09×10^{-1}
CSP	Power plant	Upstream and downstream	3.75×10^{-4}	6.44×10^{-4}
	Operation	Dish Stirling	1.89×10^{-5}	1.89×10^{-5}
		Fresnel	3.79×10^{-3}	3.79×10^{-3}

		Power tower: cooling tower	2.80×10^{-3}	2.80×10^{-3}
		Trough: cooling tower	3.29×10^{-3}	4.16×10^{-3}
PV	Operation	Flat panel	3.79×10^{-6}	9.84×10^{-5}
Geothermal	Power plant	Upstream and downstream	3.79×10^{-6}	3.79×10^{-5}
	Operation	Binary: dry cooling	1.02×10^{-3}	2.38×10^{-3}
		Flash	4.16×10^{-5}	9.46×10^{-5}
		EGS: dry cooling	1.10×10^{-3}	2.73×10^{-3}
Wind	Power plant	Upstream and downstream	4.92×10^{-5}	3.14×10^{-4}
	Operation	Onshore	3.78×10^{-6}	3.78×10^{-6}
		Offshore	3.78×10^{-6}	1.13×10^{-5}

Note*: PC, pulverized carbon; CCS, carbon capture and sequestration; CSP, concentrated solar power; PV, photovoltaic; EGS, enhanced geothermal system*

The fuel cycle is remarkably important for energy technologies that require processing or extraction before being operated: this part is significant for all the fossil fuels and nuclear power, while it is almost absent for renewables. Concerning the cooling phase, this can be distinguished in cooling towers, open loop and ponds. Additionally, cooling tower refrigerant systems can be coupled with carbon capture and sequestration, a technique which will largely be implemented in next future. CCS implementation, whose inclusion has the goal of mitigating the effects on climate change, modifies the amount of water needed to produce the unit of electricity. For solar thermal technologies like CSP, the quantification is done directly according to the kind of solar technology commercially available; concerning solar electric power, only the water needed for the cleaning of flat panel was included, considering concentrated PV negligible in the market. Finally, both offshore and onshore wind power were included.

4.3 Estimation of energy needs for water purification and of the water withdrawn for electricity generation

Three scenarios were established, so that the evolution of the dependence on the resources was tracked as a function of the mix change. The first scenario is the reference scenario (2015), in which the energy mix has been taken from a common data source for all the three countries. For 2017, the data were taken from different agencies. A forecast to 2040 was also considered, from different studies providing possible energy mixes for each chosen country. Actually, renewables-friendly forecasts were chosen for this analysis in order to visualize the impact of a significant shift towards renewable energy sources.

4.3.1 Energy required to purify one unit of water in the selected locations

In the first analysis shown in table 11, the water mix was not modified: this table reports the electricity required to produce a unit of volume of high-quality water, applied universally to the three considered locations. The figures reported in table 12 were obtained by multiplying the energy requirement to upgrade each water source (in table 9) to the correspondent percentage of the water mix for all the locations.

Table 11 *Energy required to purify one cubic meter of water in the chosen locations*

	U.S.A.			Italy			Morocco		
	Energy specific consumption [kWh/m^3]		Water mix [%]	Energy specific consumption [kWh/m^3]		Water mix [%]	Energy specific consumption [kWh/m^3]		Water mix [%]
	Min	Max	Value	Min	Max	Value	Min	Max	Value
Surface water	0.148	0.297	74.3	0.143	0.287	71.8	0.154	0.309	77.4
Groundwater	0.119	0.119	24.8	0.13	0.134	27.9	0.104	0.104	21.8
Wastewater reuse	0.006	0.016	0.65	0.0008	0.0021	0.08	0.006	0.016	0.6
Seawater desalination	0.003	0.011	0.13	0.004	0.015	0.18	0.0017	0.005	0.06
Cumulative value (Σ)	0.278	0.444	1	0.283	0.438	1	0.267	0.436	1

The last row provides cumulative values (both minimum and maximum) of the energy consumed by each country for the obtainment of one cubic meter of high quality water. The composition of combination of minimum and maximum values for U.S.A., Italy and Morocco is provided figure 26, so that is possible to visualize the contribution of each water source for the interesting task.

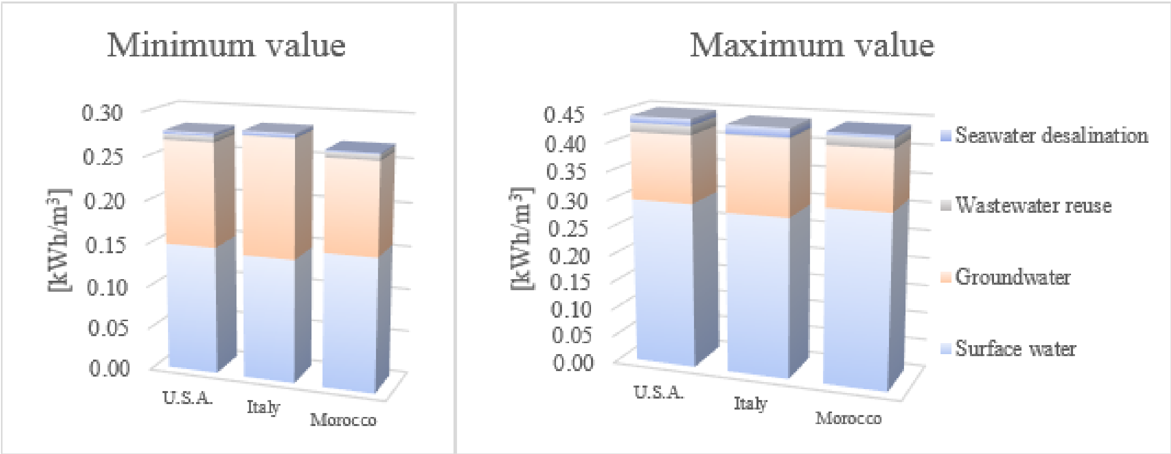


Figure 26 *Composition of minimum and maximum values of energy for water purification*

4.3.2 Water withdrawal to produce one unit of electricity in U.S.A.

Before providing the results of the analysis, the hypothesis for each case are listed.

- The repartition of cooling technologies for coal, natural gas and nuclear was equally distributed within cooling towers, open loops and ponds for scenario 1 (2015) and 2 (2017);
- The use of CCS technologies (for coal and natural gas applications) is predicted to be at least 40% of cooling tower system in scenario 3 (2040), while the traditional systems will account for the 60% of the cooling tower share;
- For geothermal and concentrated solar power, the allocation of each sub-technology has been kept, in all the cases, the same as that provided in the reference one (e.g. in U.S.A. for CSP it was considered that 75% of the solar thermal share was provided by parabolic troughs in 2015, 2017 and 2040). Nevertheless, the percentage of both solar power and geothermal, compared to the energy mix, changed according to the investigated year;
- No offshore wind installations were available in U.S.A. in scenario 1 and they were considered negligible also in case 2 (even if available) compared with onshore installations; in scenario 3, the share of offshore wind is predicted to be 9% of the renewable panorama;
- For biomass, only the operative quantities are available but distinguished into those for steam or for biogas production using this fuel as feedstock;

Table 12 Water for energy generation in the three scenarios (U.S.A.)

	2015 U.S.A.			2017 U.S.A.			2040 U.S.A.		
	Water withdrawal [m^3/kWh]		Energy mix [%]	Water withdrawal [m^3/kWh]		Energy mix [%]	Water withdrawal [m^3/kWh]		Energy mix [%]
	Min	Max	Value	Min	Max	Value	Min	Max	Value
Coal	6.82×10^{-3}	3.79×10^{-2}	34.12	6.23×10^{-3}	3.44×10^{-2}	31	3.99×10^{-3}	2.18×10^{-2}	16.07
Nuclear	6.21×10^{-3}	1.90×10^{-2}	19.26	6.26×10^{-3}	1.92×10^{-2}	19.4	4.70×10^{-3}	1.44×10^{-2}	14.57
Natural gas	5.37×10^{-3}	1.14×10^{-2}	31.83	5.45×10^{-3}	1.16×10^{-2}	32.3	6.42×10^{-3}	1.35×10^{-2}	39.26
Hydropower	2.52×10^{-6}	1.31×10^{-2}	6.29	2.56×10^{-6}	1.34×10^{-2}	6.4	1.18×10^{-6}	6.18×10^{-3}	2.96
Natural gas	5.37×10^{-3}	1.14×10^{-2}	31.83	5.45×10^{-3}	1.16×10^{-2}	32.3	6.42×10^{-3}	1.35×10^{-2}	39.26
Biomass	3.74×10^{-4}	9.27×10^{-4}	1.43	5.23×10^{-4}	1.30×10^{-3}	2	8.84×10^{-4}	2.19×10^{-3}	6.04
Oil	1.52×10^{-4}	3.16×10^{-4}	0.9	1.01×10^{-4}	2.10×10^{-4}	0.6	1.01×10^{-4}	2.10×10^{-4}	0.6
Wind	2.37×10^{-6}	1.42×10^{-5}	4.48	2.96×10^{-6}	1.78×10^{-5}	5.59	5.38×10^{-6}	3.25×10^{-5}	10.15
Geothermal	3.42×10^{-6}	8.46×10^{-6}	0.43	4.10×10^{-6}	1.01×10^{-5}	0.52	7.66×10^{-6}	1.89×10^{-5}	0.97
CSP	2.76×10^{-6}	3.51×10^{-6}	0.08	2.60×10^{-6}	3.32×10^{-6}	0.08	6.10×10^{-5}	7.77×10^{-5}	2.96
PV	2.82×10^{-8}	7.33×10^{-7}	0.74	2.66×10^{-8}	6.92×10^{-7}	0.7	1.34×10^{-7}	3.49×10^{-6}	3.55
Cumulative value (Σ)	1.89×10^{-2}	8.28×10^{-2}	99.56	1.85×10^{-2}	8.01×10^{-2}	98.59	1.62×10^{-2}	5.84×10^{-2}	97.13

Note*: the cumulative value of the energy mixes might not be one due to the absence of "other" energy sources (e.g. tidal)*

The values of table 13 were determined combining the primary data of water withdrawn (table 11) with the energy mixes of United States of America, in light of the above-mentioned hypotheses. It is possible to quantify the needs of each energy technology in terms of water withdrawal. The last row is indicative of the lower and larger amount of water required for each scenario according to the mix. The same procedure is applied next for the computation of these values for Italy and Morocco.

4.3.3 Water withdrawal for one unit of energy produced in Italy

First, the hypotheses behind each of the proposed cases are listed:

- The repartition of cooling technologies for coal and natural gas was equally distributed within cooling towers, open loops and ponds for scenario 1 and 2;

- The share of cooling tower was divided equally between traditional and CCS cooling towers in scenario 3 guessing a significant introduction of carbon capture and storage technologies (since no forecast about the repartition of the technologies were available);
- Nuclear has not been considered here, since no generation from this source is done in the country,
- No data about CSP and offshore wind were available for scenario 1, even if some plants have been already built;
- No water requirements for unit of energy from dry steam technology in geothermal field were available, but it is actually the most widely employed technology in this country;
- For geothermal and concentrated solar power, the allocation of each sub-technology has been kept, in all the cases, the same as that provided in the reference one (e.g. in Italy for CSP it was considered that 67% of the solar thermal share was provided by linear Fresnel in 2015, 2017 and 2040). Nevertheless, the total percentage of both solar power and geothermal changed into the energy mix according to the investigated year. Additionally, considering that the data source provided only the whole solar share into the energy mix of 2040, it was assumed that the ratio CSP/PV (1/10, in 2017) remains like that also in 2040;
- The share of offshore wind was assumed the same provided worldwide in 2040, hence just 6.2% of the total wind-generated electricity;
- For biomass, only the cooling quantities are available but distinguished into those for steam or for biogas production using this fuel as feedstock;

Table 13 *Water for energy generation in the three scenarios (Italy)*

	2015 Italy			2017 Italy			2040 Italy		
	Water withdrawal [m^3/kWh]		Energy mix [%]	Water withdrawal [m^3/kWh]		Energy mix [%]	Water withdrawal [m^3/kWh]		Energy mix [%]
	Min	Max	Value	Min	Max	Value	Min	Max	Value
Hydropower	6.65×10^{-6}	3.48×10^{-2}	16.6	5.12×10^{-6}	2.68×10^{-2}	12.8	5.09×10^{-6}	2.66×10^{-2}	12.7
Coal	3.21×10^{-3}	1.78×10^{-2}	16	2.75×10^{-3}	1.53×10^{-2}	13.7	2.27×10^{-3}	1.24×10^{-2}	10.1
Natural gas	6.62×10^{-3}	1.41×10^{-2}	39.2	7.24×10^{-3}	1.52×10^{-2}	42.3	6.61×10^{-3}	1.38×10^{-2}	38.6
Biomass	1.58×10^{-3}	3.92×10^{-3}	6.03	2.09×10^{-3}	5.19×10^{-3}	8	1.07×10^{-3}	2.66×10^{-3}	4.1
Oil	7.99×10^{-4}	1.66×10^{-3}	4.7	1.26×10^{-4}	2.63×10^{-4}	0.75	7.10×10^{-6}	1.48×10^{-5}	0.042

Wind	2.79×10^{-6}	1.67×10^{-5}	5.2	3.34×10^{-6}	2.01×10^{-5}	6.3	5.55×10^{-6}	3.33×10^{-5}	10.3
CSP	0	0	0	7.28×10^{-6}	8.30×10^{-6}	0.18	7.03×10^{-5}	8.01×10^{-5}	1.76
PV	3.08×10^{-7}	8.00×10^{-6}	8.1	3.10×10^{-7}	8.07×10^{-6}	8.2	6.66×10^{-7}	1.73×10^{-5}	17.6
Geothermal	2.38×10^{-6}	6.13×10^{-6}	2.2	2.28×10^{-6}	5.88×10^{-6}	2.1	3.85×10^{-6}	9.93×10^{-6}	3.5
Nuclear	0	0	0	0	0	0	0	0	0
Cumulative value (Σ)	1.22×10^{-2}	7.23×10^{-2}	98.3	1.22×10^{-2}	6.27×10^{-2}	94.4	1.0×10^{-2}	5.56×10^{-2}	98.9

Note: *the cumulative value of the energy mixes might not be one due to the absence of "other" energy sources (e.g. tidal)*

4.3.4 Water withdrawal for one unit of energy produced in Morocco

- The repartition of cooling technologies for coal and natural gas was equally distributed within cooling towers, open loops and ponds for scenario 1 and 2;
- The share of cooling tower was divided equally between traditional and CCS cooling towers in scenario 3 guessing a significant introduction of carbon capture and storage technologies (since no forecast about the repartition of the technologies were available);
- No generation from nuclear, biomass and geothermal sources belongs to the energy mix;
- No data for offshore wind were available;
- Within concentrated solar power percentage, the allocation of each kind of sub-technology has been kept the same as the one provided in the reference case;
- For biomass, only the cooling quantities are available but distinguished into those for steam or for biogas production using this fuel as feedstock;

Table 14 *Water for energy generation in the three scenarios (Morocco)*

Water withdrawal [m^3/kWh]	2015 Morocco			2017 Morocco			2018 Morocco		
	Water withdrawal [m^3/kWh]		Energy mix [%]	Water withdrawal [m^3/kWh]		Energy mix [%]	Water withdrawal [m^3/kWh]		Energy mix [%]
	Min	Max	Value	Min	Max	Value	Min	Max	Value
Coal	1.17×10^{-2}	6.5×10^{-2}	58.58	1.1×10^{-2}	6.14×10^{-2}	55.2	6.95×10^{-3}	3.78×10^{-2}	32
Hydropower	3.12×10^{-6}	1.63×10^{-2}	7.81	4.40×10^{-6}	2.30×10^{-2}	11	5.60×10^{-6}	2.93×10^{-2}	14
Natural gas	3.34×10^{-3}	7.12×10^{-3}	19.8	3.18×10^{-3}	6.76×10^{-3}	18.8	3.08×10^{-3}	6.44×10^{-3}	18

Oil	6.09×10^{-5}	1.27×10^{-4}	0.72	1.58×10^{-3}	3.30×10^{-3}	9.4	5.73×10^{-3}	1.19×10^{-2}	9
Wind	4.57×10^{-6}	2.74×10^{-5}	8.62	2.12×10^{-6}	1.27×10^{-5}	4	7.42×10^{-6}	4.45×10^{-5}	12
CSP	5.19×10^{-7}	6.45×10^{-7}	0.01	4.72×10^{-5}	5.87×10^{-5}	1.2	4.86×10^{-4}	5.86×10^{-4}	13
PV	1.30×10^{-10}	3.37×10^{-9}	0.003	9.29×10^{-9}	2.42×10^{-7}	0.2	3.79×10^{-8}	9.84×10^{-7}	1
Nuclear	0	0	0	0	0	0	0	0	0
Biomass	0	0	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0	0	0
Cumulative value (Σ)	1.51×10^{-2}	8.86×10^{-2}	95.54	1.59×10^{-2}	9.45×10^{-2}	99.9	1.63×10^{-2}	8.6×10^{-2}	99

Note: *the cumulative value of the energy mixes might not be one due to the absence of "other" energy sources (e.g. tidal)*

4.3.5 Inclusion of the imported electricity into the energy mixes

Before proceeding, a relevant aspect has to be considered: the electricity used for water treatment is the one taken from the grid, so it should include also the electricity imported from other countries. In order to add this contribution, the following assumptions were made:

- The list of the actual importers is known, but no information is available about the future importations: due to the unpredictability of this numbers, the imported share has been kept equal in all the scenarios;
- Only one single exporter is considered for each country, coinciding with the country with the largest share of imported electricity. In particular, Canada for U.S.A. (90.4% of the importation), Switzerland for Italy (50.4% of the importation), and Spain for Morocco (89.4% of the importation).

The same calculations were performed for the exporter countries (only the cumulative minimum and maximum are presented in table 16), so that a weighted inclusion of their contribution into the electricity within the grid of the three importer countries were considered.

Table 15 Water for energy generation of the exporting countries

Specific water withdrawal [m^3/kWh]	2015		2017		2040	
	Min	Max	Min	Max	Min	Max
Canada	9.32×10^{-3}	1.51×10^{-1}	8.90×10^{-3}	1.51×10^{-1}	9.0×10^{-3}	1.44×10^{-1}
Switzerland	1.14×10^{-2}	1.58×10^{-1}	1.13×10^{-2}	1.57×10^{-1}	3.76×10^{-3}	1.41×10^{-1}
Spain	1.51×10^{-2}	7.45×10^{-2}	1.26×10^{-2}	7.29×10^{-2}	6.30×10^{-3}	6.36×10^{-2}

In order to contextualize the figures provided in table 16, the energy mixes for the exporter countries are reported in figures 27-29.

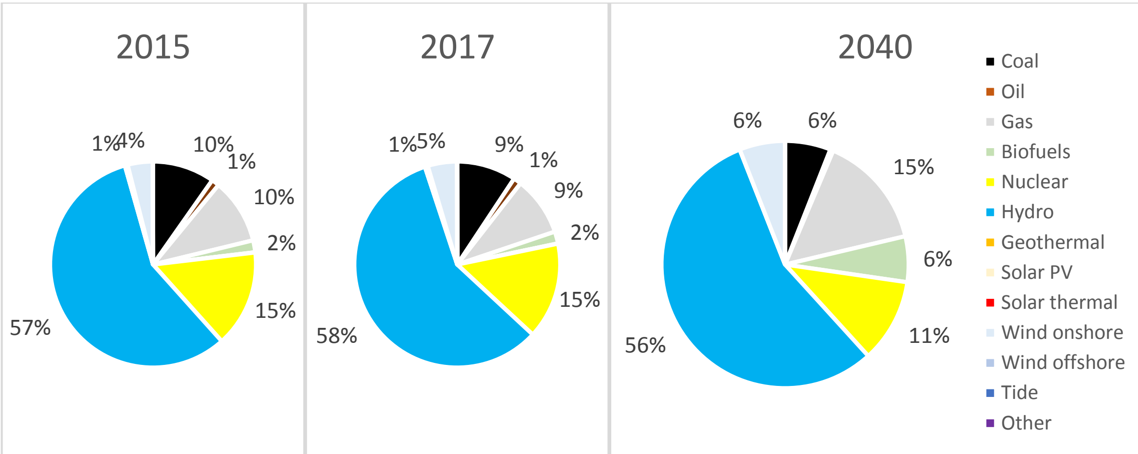


Figure 27 Generation energy mixes for Canada

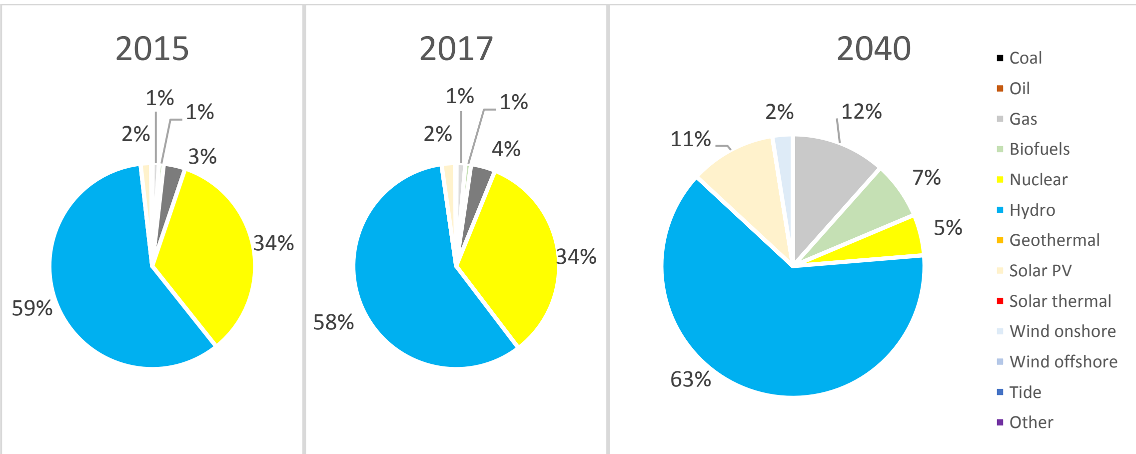


Figure 28 Generation energy mixes for Switzerland

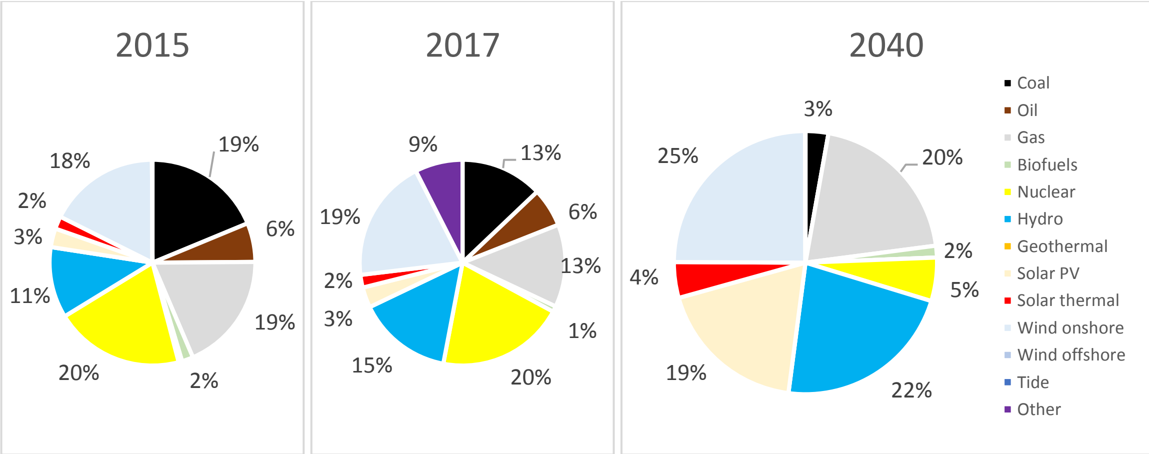


Figure 29 *Generation energy mixes for Spain*

The spider charts in figure 30-31 represent the impact of short and long-term changes in the energy mix on water withdrawn per cubic meter in all the countries involved in the study. The arrows indicate the relation exporter-importer and the values reported (whose units are m^3/kWh) are relative to the water withdrawal for one unit of electricity generated by each of these countries. Later, the results provided in these graphs are combined to obtain the values accounting for electricity imported by the three countries.

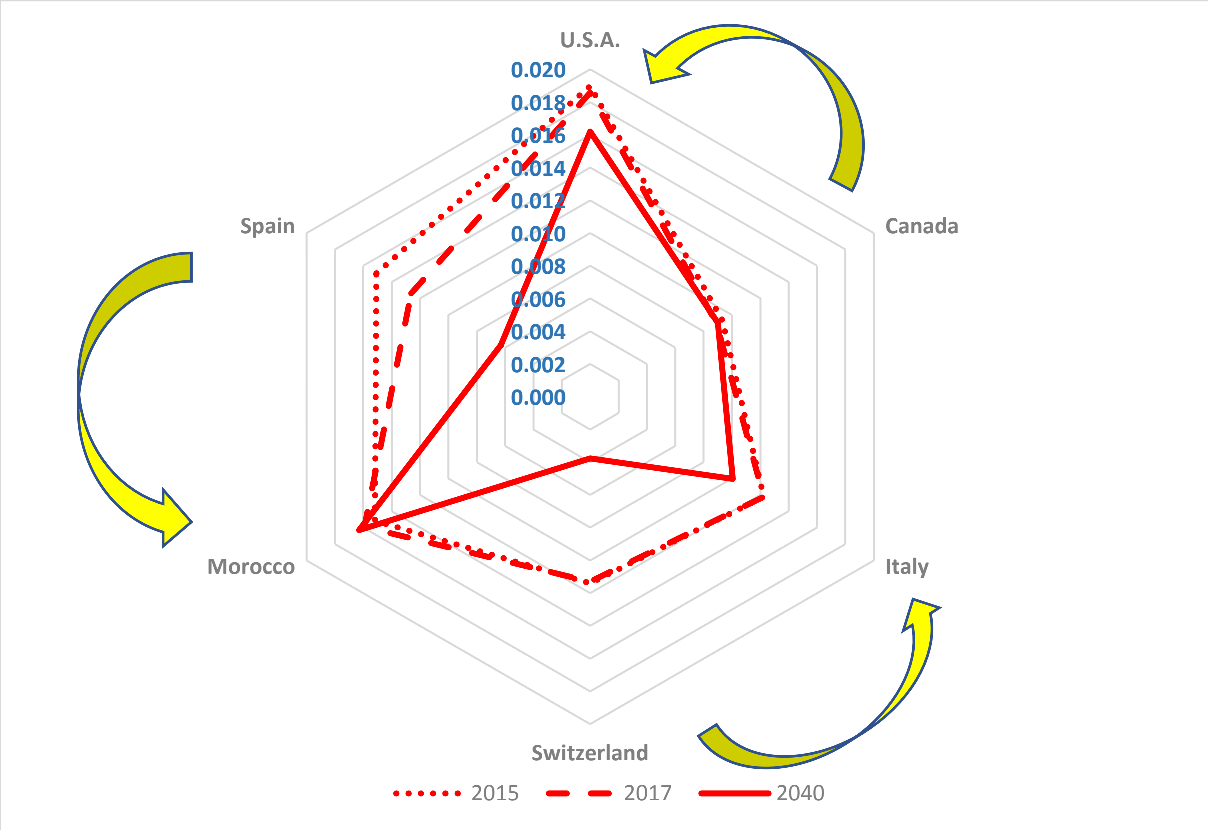


Figure 30 *Minimum specific water withdrawal for energy generation of the three scenarios and their importers*

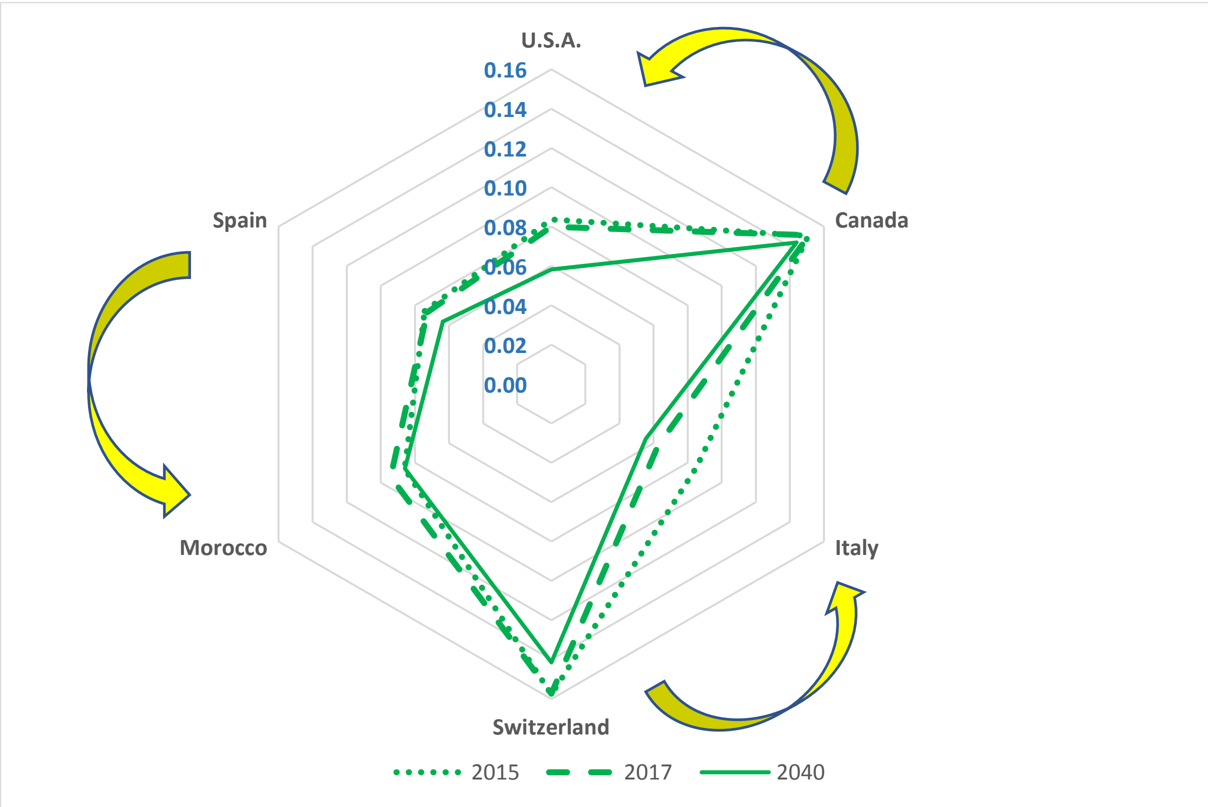


Figure 31 *Maximum specific water withdrawal for energy generation of the three scenarios and their importers*

Looking at minimum values of water withdrawn to produce electricity, the situation is qualitatively homogeneous: there is not a relevant variation between 2015 and 2017, while almost all the countries will reduce their water withdrawal in 2040. A remarkable reduction will be experienced by Switzerland and Spain due to their future energy mixes: as visible in figure 28-29 the significant lowering of high water-demanding sources like coal and nuclear (mainly from Spain) and the routing to photovoltaic and wind will produce this effect. The only exception is Morocco, where the 2040 value would be slightly higher if only its own electric generation is considered.

The gap between minimum and maximum values for Canada and Switzerland is considerably high. This is because of the percentage of hydropower which constitutes more than half of the energy mixes of these countries and that is the energy technology with the highest value of water withdrawal. The trend of the maximum specific values is similar to the minimum values: generally decreasing in the future, except in Morocco.

The values reported in table 17 include the shares of importations and they are derived by the application of a weighted average of the figures obtained in table 16 (exporter-related) and the ones of tables 13-15 (importer-related). The weights are the percentage of traded electricity (according to 2016 figures):

- Canada-U.S.A.: 1.6%;
- Switzerland-Italy: 14.9%;
- Spain-Morocco: 16.5%.

Table 16 *Water for energy accounting the import*

Specific water withdrawal [m^3/kWh]	2015		2017		2040	
	Min	Max	Min	Max	Min	Max
U.S.A.	0.0188	0.0837	0.0184	0.0811	0.0161	0.0597
Italy	0.0121	0.0850	0.0121	0.0767	0.0091	0.0683
Morocco	0.0152	0.0860	0.0154	0.0907	0.0147	0.0822

Both Italy and Morocco, which do not generate electricity by nuclear plants, now also present a contribution from this energy source as their respective exporter countries have this source within their energy mix (Switzerland and Spain).

Figure 32 shows the share of renewable energy sources in the energy mix for the three countries and the three scenarios.

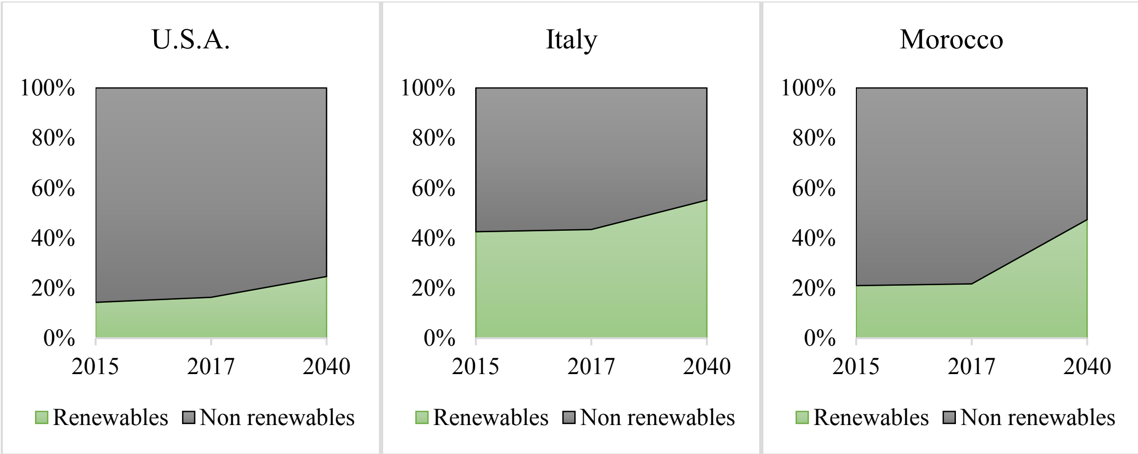


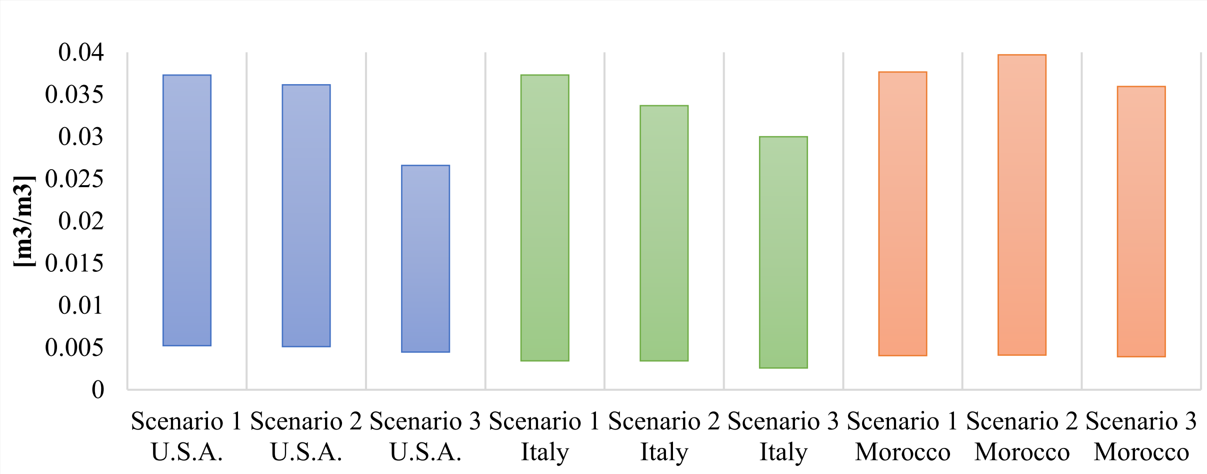
***Figure 32** Trend of grid electricity from renewable and non-renewable resources*

The graph implies a general increase of renewable electricity share compared to non-renewable electricity. The American dependence on fossil and nuclear power will still be predominant over the more sustainable alternatives; on the contrary, both in Morocco and Italy, the presence of renewables in grid electricity will be strong (48% and 55% respectively).

4.4 Water withdrawn for the electricity used for water supply (water hidden in water)

Once the specific water withdrawal (per unit energy in the grid) and the specific energy to purify a unit of water are computed, a further step may be taken to estimate the water required by each country in 2015, 2017 and 2040 to produce the electricity needed to purify a cubic meter of water. The way by which the study has been carried out allows generalizing the answer, thus referring to the production of one unit of water without distinguishing between the sources of water or electricity. The matrix product produces the results provided in figure 33.

Figure 33 Water withdrawn to produce a generic unit of volume of water



Water for water [m^3/m^3]	Scenario 1, 2015		Scenario 2, 2017		Scenario 3, 2040	
	Min	Max	Min	Max	Min	Max
U.S.A.	0.0052	0.0372	0.0051	0.0361	0.0045	0.0265
Italy	0.0034	0.0373	0.0034	0.0336	0.0026	0.0300
Morocco	0.0041	0.0375	0.0041	0.0396	0.0039	0.0359

It is evident that the location suffering more water scarcity (Morocco) is also the one that for the long-term forecast will withdraw more water to produce the energy needed to obtain one volumetric unit of high-quality water. The trends in both Italy and the U.S.A., particularly the maxima values, are expected to decrease in time: water for energy hidden in water will be reduced of 28.7% (U.S.A.) and 19.5% (Italy) according to the maxima values of 2015 and 2040.

Considering that in this evaluation no water mix change was considered, it is interesting to evaluate the average contribution of each energy technology in the water withdrawn for electricity production, to understand the evolution of the figures. In figure 34, the average water withdrawal for energy production purposes from different sources is accounted.

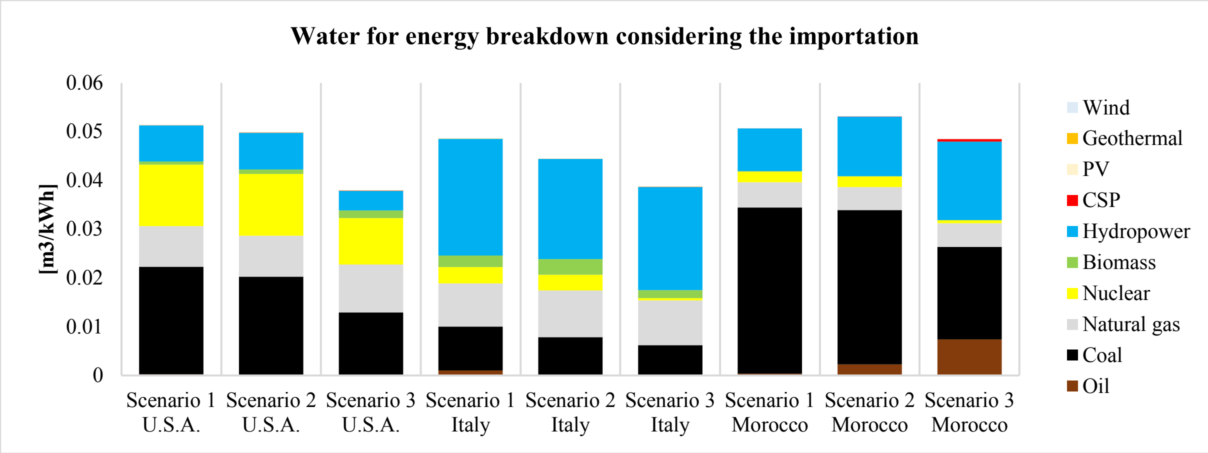


Figure 34 *Fuel breakdown into the evaluation of water withdrawn for energy*

The analysis of Moroccan profile highlights that, despite the significant reduction in the use of fossil fuels (scenario 1 and 2 respect to scenario 3), the water requirement will remain high. This can be attributed to two causes: the first is the continued use, within the non-renewable share, of a significant percentage of coal (33% in 2040), which is the second most water-demanding source, together with nuclear power (it must be pointed out that coal contribution is the major actor in water withdrawal in all the analysed scenario of this country). Secondly, the increase of renewables will bring to a duplication of the percentage of hydropower, which is intrinsically related to large water withdrawals. Regarding U.S.A. and Italy, the quantity of water required in each of the considered scenario is comparable, but the quality (meaning the composition of the figure) changes considerably. For United States, the analysed quantity is mainly composed by coal, nuclear, hydropower (showing a decreasing trend in the contribution, in line with the energy mix) and natural gas (which is the only one that will be boosted in the future energy scenario).

Despite of the "greener" energy mix, Italy itself, as well as its main exporter, relies heavily on hydropower, which ultimately determines a level of water withdrawal requirement for electricity production comparable with that of the U.S.A. The reduction of 5 % of coal in the energy mix (from 16% to 11%, scenario 1 to 3), produces an evident positive effect on the total withdrawn water. The use of biomasses, whose main employer is Italy, are not so incisive: even if their contribution in terms of water demand for the production of a single kilowatt-hour is one of the highest (just behind nuclear and coal and before natural gas), its presence in the mix is not so effective to induce a strong effect over the overall distribution.

The data discussed up to now highlighted that in the case of an improvement of the energy mix, the best solution from a water-saving perspective is the choice of renewables, notwithstanding the use of hydropower, whose impact is significant on the final outcomes. Concerning this source, it must be stressed that the ranges used for the calculations are a worldwide interval, but it was already pointed out that the size of the power plant is directly related to the amount of water involved. In the evaluations, hydropower contribution was applied indistinctly to the three selected locations, but this is surely a limiting generalization, mainly caused by the absence of local figures. To understand how the weight of the interval might have been more justly adapted, the size of the largest hydropower plant for each of the locations is listed:

- U.S.A.: Grand Coulee Dam (6,809 MW);
- Italy: Entracque plant (1,317 MW);
- Morocco: Afourer station (465 MW).

4.5 Analysis of water mix modification

The previous analysis has been conducted assuming that the water mix will be constant during the time frame considered. This approximation can fit more the countries in which the water stress index is relatively high, like U.S.A. and Italy, but not for Morocco. By using the value of water hidden into the production of one cubic meter of water in 2040 as reference, now the task is to verify what would happen in the case that the water mix changes dramatically, applying the energy mix forecast for 2040. Five cases were hypothesized (A-E), in which the repartition of conventional (surface and groundwater) and unconventional (treated wastewater and desalinated) was supposed as listed:

- Case A: equal (1/4) repartition between the considered water sources;
- Case B: 80% deriving from conventional water (40% and 40%) and 20% from unconventional (10% and 10%);
- Case C: 20% deriving from conventional water (10% and 10%) and 80% from unconventional (40% and 40%);
- Case D: 40% deriving from conventional water (20% and 20%) and 60% from unconventional (30% and 30%);
- Case E: 60% deriving from conventional water (30% and 30%) and 40% from unconventional (20% and 20%).

The proposed cases are extreme cases considering that the reference scenario is composed for more than 90% (approximately 70% surface water and more than 20% groundwater) by conventional sources and a very low percentage by unconventional water. Due to the valuableness of freshwater and the future chance of major employment of desalinated water and recycled wastewater to reduce social tensions, the massive use of these unconventional sources were hypothesized especially in case C and D. Thus, keeping the energy mix of 2040 and changing the water mix as listed in cases A-E, the new intervals of water required to produce the electricity needed to supply one cubic meter of water are thus obtained. To better visualize the results, only the average values are considered in figure 35-37.

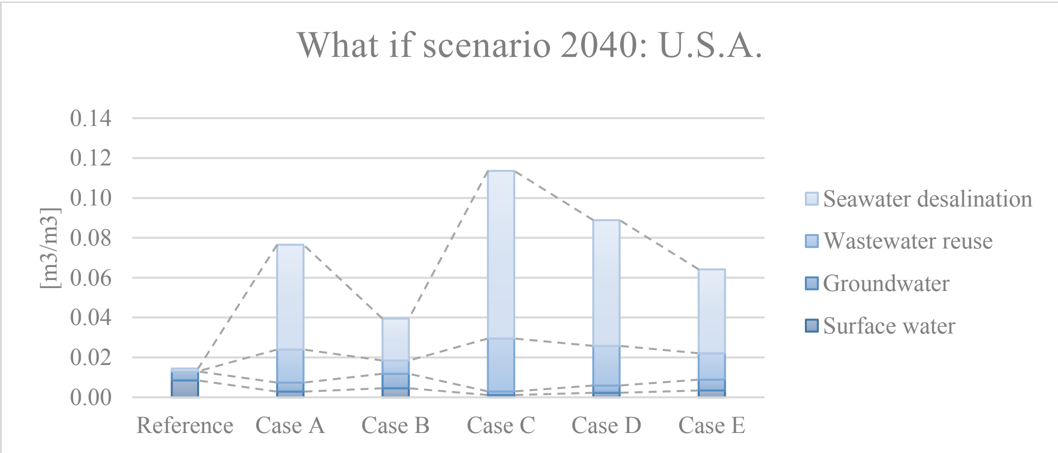


Figure 35 *Water for water what if scenario in 2040 for U.S.A.*

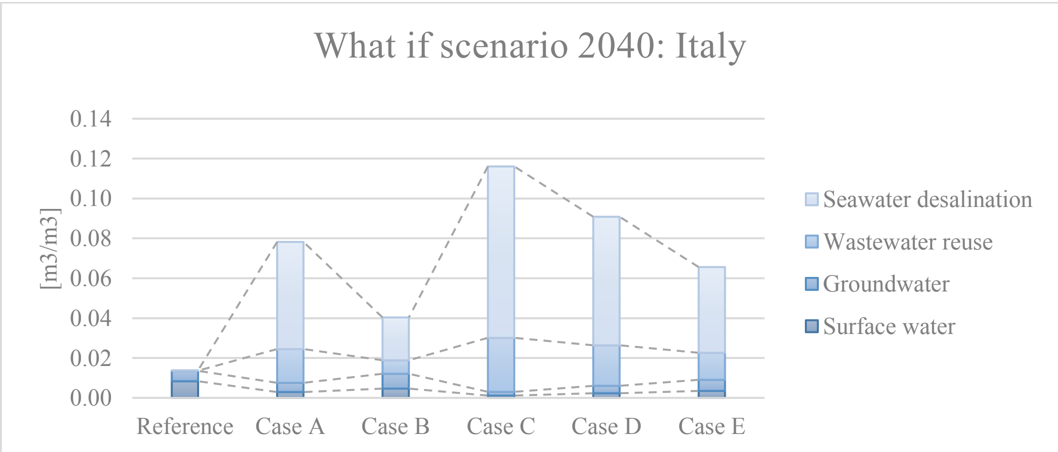


Figure 36 *Water for water what if scenario in 2040 for Italy*

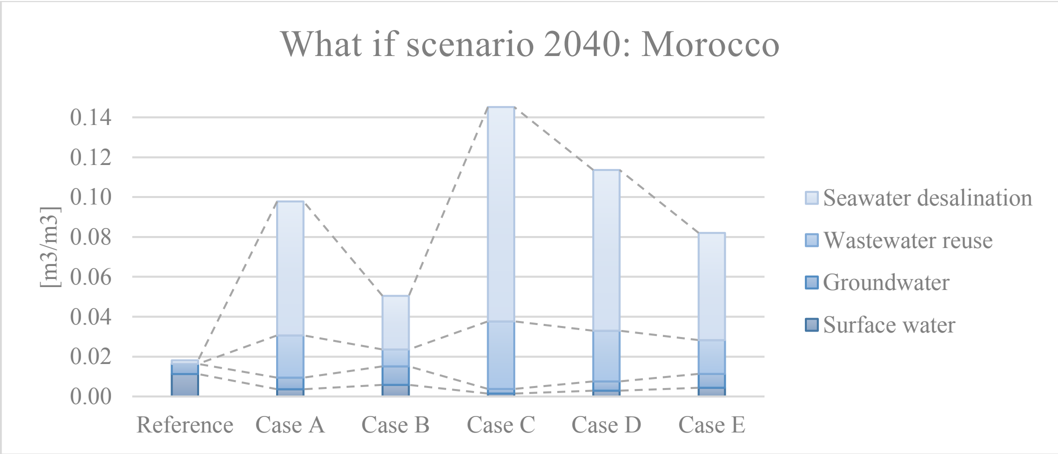


Figure 37 *Water for water what if scenario in 2040 for Morocco*

Qualitatively, the trends describing the evolution of water withdrawn are very similar within the three locations. This highlights that the weight of the energy mix is less effective on the results compared to a strong change in water mix, due to the remarkable energy consumption that unconventional water treatment requires. Secondly, the amount of water required in any scenario, is significantly higher than that calculated in the reference case, oscillating between 40-150 L/m^3: in particular, case C for every locations and case D only for Morocco, would overcome the threshold of 10% of water withdrawn to produce one unit of high-quality water. These results were expected, since the energy required by the treatment of unconventional water sources is relevantly higher than that required by conventional ones. Another quick observation is linked to the various requirements for the different sources. The heaviest contribution would be played by desalination in all the cases. It must be kept in mind that the energy consumption of this process is very high (between 2.6-8.5 kWh/m^3) and additionally the percentage of its contribution in the presented scenarios is between 10% (case B) and 40% (case C), which is much higher compared to present day values (below 1%). Considering that in almost 20 years it is unlikely that unconventional water sources will cover more than 20% of the water mix, it seems reasonable to focus on the most likely of the provided scenarios. Case B, reveals values of water withdrawal which would be more than twice with respect to the reference case. By keeping the ratio of seawater desalination to 10% (half of the unconventional water share), this would still weigh more than all the other water sources. On contrary, satisfying the water mix of 2040 with one tenth of water deriving from wastewater treatment will not have a dramatic impact. This observation highlights the potential of the application of this technique instead of desalination, also related to the continuity and reliability of the wastewater source worldwide and in any society, regardless of the geographical position.

The consistent treatment of unconventional sources would be increasingly required in future, but it was shown that their wide application would mean a higher overall specific energy use, thus hidden water. The approach should include the optimization of the techniques to purify unconventional water sources. The “what if” scenario analysis determines a quantification of the water employed for a single unit of volume produced, stressing the high “water cost” as hidden value of the energetic component under the current conditions. The energy gap between the management of conventional and unconventional sources is still too relevant and in case no energy efficiency solution will be applied in future, the dependency of humans to unconventional water sources will be definitively more expensive.

4.6 Water consumption vs. withdrawal

So far, the withdrawn quote of water used for electricity production has been evaluated. However, it would be also interesting to conduct the same investigations for the consumed water, as defined above in the previous chapter. The quantities obtained through this estimation are:

- The water consumed to obtain one unit of electricity;
- The water consumed to produce the electricity needed to purify one cubic meter of water (hidden water).

An energy technology can require very high withdrawal but low consumption. Considering this discrepancy within the steps of energy-producing technologies, it is relevant to quantify the range of consumption required by the various investigated sources in the energy mix (figure 38).

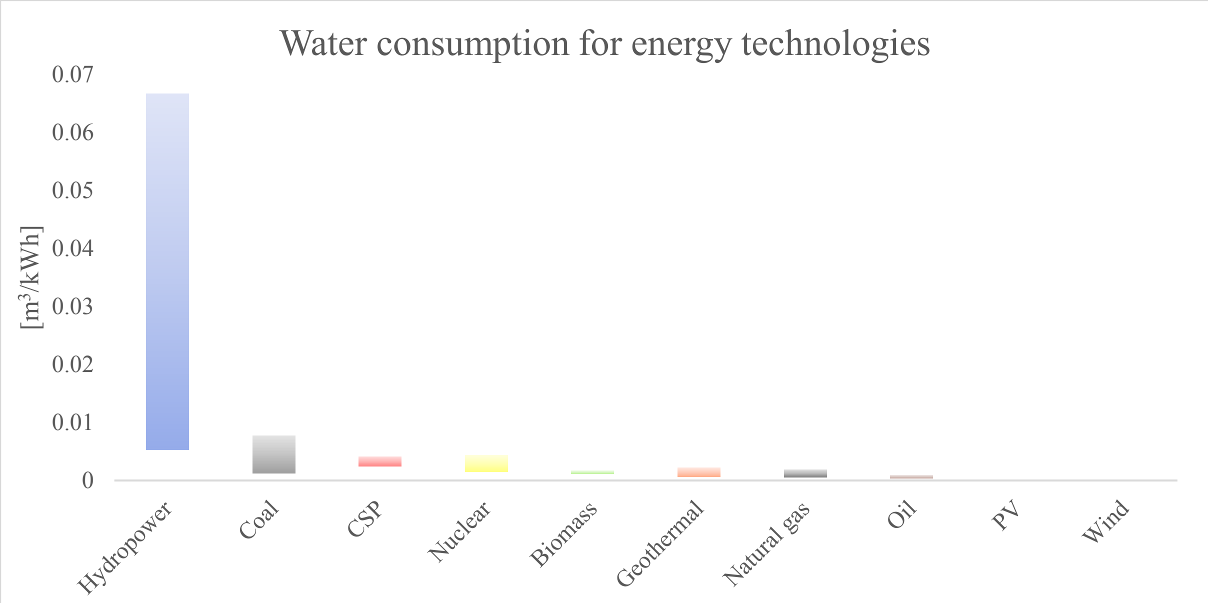


Figure 38 *Range of water consumption for energy technologies*

Hydropower has a very large figure of consumption compared with any other energy technologies. Nevertheless, it can be observed that some renewables like concentrated solar and geothermal have water consumption comparable with nuclear and natural gas. These figures anticipate that, changing the energy mix in favour of renewable energy technologies could not be as effective under a consumption perspective as it was with withdrawals.

The methodology applied in paragraphs 4.1-4.4 was repeated, considering the values for consumption instead of the withdrawal. The outcomes of water consumed for electricity production can be observed in figure 39.

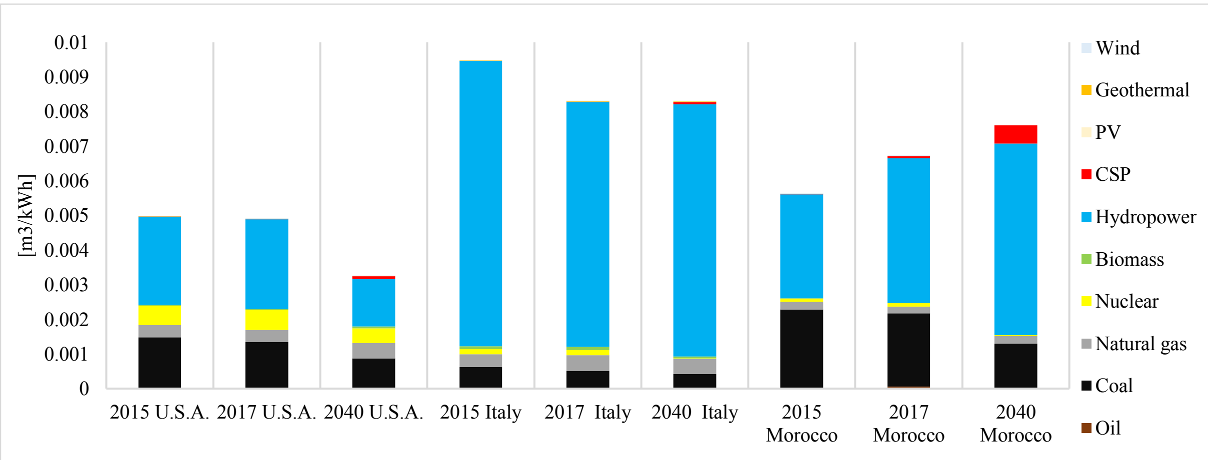


Figure 39 *Fuel breakdown into the evaluation of water consumed for energy*

Within the U.S.A. a remarkable drop of consumption can be noticed in the 2040 scenario. This would be the result of a reduction of hydropower and coal share together with a rise of low consuming sources such as PV, wind and biomasses. It must be stressed that a non-negligible part will be covered by other sources like tidal, waste, etc., whose consumption was not estimated. Moving to Italy in the 2040 scenario, the hydropower share will remain the same, but the reduction in water consumption due to a reduced use of coal and natural gas will be compensated by CSP. Morocco reveals the most worrisome scenario. From 2015 the hydropower share will more than double in 2040, carrying the highest contribution to water consumption. The use of CSP will almost balance the significant reduction of coal use in terms of water depletion.

The evaluation of water consumed hidden in high-quality water is obtained following the steps applied in paragraph 4.4. Figures 40-41 provides the minimum and maximum values of "water for water", with respect to water withdrawal.

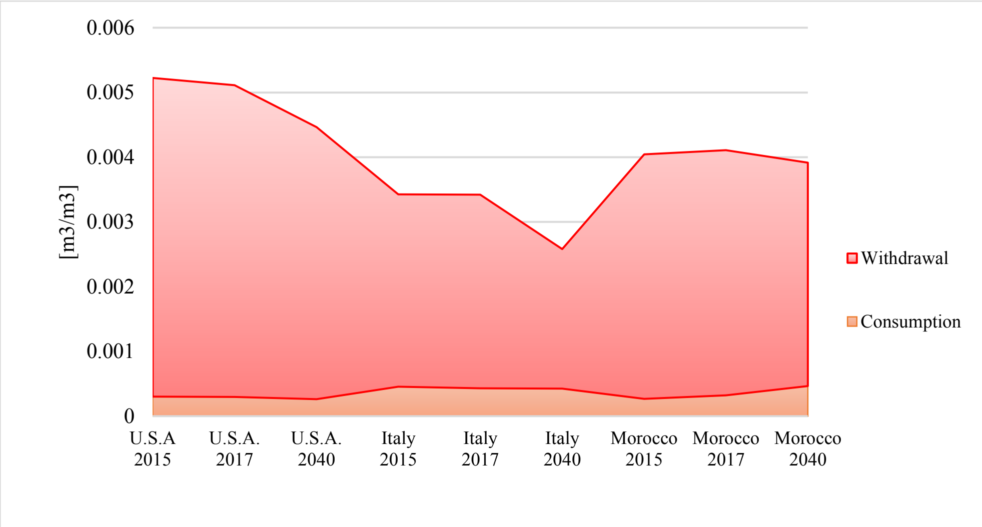


***Figure 40** Minimum water withdrawal and consumption for water purification*

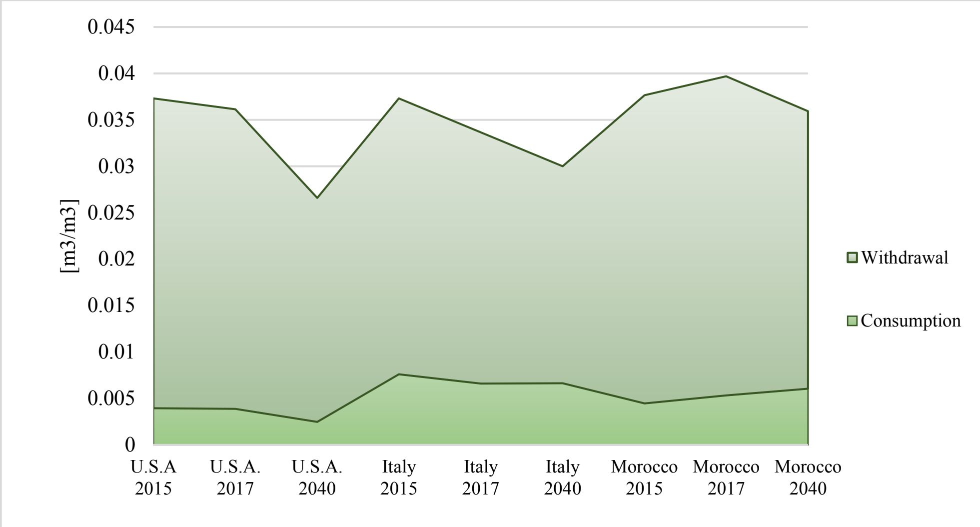


***Figure 41** Maximum water withdrawal and consumption for water purification*

Both minimum and maximum trends reveal that each location will experience a reduction in water withdrawal during the considered timescale, but the same cannot be stated for consumption.

4.7 Absolute amount of water allocated for energy production purposes

Dealing with historical values, it is possible to quantify the amount of water required to satisfy the energy demand of the studied countries. Referring to 2015, both electricity consumption and energy pro capita have been used to obtain the values presented in figure 42.

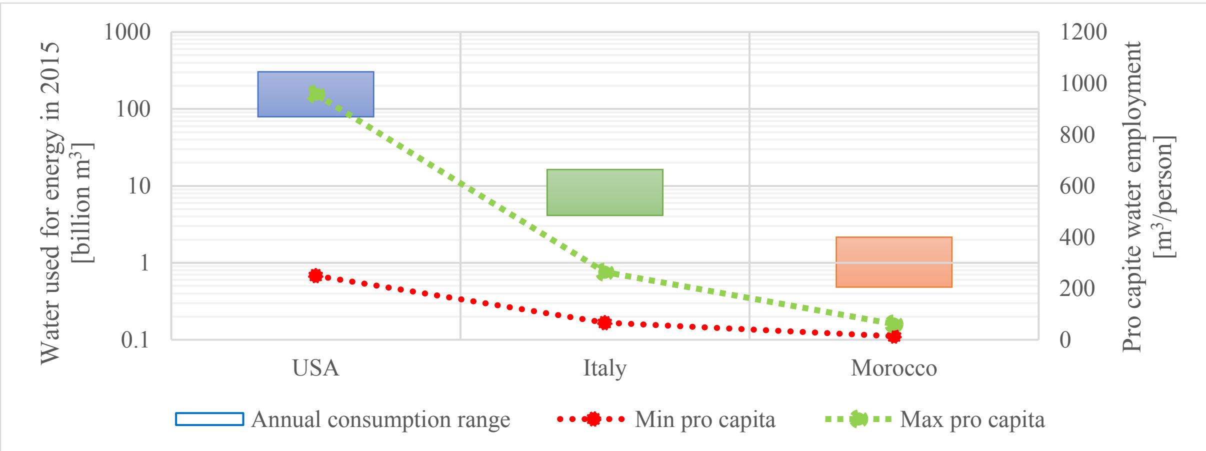


***Figure 42** Amount of water used for energy purposes and pro capita ranges in 2015*

***Note**: bars must be referred to the left axis, which is in logarithmic scale, while dotted lines to the right one*

The range of water consumption was calculated using the annual electricity consumption extracted (2015) from the IEA database:

- 4,129 TWh by U.S.A. and a pro capita consumption of 13 MWh/capita;
- 310 TWh by Italy and a pro capita consumption of 5 MWh/capita;
- 31 TWh by Morocco and a pro capita consumption of 0.88 MWh/capita.

Applying to these values those reported in table 17 (referred to 2015), it is possible to obtain the results of figure 42, that is, the water required to cover the annual demand of electricity in each country and the same figure referred for a single person.

- U.S.A. required between 77-346 billion cubic meters of which 244-1,090 m^3 per person;
- Italy required between 3.8-22.6 billion cubic meters of which 60.5-425.2 m^3 per person;
- Morocco required between 0.5-2.6 billion cubic meters of which 13.3-75.9 m^3 per person.

Unfortunately, the amount of total water withdrawn for 2015 is not available, hence it is not possible to estimate how much of the whole part was devoted to energy applications. However, it is possible to state that, between 2008 and 2010, the values of total water recorded by AQUASTAT were:

- 486 billion of cubic meter in U.S.A;
- 54 billion of cubic meter in Italy;
- 10 billion of cubic meters in Morocco.

Assuming that these values have not dramatically changed during the quinquennium, using the average of the previously evaluated range of water consumption in 2015, it can be stated that the energy field accounted for almost 35% of the American water use, while 24% and 12.7% for Italy and Morocco, respectively.

4.7 Inclusion of water distribution and losses

Dealing with the energy requirements for water supply, water transportation should also be considered. This operation requires between 0.045 and0.217 kWh/m^3. Therefore, the intervals of energy used in 2015 to transport the whole amount of water of each location are:

- Between 21.8 and 105.3 TWh for U.S.A.;
- Between 2.41 and 11.6 TWh for Italy;
- Between 0.46 and 2.26 TWh for Morocco.;

A relevant share of water losses occurs during the distribution of purified water, as reported in table 18.

Table 17 Percentage of losses during the distribution and their quantification

Location	Losses of the distributed water in percentage [%]	Year of reference	Average energy for distribution [TWh]	Average energy lost [TWh]
U.S.A.	40	2013[62]	39.2	15.7
Italy	38.5	2015[63]	2.95	1.13
Morocco	35	2012[64]	0.3	0.1

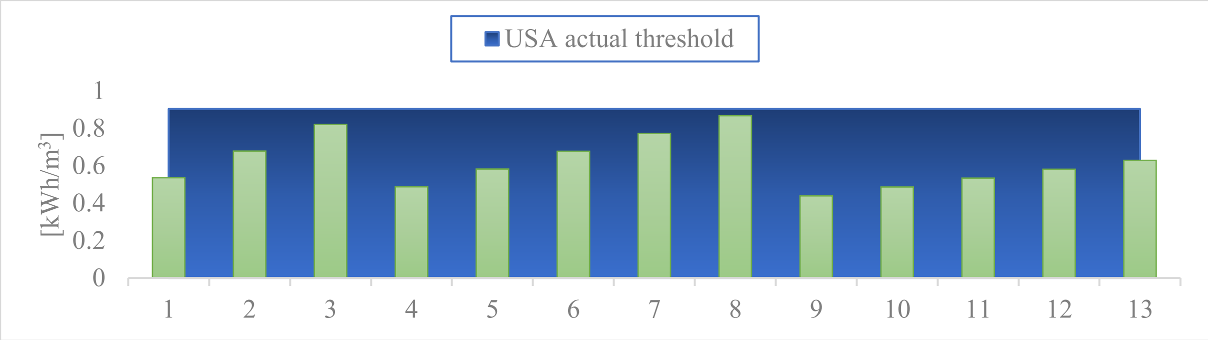
The figures provided are the estimations of the energy yearly lost by all the locations analysed due to distribution and loss of water. The losses accounts for a non-negligible percentage of the overall water supplied. The last column presents the annual electricity consumption associated to water that gets ultimately lost during distribution. The energy lost associated to water losses accounted for 0.41, 0.39 and 0.37% of the total consumption of electricity in U.S.A, Italy and Morocco, respectively in the reported reference years.

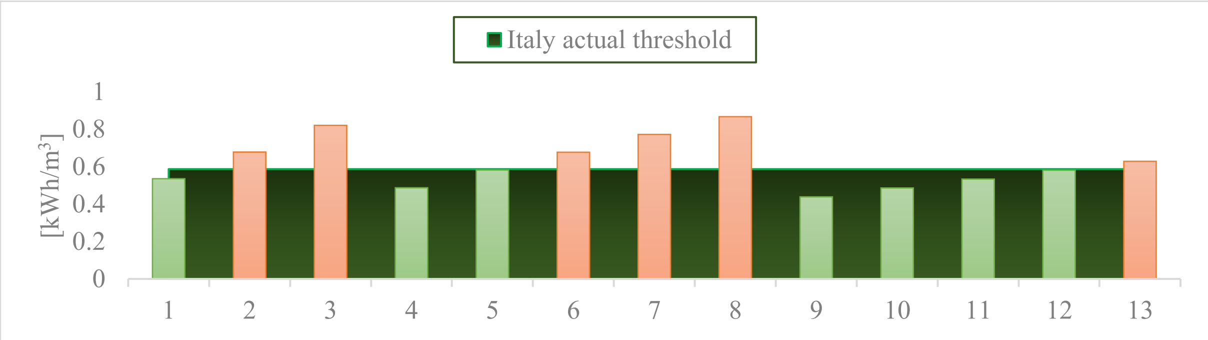
Apart from the quantification of the water, hence the energy lost due to the non-ideal performance of real system, the question is the following: what would happen in case the system was optimized, so that this kind of losses would be negligible? Using the same amount of energy invested presently to supply water, it could be possible to increase the use of unconventional water sources, thus lowering human impact on the natural water cycle, or in other terms, it could be possible to invest the saved energy in the boost of wastewater reuse and desalination (figure 43).

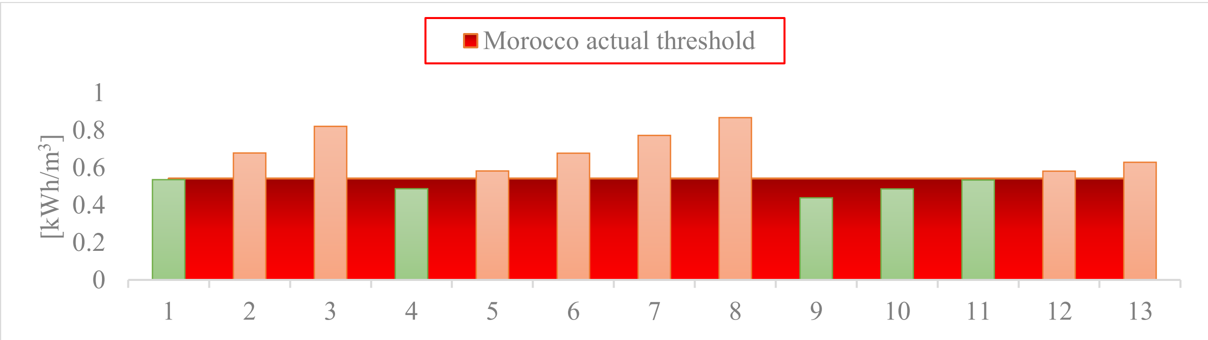
62 https://www.forbes.com/consent/?toURL=https://www.forbes.com/sites/heatherclancy/2013/09/19/with-annual-losses-estimated-at-14-billion-its-time-to-get-smarter-about-water/

63 https://www.istat.it/it/archivio/207497

64 www.socialwatch.org/node/14006







Case	1	2	3	4	5	6	7	8	9	10	11	12	13
Surface water [%]	35	35	35	40	40	40	40	40	45	45	45	45	45
Groundwater [%]	35	35	35	40	40	40	40	40	45	45	45	45	45
Wastewater reuse [%]	15	11.25	7.5	10	7.5	5	2.5	0	1.25	3.75	2.5	1.25	0
Seawater desalination [%]	0	3.75	7.5	0	2.5	5	7.5	10	3.75	1.25	2.5	3.75	5

Figure 43 *Acceptable water mixes rising unconventional share in a system without losses*

Figure 43 presents the threshold values of energy employable for unit of water supplied following distribution and losses in the investigated locations. This value has been obtained by normalization of the energy required for water treatment of each country (average values of table 12) with the fraction of water actually reaching the end-users. By optimizing the supply system cutting losses, the range of unconventional water sources could increase up to a range 5-15% of the water mix, without increasing the total energy used for water supply. The most interesting situations, which would be appropriate in the considered countries, are cases 9-10-11. Even if the conventional water sources should cover 90% of the mix, desalination could be used to satisfy 3.75% of the demand (case 9). This result is notable, considering that the actual value of desalination (for the involved countries) is almost twenty times lower (0.18%). Broadly, it is confirmed that the pushing on wastewater rather than desalination in unconventional water usage would consent the achievement of a better performance.

5. Case study: Urban greywater reuse

This section is devoted to the evaluation of a possible system of wastewater reuse in the urban water context, including its energetic and techno-economic assessment. The panorama previously investigated highlights that conventional water sources could be used less in future, due to several factors such as scarcity and socio-political tensions. In the evaluation of possible scenarios, when unconventional water sources are applied and wastewater reuse is preferred to desalination, the performance of the energy-water system allows lower impacts on the natural water cycle while maintaining low energy needs.

Specifically, the task of this case study is to recover domestic greywater, sending it to a wastewater treatment unit and extract a valuable product employable for a high-end application. The context selected is the following: in domestic framework, water accounts for a heavy percentage of the waste generation due to the production of grey and black effluents. The main difference that lies between these two flows is the contact with faecal bacteria, which characterizes black waters, and that is cause of difficulty in recovering this wastewater. The production of greywater is instead mainly from the following sources: hand basins, showers and baths, dishwashers, washing machines and kitchen basins. Due to the different interactions that each element has with human activities, their characterization varies significantly. The choice of the treatment train needs to be assessed according to the initial feed water quality, and the required quality of the reused water. The case proposed would be located in Italy: the evaluation is performed in a district composed of 100 townhouses, in which the average occupancy is of 4 people per house. In order to minimize the operative costs associated to transport of the recycled water, its use is assumed in the same district, for urban irrigation or other purposes, as clarified later.

Next to the design of the proposed treatment, estimations in economic and energetic terms are made, in order to provide some terms of comparison between the proposed alternative and the current situation where greywater is not reused and instead sent as a wastewater effluent combined with rainwater and black waters. Considering that almost all the greywater sources are employed at temperatures which are higher than that of tap water, recovery of the thermal content before the water treatment is also a possibility that will be analysed.

5.1 Framework of application

The quantification of greywater was performed in line with the suggestion expressed in criterion C.4.1 of Protocollo Itaca. Protocollo Itaca is a tool to evaluate not just the energetic performance of a building, but also its sustainability and its environmental impact. To quantify the magnitude of the overall stream, equations 3 and 4 were employed.

***Equation 3** Occupants evaluation*

$$ab = \frac{S_u}{25}$$

Where S_u is the useful surface of the building, hence supposing a 100 m^2 townhouse, the number of occupant is four. Next, the yearly production of greywater is consequently obtained, as:

***Equation 4** Greywater to the sewer*

$$V_{g,std} = \frac{ab * V_{g,gc} * n_{gg}}{1000}$$

Where $V_{g,gc}$ is the reference greywater pro capita, amounting to 90 l/p-day, and n_{gg} the number of days. From equation 5, the calculated flow rate produced by a single house would be of 131.4 m^3/year, which means that the production of the district would be attested to 1.5 m^3/h.

5.2 Quality parameters of the water streams

Greywater water contains contaminants: the featuring elements can be grouped in dissolved and suspended solids, surfactants, nutrients, heavy metals and emerging pollutants. The parameters considered fundamental to define the greywater and to define the water quality are listed below.

- pH;
- Conductivity;
- Total solids (TS, including TDS, TSS, VSS etc.);
- BOD_5 and COD;
- Turbidity;
- Total Organic Carbon (TOC);
- Nutrients (i.e. nitrogen and phosphorous compounds);
- Silt density index (SDI);

- Sodium adsorption ratio (SAR);
- Hardness;
- Pathogens.

Within the parameter listed, the ones that deserve a deeper understanding, to contextualize the value associated with the characterization and eventual treatment considerations are SDI, SAR and hardness. Silt density index (SDI is associated with colloidal fouling in membrane-based purification. It gives indication of the way to operate a membrane system in a proper way, as shown in table 19.

Table 18 *Silt density index feature*

SDI:	Action:
<1	Operates for years without colloidal fouling
<3	First cleaning after months
3-5	Frequent cleaning required
>5	Pre-treatment is mandatory

Sodium adsorption ratio is a widely used parameter that verifies the adaptability of a water stream to be used for irrigation, which seems to be one of the most attractive wastewater reuse applications. The evaluation of this parameter is related to the concentration of three cationic species, as shown in equation 5.

Equation 5 *Definition of sodium adsorption ratio (SAR)*

$$SAR = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}$$

Where the cations concentration is expressed in milliequivalents/litre. As optimal condition, a value lower than 3 is desired, but the range of tolerance can be wider depending on the type of crop.

Hardness provides a quantification of the mineral content in a water stream. The most evident effect of this parameter is the corrosive action and incrustation of pipelines. It consists of a permanent and temporary hardness:

Equation 6 Total hardness evaluation

$$[CaCO_3] = 2{,}5 * [Ca^{2+}] + 4{,}1 * [Mg^{2+}]$$

According to this expression, both calcium and magnesium are estimated as if they were available in the form of calcium carbonate. Several units of measurement can be used to quantify this parameter: one of the most known is the French degree (°f), which corresponds to 10 mg of $CaCO_3$.

5.3 Characterisation of greywater

The characterisation of greywater is not simple because of the variability within households. Noutsopoulos et al. provided three case studies[65] in which the occupancy was used to analyse the composition of the greywater domestically produced by a student, two middle age people and a family composed by four members. A typical composition of greywater in accordance of each of the sources was thus presented.

In this work, a blending of all the greywater streams within the household is considered. The majority of the parameters, provided by Noutsopoulos, were estimated through a simple mass balance, as shown in equation 7.

Equation 7 Mass balance equation

$$\dot{m}_{MIX} = \sum_i \dot{m}_i = \sum_i \overline{c_i} * \dot{V}_i = \overline{c_{TOT}} * \dot{V}_{TOT}$$

Where $\dot{m}$ is the mass flow rate, in kg/person-day; c_i the i-th pollutant concentration in mg/litre and $\dot{V}$ the volumetric flow in litre/person-day. This hypothesis is appropriate for all the parameter considered whose unit of measure is indicative of a concentration (generally a mass concentration in a unit of volume). The amount of greywater produced by a single Italian occupant can be observed in figure 44, as provided by Protocollo Itaca.

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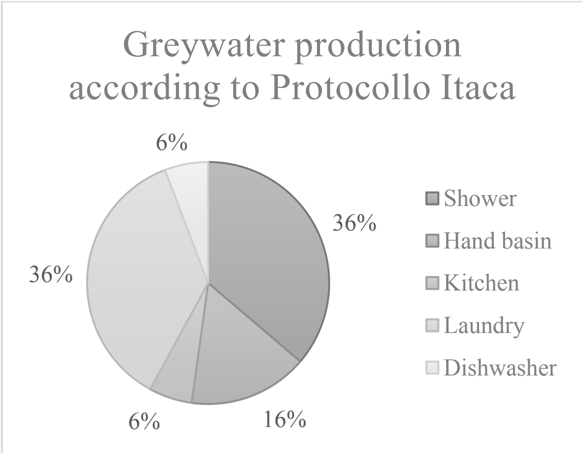
[65] [65] Greywater characterization and loadings-physicochemical treatment to promote onsite reuse; C. Noutsopoulos, A. Andreadakis, N. Kouris, D. Charchousi, P. Mendrinou, A. Galani, I. Mantziaras, E. Koumaki



Source:	[L/person-day]
Shower	32.4
Hand basin	14.4
Kitchen	5.4
Laundry	32.4
Dishwasher	5.4

Figure 44 *Domestic percentage and amount of greywater generated in a single building*

The application of the mass balance leads to a weighted average of the concentration of the pollutants. The composition of the grey water mixture is presented in tables 20-21.

Table 19 *Physical characteristics, solids and nutrients of greywater mixture*

pH	TSS	TDS	TOC	Turbidity	SDI	VSS	TKN	NO_3-N	NH_4-N	TP	BOD_5	COD
[-]	[mg/L]	[mg/L]	[mg/L]	[NTU]	[-]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]
8.8	121.4	782.6	146.7	143.0	3.0	103.6	3.6	0.4	0.8	16.1	696.6	1048.8

Table 20 *Indicative pathogens of greywater mixture*

E. coli	Enterococci
[log10/100mL]	[log10/100mL]
2.29	3.31

The values provided by Leal et al. were employed for the evaluation of mono and multivalent ionic dissolved species. Since the evaluation of these parameters is done after a sequence of sampling, the data are presented with their mean value (μ) and standard deviation (σ). A computation was performed to consider the fluctuation of the load in the mixture. For each ionic species, a normal distribution of the values was re-constructed, and a normal cumulative distribution was assumed:

$$x \in [\mu - 3\sigma; \mu + 3\sigma]$$

The selection of this range is motivated by the presence of significant quantities: 68%, 95% and 99.7% of the values of the sampling are included in the provided interval. A Gaussian distribution was thus applied to the data:

Equation 8 *Distribution function*

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}}\, e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

Next, the correspondent cumulative density function was obtained through integration, as provided in figure 45.

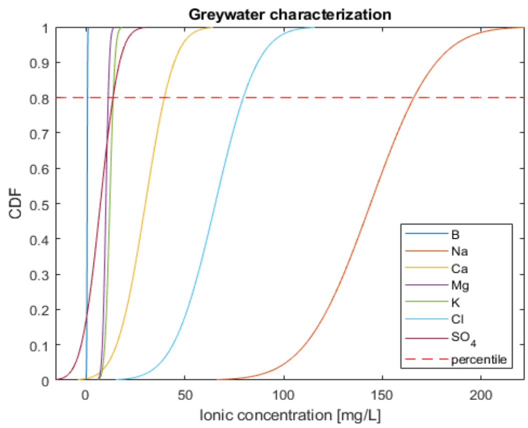


Figure 45 *Cumulative function of ionic species*[66]

To be conservative, instead of characterizing the greywater simply using the mean value, the eightieth percentile was considered. The choice of this value was done so that the figure imposed for the concentration of ionic species has a probability of appearance equal or below the set threshold. Thus, the final amounts of ionic species available in the blending as dissolved species are listed in table 22.

[66] Characterization and anaerobic biodegradability of grey water; L. Hernández Leal, H. Temmink, G. Zeeman, C.J.N. Buisman

Table 21 *Ionic species characterization*

Ion	Concentration [mg/L]	Concentration [meq/L]
B	0.69	-
Na	165.8	7.22
Ca	39.6	1.98
Mg	11.1	0.92
K	13.6	0.35
Cl	79.5	2.24
SO_4	13.6	0.28
CO_3	25.76	0.86
HCO_3	426.8	7
CO_2	0.86	-

The charge balance of the aqueous solution was adjusted using carbonate species. To complete the picture, the evaluation of SAR, hardness and conductivity of the considered water is reported. The SAR value is 5.2. The estimated value of hardness is 145 mg/L of $CaCO_3$, which translates into 14.5 °f: this value is classifiable as moderately to hard water. However, in the case of irrigation purposes, a value below 150 mg/L may be considered at the edge of the acceptability[67]. For the achievement of a lower value, a softening by using ion exchange resins should be implemented. To conclude with conductivity, the calculated value from the composition of ionic species is 1024 µS/cm.

5.4 Water treatments needed to reuse greywater

The parameters to be satisfied are provided by the Italian legislation in force. Consequently, a selection of a train of treatments is made, which is analysed in each step, according to its specific objective. For all the treatments, the most relevant features and design parameters are provided and aligned to the case study requirement. A sensitivity analysis over ultrafiltration is applied to verify the performance of the technology in some emblematic configurations.

[67] https://extension.psu.edu/interpreting-irrigation-water-tests

5.4.1 Target quality values of the recycled water

D.M n.185 provides a table of values that must be reached to reuse wastewater for one of the following purposes:

- Irrigation of both edible (by humans and animals) and non-edible crop as well as green areas or recreational and sportive areas;
- Civil, such as street cleaning, feeding of heating and cooling systems or adductive network;
- Industrial, as fire-fighting water or process water or cleaning water.

The quality to be achieved can be found in table 23.

Table 22 *Water quality requirements by D.M. n.185*

Parameter	Value	Unit
pH	6-9.5	-
SAR	10	mg/L
TSS	10	mg/L
BOD_5	20	mg/L
COD	100	mg/L
TP	2	mg/L
NH_4-N	2	mg/L
Conductibility	3,000	µS/cm
B	10	mg/L
SO_4^{2-}	500	mg/L
Cl	250	mg/L
F	1.5	mg/L
Escherichia coli	100	UFC/100mL

The reuse of the greywater for edible irrigation is neglected, which would require a higher degree of control among nutrients, such as nitrogen and phosphorous compounds. The treatment proposed next can instead be considered suitable for all the other applications mentioned above. A semi-batch process is designed: the collection of the greywater blend is sent to three equalization tanks (each of 15 m3 of capacity) where, once the adequate volume is reached, this can be sent to the treatment unit at an appropriate flow rate. This operation would require roughly 30 hours. Considering that the production of greywater is not constant over the day, the operation of the treatment plant is precautionary set every two days, thus reaching an influent of 45 m^3/h.

The observation of quality requirements imposed by D.M. n.185 highlights the request of a biological treatment to lower the concentration of BOD_5 and COD. To accomplish these limits, an anaerobic biological treatment can be included as primary step. This step can be followed by a membrane-based ultrafiltration, providing an adequate compromise between cost and effectiveness. The final step would be a disinfection step. Therefore, a summary of a suitable treatment train is reported below:

1. Equalization tanks
2. Anaerobic treatment: preliminary removals of biological and suspended matter, as well as phosphate;
3. Ultrafiltration: complete abatement of turbidity and suspended solids and removal of macro-molecules and some viruses and bacteria;
4. Disinfection: inactivation of pathogens.

The selected system would not significantly lower the dissolved species. However, SAR, hardness and conductivity levels in the influent greywater allow the selection of the proposed treatments without concerns about TDS-related variables in the effluent.

5.4.2 Anaerobic treatment

In the anaerobic bioreactor, a significant part of the suspended solid and biodegradable compounds can be adequately removed. A possible solution is a well-established technology (similar to a septic tank) which has not a large complexity in design, operation and maintenance and could be an appropriate economical solution. To briefly describe it, this is constituted by a tank[68] made of two or three compartments (ratio 2:1 or 2:1:1) in which the effluent flows very slowly. Two processes occur together: clarification of the stream and digestion of sediments. Solids settle on the bottom due to sedimentation or flocculation and consequently, their anaerobic digestion occurs. The introduction of compartments is needed in order to transport

[68] Trattamenti delle acque reflue, L. Bonomo

sediments (the larger in the first compartment and the smaller in the next) and the interaction of suspended materials with the gas generated by the digestion creates a superficial scab. To avoid the leakage of scab or oil and grease accumulated on the top, a baffle is located into the tank: it dissipates also the inlet speed, so that the solids have an adequate hydraulic retention time to better precipitate. Typical removal efficiencies[69] of this process are listed in table 24.

Table 23 *Average removals by a simple anaerobic treatment*

Parameter:	Removals [%]
COD	56
BOD_5	54
TKN	22
TP	40
TSS	73
Settable solids	96

The removals associated to BOD_5 and COD is not sufficient, but these are average values and a well-designed system with a large volume capacity (as that of this case study) combined with an accurate degree of compartmentalisation could guarantee a higher performance. Moreover, considering that the subsequent step is an ultrafiltration, a significant quantity of the biodegradable and oxygen-demanding compounds are part of the suspended solids and they can be thus removed by the membrane. The recommendations to be followed in order to guarantee an accurate operation of this unit are related to sludge production and odour. Once or twice a year, the settled solids on the bottom of the tank have to be removed and must be treated as special waste. Since the digestion of settled solids generates gas, a well-designed vent must be provided. This unit must be located at least 1 m far from foundation walls and 10 m from any pipeline, well, or tank devoted to potable water.

To provide a rough design of such a tank, the following procedure can be undertaken[70]. From a commercial catalogue it is possible to select a three-chamber tank, suitable for 100 persons

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[69] Depurazione delle acque di piccole comunità; L. Masotti, P. Verlicchi

[70] https://www.ording.ct.it/download/ing_nicosia_fabio.pdf

equivalent (pe), whose capacity is 30 m^3. This is one of the largest options available. As it would not be adequate to design a single tank in charge of all the greywater considered, four tanks are selected to match the requirement for this case study. Considering that each tank deals with the greywater generated by 100 people, it is possible to quantify the amount of sludge produced by each tank, according to the Van der Graaf plot (figure 46).

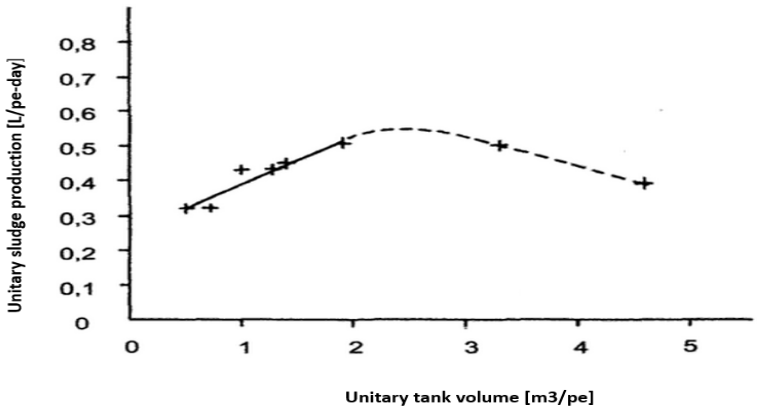

Figure 46 *Van der Graaf plot for sludge production estimation*

The study of Van der Graaf et al. allows the determination of the unitary sludge production. The range provided in this study suggests 0.7-1.5 m^3/pe when the population is between 50 and 500 people, thus by linear interpolation a value of 0.789 m^3/pe of unitary tank volume can be used to extract value of sludge production of a single tank: 0.34 l/day-pe, thus the district daily production (considering the four tanks) is 0.136 m^3/day.

5.4.3 Ultrafiltration

The membrane process can be considered the core of the proposed treatment chain. Pressure driven ultrafiltration is a technology based on the retention of particles whose size is larger than the dimension of the surface pores (1-100 nm) of the fibre membranes: it can be effective against suspended solids and colloids as well as bacteria and viruses (even if a further disinfection is commonly practiced). The model that better describes flux is the porous membrane model, obtained by Hagen-Poiseuille (equation 9):

Equation 9 *Hagen-Poiseuille equation*

$$J = \frac{\dot{V}}{A} = \frac{\varepsilon\, r^2 \Delta P}{8\, \mu\, \tau\, d}$$

Where $\dot{V}$ is the water flow rate, A the membrane area, ε the porosity, r the average pore radius, ΔP the hydraulic pressure difference, μ the viscosity, τ the tortuosity, and d the membrane thickness. All the terms apart from the driving force represented by the pressure gradient are relative to intrinsic membrane features and constitute the permeance of the membrane. The above-mentioned model is adequate only under ideal conditions because it does not account for fouling. Fouling description can be summarized as an irreversible event that leads to the decline of the flux due to pore size reduction as well as cake or gel layer formation over the surface of the membrane. Figure 46 shows the combination of the reversible and irreversible effect of the phenomena.

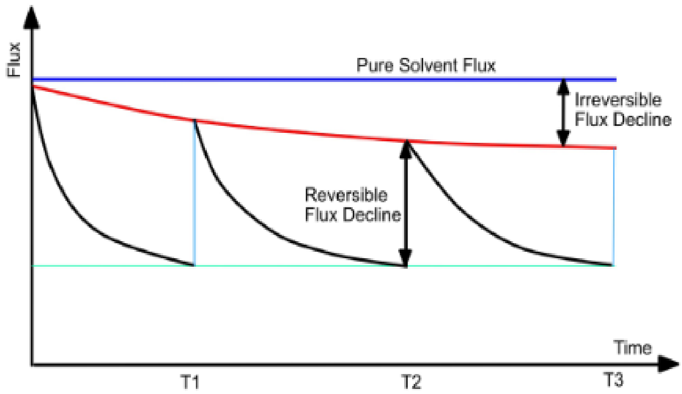

Figure 47 *Flux decreasing during the life cycle*

For each working cycle associated to a characteristic timing (T_i), there is a reduction of flux caused by fouling that can be restored only partially in the next cycle due to the irreversible component. The layout of a wastewater treatment plant based on ultrafiltration is provided in figure 48, as returned by the software Wave.

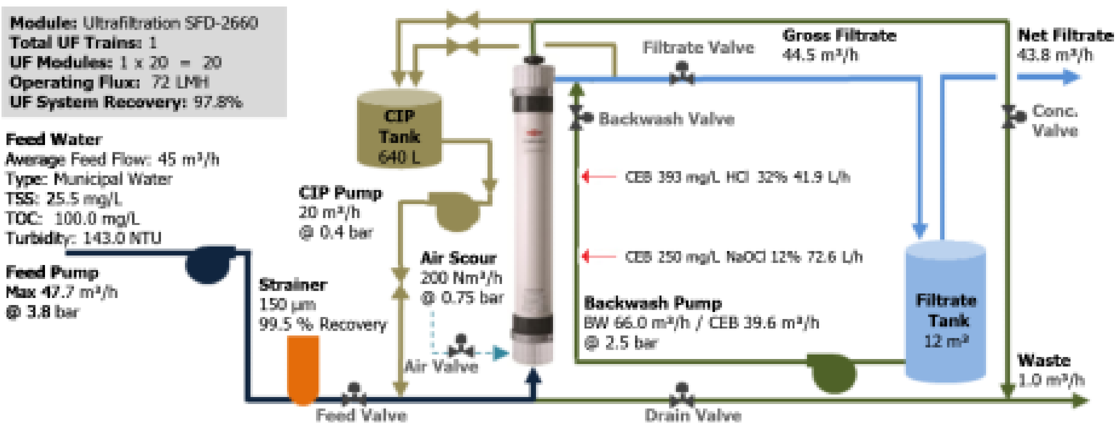

Figure 48 *Wave configuration for ultrafiltration*

Except for the membrane unit and the feeding pumps, three additional equipment units are present: the strainer, the clean in process (CIP) tank, and the filtrate tank. The strainer is nothing more than a device acting as primary filter: it retains particles whose diameter is higher than the mesh size, usually around 150 μm. The CIP tank is used to recycle the chemicals used during the cleaning step, while the filtrate tank receives the permeate stream and from there, it is partially sent back to the membrane to perform the backwash, when needed. An air compressor, not included in the figure, is an additional item necessary for air scour purposes, which is another methodology to prevent the fouling.

Membrane technology requires care to be operated in a proper way and cleaning is one of the most relevant processes to lengthen both the operating cycle and its entire lifetime. A typical filtration cycle can vary between 20 and 60 minutes[71]. During this operation, due to the accumulation of undesired species on the membrane, the transmembrane pressure will increase. This quantity, defined in equation 10 is one of the parameter to be controlled in order to guarantee an appropriate operation of the ultrafiltration plant.

Equation 10 *Transmembrane pressure*

$$TMP = \frac{P_I + P_O}{2} - P_P$$

Where the subscripts indicate the pressure at different section: I for inlet, O for outlet and P for permeate. Figure 49 provides the relation between filtrate flux and transmembrane pressure.

[71] http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0914/0901b80380914f2a.pdf?filepath=liquidseps

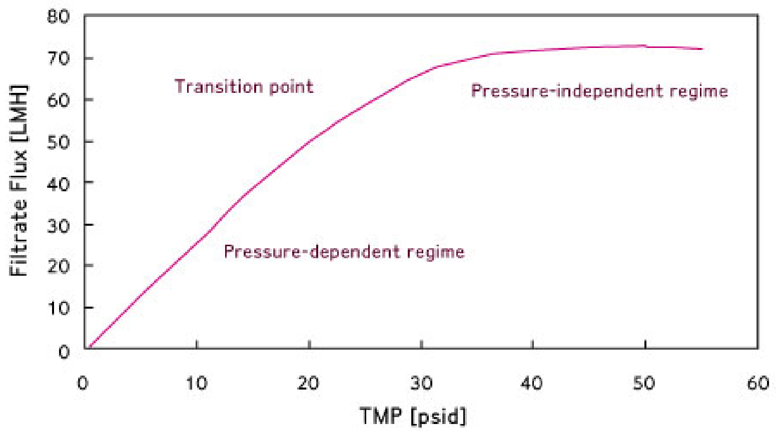

Figure 49 *Filtrate flux as function of transmembrane pressure* [72]

Usually, when the trans-membrane pressure increases roughly 15%, cleaning is performed in backwash mode to restore the flux due to reversible fouling. The steps to be followed during a backwash are the following:

- Air scour;
- Drain;
- Top/bottom backwash;
- Forward flush.

Eventually a chemical cleaning is needed to tackle irreversible fouling. According to the effluent quality, the addition of mineral or organic acid rather than alkali or oxidants may be necessary. It is common to apply citric acid or hydrochloric acid to get rid of inorganic compounds, caustic chemicals to target organics, and oxidants or disinfectants (NaOCl, Cl_2 and H_2O_2) when target foulants are organics and biofilms.

5.4.3.1 Evaluation of the performance of ultrafiltration

Within the overall treatment train, the ultrafiltration step is supposed to be the most energy-intensive. The energy required to operate the membranes and keep the process under a proper

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[72]http://www.merckmillipore.com/IT/it/ps-learning-centers/ultrafiltration-learning-center/optimization-process-simulation/d_eb.qB.ZWQAAAFAUV8ENHoL,nav?ReferrerURL=https%3A%2F%2Fwww.google.com%2F&bd=1

working condition, can be distinguished in electric and thermal. Obviously, the former is the larger since it is needed for the alimentation of all the equipment like pumps (feeding, backwash, CIP and CEB chemicals addition), air compressor (air scour), programmable logic controller (PLC) and electro-valves. However, there is also a thermal component, provided by the heating up of the CIP chemicals.

The minimization of energy requirements passes through the optimization of the membrane configuration, performed here using the software “Wave”. The following parameters were chosen as input to the system, corresponding to a worst-case scenario for fouling, thus the most energy-intensive system required to maintain is performance high:

- Same influent water composition as obtained from the greywater characterization considering some abatement of the value of TSS from biological treatment (UF inlet value 32.6 mg/L);
- TOC removals set to 10%;
- TMP increase between backwash cycles set as 0.5 mbar/h;
- Backwash flux of 120 LMH, chemically-enhanced backwash flux of 120 LMH, forward flush flow of 6 m^3/h/module, air flow of 20 Nm^3/h/module, membrane integrity testing 30 min/day, filtration duration 30 min;
- Backwash, CEB, and forward flush duration about 60 s per step, one single backwash, soaking duration 10 min with addition of HCl and NaOCl;
- CIP recycle temperature at 40°C with flow rate of 4 m^3/h-module, heating and soaking of 30, 60 and 90 minutes, respectively, with addition of HCl, NaOH, NaOCl and citric acid;
- Maximum air scour pressure lower than 1 bar (0.75 bar which can be considered a quite high value compared with the recommendation which is almost the half) and a permeate pressure just above the atmospheric value (1.2 bar).

Two different membranes and configurations were investigated, reported in tables 25-26.

Table 24 *Recommended configuration for Ultrafiltration SFD-2660*

Total trains	Module/Train	Total module	Operating flux [LMH]
1	20	20	72
2	10	20	72
3	8	24	60
4	4	24	60
5	4	20	72
6	4	24	60
7	4	28	51
8	4	32	45

Table 25 *Recommended configuration for IntegraFlux SFD-2860XP*

Total trains	Module/Train	Total module	Operating flux [LMH]
1	14	14	67
2	8	16	58
3	6	18	52
4	4	16	58
5	4	20	46

The evaluation of the performance of each system can be done on the basis of two parameters: specific energy and overall water recovery. The first is defined as the ratio between the energy requested by the whole plant in terms of electricity over the production of permeate obtainable by the plant and is measured in kWh/m3. The second indicates the relative amount of filtrate obtainable from the system and is defined as shown in equation 11.

Equation 11 *Recovery definition*

$$R(\%) = \frac{\dot{V}_F - \dot{V}_C}{\dot{V}_F} * 100$$

Where $\dot{V}_F$ and $\dot{V}_C$ are the volumetric flow rate of feed and concentrate. A sensitivity analysis was performed with the results shown in figure 50.

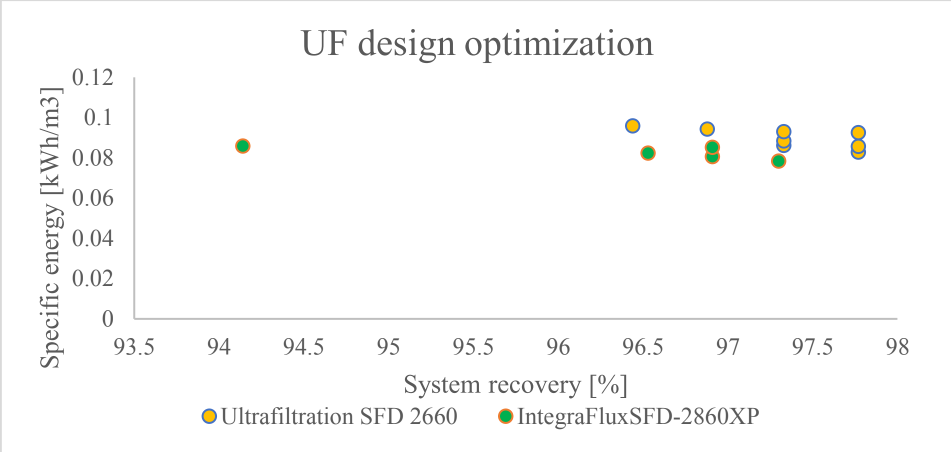

Figure 50 *Performance of different design for the selected membranes*

Independently of the configuration proposed by the software, the recovery sits in a high-values range, always higher than 94%. Thus, the system recovery would not be significantly affected by the selection of the configuration in the same way as its specific energy. The final selected configuration in this work is IntegraFluxSFD-2860XP, which includes only one train and fourteen modules, guaranteeing a great performance in terms of recovery and energy demand: the recovery would be 83.4% with a specific consumption of 0.097 kWh/m^3. The performance of this configuration can be observed as summarized in table 27.

Table 26 *Energetic performance of the optimal configuration*

Parameter:	Value:	Unit:
Peak power	25.9	kW
Energy	87.6	kWh/d
Daily electricity cost	16.6	€/day

The major portion of the electricity would be devoted to ensure the required pressure as a driving force for filtration (2 bar), followed by the energy required to the electronic control devices (PLC), backwash operation, and air compressor needs. In table 28 the effluent quality can be found, together with the main parameters that characterize the ultrafiltration treatment, as calculated by the software.

Table 27 Effluent quality and other parameters for the optimal ultrafiltration configuration

Parameter:	Value:	Unit:
Turbidity	≤ 0.1	NTU
TSS	Absent	mg/L
SDI	≤2.5	-
TOC	90	mg/L
Operating flux	58	LHM
Filtration duration	60	min

5.4.4 Disinfection

Both inactivation and killing of pathogens is appropriate to remove the threat of dangerous effect of contaminants such as E. coli and Enterococci. In Italy, the most common chemicals employed to achieve pathogen disinfection are free chlorine and chlorine dioxide, which provides a very effective removal of the action of both bacteria and viruses (the latter chemical performs better in case also protozoa and endospores are considered). To analyse the rate of disappearance of pathogens a simplified first order model can be applied: Chick's law. The velocity of removal is reported in equation 12.

Equation 12 *Disappearance rate of species in differential form*

$$\frac{dN}{dt} = -k * N$$

Where N is the number of bacteria, k the coefficient of bacterial disappearance, and t is time. The integration of the formula provides the expression available in equation 13.

Equation 13 *Disappearance rate of species integrated*

$$\frac{N}{N_0} = e^{-kt}$$

Where N_0 is the bacterial amount at the initial time. The unique limitation of the model proposed is that the amount of disinfectant employed to complete the task is not included in the evaluation. With the Chick-Watson model (equation 14), this parameter is considered.

Equation 14 *Reaction rate as function of Chick-Watson model*

$$r = -\Lambda_{CW} * C * N$$

Where r is the reaction rate (measured in organism/L-min), Λ_{CW} the coefficient of specific lethality (L/mg-min), C the concentration of disinfectant (mg/L) and N the concentration of organisms (org/L). In this work, a simple disinfection via sodium hypochlorite is considered. Compared with the application of chlorine dioxide, this practice is simpler and does not require the production on site of the required disinfectant. Typical concentrations[73] of sodium hypochlorite for wastewater treatment are between 5 and 40 mg/l. The reaction occurring when this reactant enters in contact with wastewater is reported in equation 15.

Equation 15 *Sodium hypochlorite reaction*

$$2NaClO + H_2O \rightarrow HOCl + Na + OH^-$$

Both contact time and the concentration of disinfectant are correlated with the efficiency of disinfection. To ensure an appropriate timing, baffles design is fundamental for this stage.

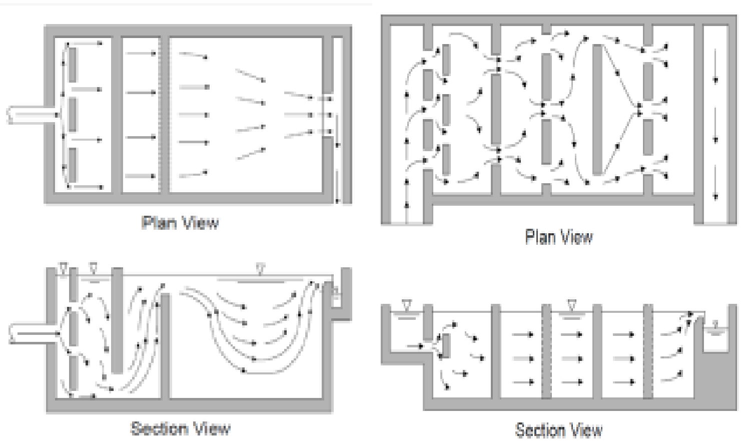

Figure 51 *Baffle configurations to guarantee an appropriate contact time*

Disinfection is the last step of the treatment train to be applied to guarantee the accomplishment of D.M. n.185. The effluent outgoing from the wastewater treatment unit can be applied for the previously mentioned end-uses.

[73]http://dissemination.echa.europa.eu/Biocides/ActiveSubstances/1391-02/1391-02_Assessment_Report.pdf

5.5 Economic-energy-sustainability assessment

Once the design-related evaluation has been provided, the feasibility of the investigated case study should be quantified:

- Economic evaluation, which means to quantify the capital and operative costs associated to the selected technologies and comparison of the costs to tap the same amount of water from a decentralized system to perform the same activities;
- Energy comparison, to analyse each energy-consuming step of the greywater treatment compared to the energy computed to supply water in the present scenario;
- Water saved and additional chances arising from the studied configuration like waste management and its valorisation.

5.5.1 Economic evaluation

Concerning the anaerobic treatment, a commercial tricameral tank able to carry out request for this step for 100 people costs about 10,000 €, price that needs to be quadruplicate considering the district context in which it would operate. It is suggested a negligible request of manpower and energy consumption, although, the necessity of managing the produced waste (sludge) has to be considered: according to the European Directive 75/442/CEE this waste belongs to the category of "urban waste and associable products of commercial, industrial and institutional activities", marked CER 20.03.04 (Codice Europeo del Rifiuto). The disposal of this waste must be considered as part of the operative costs: from the former consideration, the estimated sludge production is about 50 m^3/year, assuming a cost of disposal[74] of 120 €/ton and a density of sludge of 1,400 kg/m^3, the cost can be quantified as 8,339 €/year. To be included into the operative costs, is the electricity cost to feed the tanks. Since the pressure required is just slightly above the atmospheric level and a small distance to be covered is considered, a value of 0.1 kWh/m^3[75] can be hypothesized, thus an annual expense of 3,311 € has to be accounted.

The evaluation of the economics of the ultrafiltration membrane is done applying the ranges provided by the BREF of wastewater and can be summarized as follow:

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[74] http://www.asl2.liguria.it/pdf/bandi/Allegato_1Capitolato_rete_scarico.pdf

[75] Water, energy and food interactions: threats and opportunities; G. Olsson

- Investment cost: 570-2,150 €/m^2 of membrane. Considering the relatively small flow rate associated to the district application, a cost of 1,000 €/m^2 can be considered adequate. IntegraFluxSFD-2860XP module has useful surface of 51 m^2 thus, considering the optimal configuration (1 train-14 modules), the total investment cost would be 714,000 €;
- Operating costs: in absence of a value for ultrafiltration, the figure proposed for microfiltration (MF) can be used. For MF the cost is associated to the application of the driving force, accounting for 0.1 €/m^3, thus the annual operating cost can be estimated as 17,520 €;
- Membrane replacement costs: 110-500 €/m^2 of membrane. A value of 225 €/m^2 can be considered, so that the costs can be accounted as 160,650 € for replacement.

The costs are divided roughly as such:

Investment costs: pumps (30%), replaceable membrane components (20%), housing of membrane modules (10%), pipework, valves and framework (20%), control system (15%), other (5%).

Operating costs: replaceable components (35-50%), cleaning (15-35%), and energy (15-20%), labour (15-18%). Energy costs was coherently added into the operating voice thus, is considered hidden into that cost, as well as the disposal of the retentate (1.4 m^3/h to be allocated in two operative days), for which an economic benchmark is provided by Wave: 0.6 €/m^3 is the cost to be included for its management, hence considering a yearly production of 6,132 m^3, the annual associated cost is 3,679 €. This estimation is considered already included into the operation cost, as already mentioned. Replacement of membrane is precautionary considered to occur three times during the lifetime of the ultrafiltration, but with a careful maintenance it could be done two times.

Concerning the disinfection costs, it must be taken into consideration the operative (electricity per cubic metre) as well as the feedstock (NaClO) one. The former can be estimated equal as the one required by a traditional chlorination, as reported in figure 52.

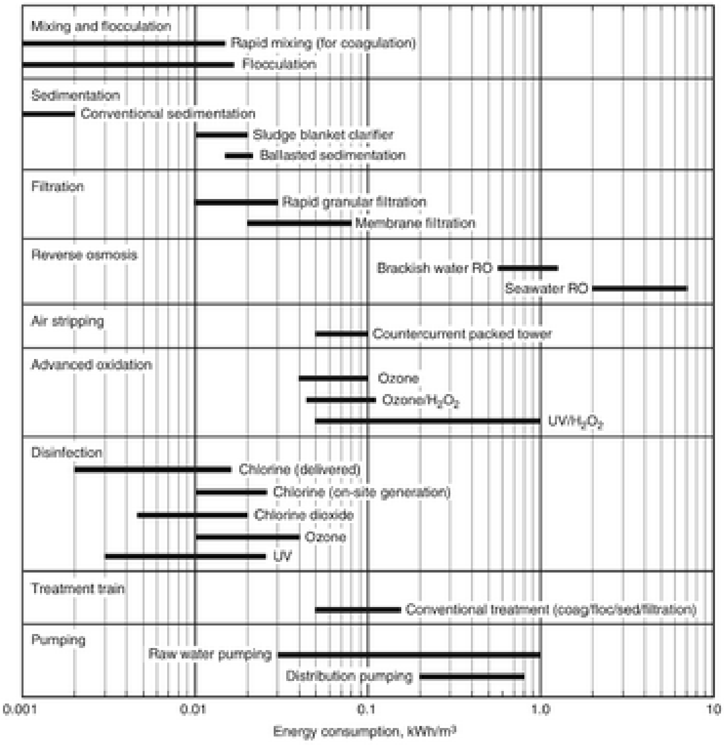

Figure 52 *Specific energy consumption of common water treatment*

Operative cost can be estimated once the specific energy consumption of sodium hypochlorite disinfection is set as 0.18 kWh/m^3: this step requires every year 5,958 €. Moving to the cost associated to the disinfectant, its cost can be approximatively 0.39 €/kg, thus considering a concentration of 0.04 kg/l, the annual cost is 2,732 €. Investment cost is neglected.

To verify if the plant is worth from an economic point of view, a possible way is to quantify the avoided cost of supplied water that should have been used for irrigation purposes, in case of absence of the treatment plant. The annual production of reused greywater is 175,150 m^3, but to evaluate the avoided cost an indicative water price is needed. This value is sensible to the location and to the end-users: just to provide a monetary quantification of this saving, a value that fits the agriculture use[76](0.682 €/m^3) is considered. From these data is possible to quantify the yearly avoided cost of water, which account for 119,452 €/y. A summary of all the costs considered is provided in table 30.

[76] https://www.cometea.it/costa-poco/tariffe-vigore/

Table 280 Economic expenses of the treatments

Treatment	Investment cost [€]	Note	Operating cost [€/year]	Note
Anaerobic treatment	40,000	Tanks	3,311 8,339	-Feeding; -Sludge disposal
Ultrafiltration	714,000	Capital cost	17,520 160,650	-Including waste management and electricity consumption; -Replacement cost (2-3 times in a lifetime)
Disinfection	-	Capital cost negligible	2,732 5,958	-NaClO; -Treatment

An approximate payback-time evaluation can be performed, where the avoided cost of supplied water is providing a positive contribution in the net cash flow evaluation. The expression of the payback time, in which the actualization of the cash flow is included, is provided in equation 16.

Equation 16 Actualized payback time expression

$$-I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} = 0$$

Where I is the investment cost, and all the terms compound in the summation as the actualized cash flow, which is characterized by the yearly net cash flow B_t and the discount rate. An appropriate value of 4% can be set as discount rate, hence a comparison between the simple payback period and the actualized one can be observed in figure 53.

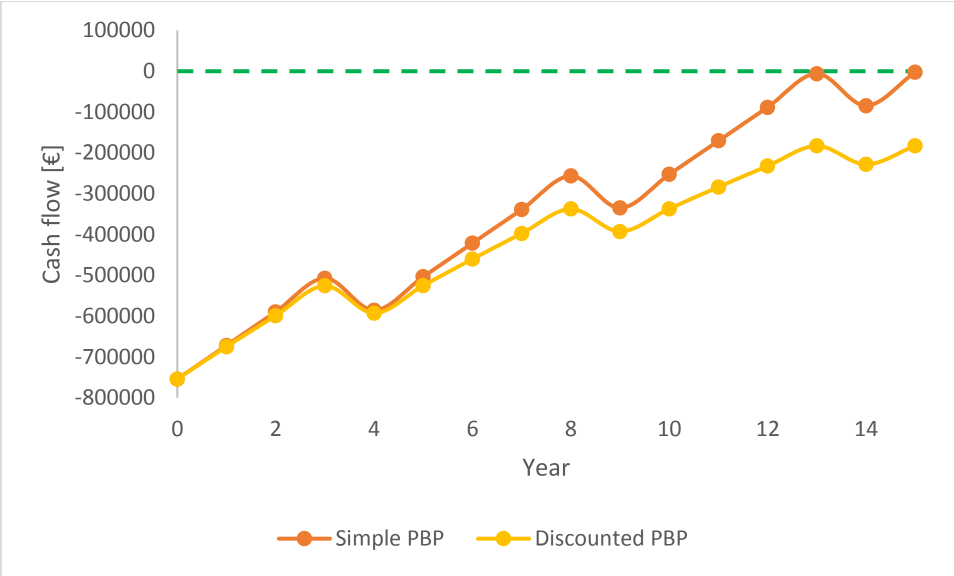

Figure 53 *Simple and actualized payback period of the treatment train*

The economic performance of this treatment train per se will not guarantee a return. In fact, neither including the inflation nor evaluating the simple net cash flow, the null value is achieved in the considered lifetime. To obtain a successful performance, the lifetime of the plant should be extended or the membrane replacement should happen less frequently (most significant negative contribute in the evaluation). However, it must be considered that the cost associated to each step have been deliberatively taken in the high band of the provided intervals, to be as conservative as possible.

This sort of economic evaluation is strictly connected to the type of destination of use of the treated wastewater: as provided by the D.M. n.185, the chances are multiple. In case the water would be employed for zootechnical purposes, there would not be a net benefit since the avoided cost of water for this task is set to 0.35 €/m^3. On the other hand, in case the objective is potable water, the savings would have been higher (potable water cost is 1.46 €/m^3). Despite of the remarkably high avoided cost, the treatment train proposed here would not be suitable to obtain potable water: a more accurate control among the chemicals and microbiological parameters as well as emerging contaminants should have been guaranteed. Just as exemplificative example, a massive denitrification and dephosphorisation steps would have been required, adding costs and complexity to the treatment chain.

5.5.2 Energy comparison

An additional comparison concerns the specific energy. To do that, it is necessary to compare the energy required in the case study with that of a traditional treatment train involving the conventional water sources like surface or groundwater. A comparison of this kind has been conducted by Lee[77] et al. study, whose outputs can be observed in table 31.

Table 291 Specific energy requirements for each stage of urban water cycle

Stage:	Minimum [kWh/m^3]	Maximum [kWh/m^3]
Abstraction and Conveyance	0.001	3.7
Treatment (preliminary)	0.03	4.23
Distribution	0.03	0.58
End-use	>50	>50
Collection	0.16	0.16
Treatment (after the use)	0.18	10

The very wide range for some specific stages can be justified by the fact that in the water cycle, also brackish water and seawater are included. To make an adequate estimation, some reasonable values belonging to these ranges are selected: the paper from which the data are extracted quotes figures for Torino[78] thus, considering that the case study is placed in Italy, these values are considered appropriate. The upstream data of energy requirement for the availability of one unit of volume of water is 0.81 kWh/m^3, which includes the stages of extraction, primary treatment and distribution. Concerning the downstream values, wastewater transportation and treatment account for 0.44 kWh/m^3.

In the evaluation of the alternative proposed by the case study, abstraction, preliminary treatment and distribution may not been included, since for the considered scenario, greywater needs only to be mixed (collection stage), sent to the treatment unit and locally distributed for the use. Collection requires roughly 0.16 kWh/m3. The specific energy needed by the

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77 Water-energy nexus for urban water systems: a comparative review on energy intensity and environmental impacts in relation to global water risks; M. Lee, A. A. Keller, P. Chiang, W. Den, H. Wang, C. Hou, J. Wu, X. Wang, J. Yan

78 Life cycle energy and GHG emission within the Turin metropolitan area urban water cycle;M. Zappone, S. Fiore, G. Genon, G. Venkatesh, H. Brattebø, L. Meucci

treatments is 0.1 kWh/m3 for anaerobic process, 0.097 kWh/m3 for ultrafiltration, and an approximate value of 0.02 kWh/m3 for disinfection. Considering that the selected final use (urban irrigation) can occur in a neighbouring area with respect to the treatment unit, the value of distribution should be significantly lower compared to the transportation of any alternative water source from the water treatment plant to the end user. Assuming an energy consumption of the same order of magnitude of the feeding pumps for the anaerobic treatment, 0.1 kWh/m3 can be considered for distribution purpose. The comparison of specific energy required by the processes is visible in figure 54.

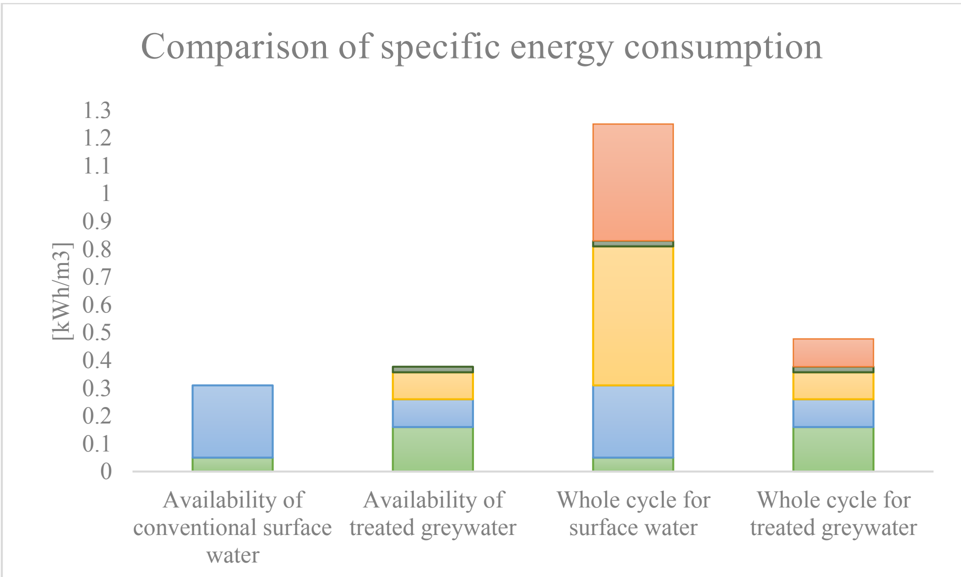

Figure 54 *Specific energy consumption of traditional water sources compared with the case study*

The graph can be split into two sides: the left-hand side, which compares the two alternatives considering the amount of energy necessary to supply water and the right-hand side, accounting for all the stages experienced by the water sources in their life cycle. Focusing on the first two bars, it is evident that the energy required by greywater treatment is slightly higher than that requested to supply water from conventional sources: the conventional one requires 0.31 kWh/m3 to be extracted (0.05 kWh/m3) and treated (0.26 kWh/m3), while the process linked to greywater treatment needs roughly 0.38 kWh/m3. If the provision of surface water seems to be more convenient, things change when all the water cycle is considered. To complete the energy requirement of its cycle, greywater needs to account only for the additional distribution, thus its final value of specific energy is 0.48 kWh/m3. Traditional water, however, has to experience distribution (0.5 kWh/m3), transportation (0.02 kWh/m3) and wastewater treatment (0.42 kWh/m3), requiring a final value of 1.25 kWh/m3. The comprehensive comparison highlights that the proposed treatment is less energy intensive than the classical entire water cycle when all the stages (cradle to grave approach) are included.

To realise a suitable system, a proper location of the plant seems to be crucial, in order to abate the distributional energy demand which, as proven, can significantly change the value of the investigated benchmark. As a final general consideration, the electricity requested by a single cubic meter of water for both traditional surface water and unconventional source falls into the range analysed in the previous chapter, as presented above in table 9.

5.5.3 Avoided resource depletion and opportunities

Beyond the economic and energetic evaluations, which clearly have an essential place in the feasibility evaluation of any plant of this feature, the sustainability related to this project should be highlighted. The approach used for this application follows a paradigm very similar to that of integrated wastewater management. The valorisation of a waste is an undeniable benefit which must be considered to promote a circular and sustainable economy. Similarly, we should consider the avoided use of a valuable resource that would have been used to fulfil the same task. In the district context proposed by the case study, an annual regenerated quote can be quantified as 175,150 m^3 (reduced by sludge production in anaerobic treatment), stressing the positive reduction of environmental impact over the water resource.

In the economic analysis, the importance of waste management was already accounted by adding the disposal costs into the list of operating expenses of the plant. But what else could be done about waste? Any process generates unavoidably waste; in this case study, considering that the feed itself is by definition a waste, the statement is definitely appropriate. The analysis of the treatment can highlight two main waste effluents: the sludge generated during the anaerobic process and the retentate of ultrafiltration. Hopefully, part of this waste would be re-integrated into a new cycle so that they could be used as resources instead of being discarded. Concerning the nature of the materials constituting the concentrate of the ultrafiltration membrane, a potential recovery seems difficult. From the perspective of the anaerobic treatment, things are different. The biomass generated by the operation of the treatment can be sent to an anaerobic digester, which uses this waste as feedstock for biological methanogenesis. The disposal of sludge could happen in a tank where flows with a high solid content are managed. Moreover, the feature of this system could permit the introduction of two additional waste sources. The first is black water (i.e. toilet flushes), whose employment would close the cycle of domestic wastewater reuse. A second input for this system could be the introduction of food waste, as well as organic solid waste. This option could not only reuse and manage further waste, but also generate biogas, ideally used within the district for thermal or energy purposes. It has to be mentioned that the addition of complications is not negligible and most likely also the legal procedure to be developed before running a solution like that may not be easy.

As a final observation, the possibility of recovering thermal content can be considered. Each of the sources considered for the composition of the greywater mix have a thermal content which is higher than the temperature at which water is withdrawn from the network. Before being classified as greywater, the temperature of each current can be roughly estimated. All the flows associated to the interaction with human skin must have a limited temperature of 42°C: this is the value over which hot streams could provoke skin-burns. Consequently, this is the maximum allowable discharge temperature that sinks can reach. About laundry, the temperature can vary according to the habits of the building's tenants. According to the study of Pakula and Stamminger[79] the load size per wash cycle as well as the typical temperature at which laundry is done, is sensible to the geographical areas: in Europe the most frequently used wash temperature is 40°C, while in North America it fluctuate between 15-48 °C, Asiatic countries like China, South Korea and Japan, can use even colder water for this purpose. However, providing a single water temperature for laundry would not be easy since specific programmes work with several temperature levels (i.e., prewash at lower temperature). The same consideration can be done for the dishwasher water, for which the temperature swings between 45-65°C according to the hot or cold rinse rather than the wash phase. The thermal content that can be recovered by a hot water stream is provided by the energy balance associated to this configuration, as provided in equation 17.

Equation 17 *Energy balance for a water stream*

$$\dot{Q} = \sum_{i} \dot{m} * \Delta h - \sum_{o} \dot{m} * \Delta h = \sum_{i} \dot{m} * c_p * \Delta T - \sum_{o} \dot{m} * c_p * \Delta T$$

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[79] Electricity and water consumption for laundry washing by washing machine worldwide; C. Pakula, R. Stamminger

Where $\dot{Q}$ is the power exchanged (kW), $\dot{m}$ the mass flow (kg/s), Δh the enthalpy gap between the conditions assumed by the stream (kJ/kg), c_p the heat capacity (kJ/kg-K) and ΔT the temperature difference (K). The subscripts i and o are related to the incoming and outgoing streams with respect to the boundary of the system considered, while the shift from enthalpy to temperature is possible due to the absence of phase changes.

To consider the energy recovery, firstly an estimation of the temperature of the greywater mixture is necessary. In case the collection happens adiabatically and neglecting the fluctuation of the heat capacity at different temperature (it is an appropriate assumption considering the range of evaluation), the mixture temperature can be evaluated as: $T_{MIX} = \frac{\sum_i \dot{m}_i * T_i}{\dot{m}_{MIX}}$.

Reasonable temperature of each source can be:

- Hand basin and kitchen: 25°C;
- Shower: 40°C;
- Dishwasher: 55°C;
- Laundry: 40°C.

Applying the mass flow for each of the considered source of greywater, as provided in figure 43, to the listed temperature, an expected temperature of the mixture of 37.6°C is obtained. Considering the maximum temperature set for the treatments evaluated (which was 30°C), a water heat capacity of 4.18 kJ/kg-K, and a mass flow produced by a single house of 4.16 $\times 10^{-3}$ kg/s (from 360 l/day per house), the recoverable amount of thermal power is 0.132 kW per building, which is not a significant amount, but could be used to pre-heat a stream, especially if low temperature terminals are used for heating purposes. Considering the chance of increasing the temperature of the stream by 5°C by pre-heating, thus bringing it from a reasonable aquifer temperature of 15°C to 20°C, the maximum flow rate that would guarantee this thermal exchange is only 22.7 l/h.

Due to this low content, another chance could be the coupling of the circuit with the evaporator of a heat pump, which deals with low boiling point fluids, but this opportunity requires more data concerning the flows and thermo-dynamical features of the system. Alternatively, in new buildings a dedicated heat recovery may be provided by the direct application of heat exchangers to the shower water: solutions like this are probably more expensive but would possibly allow reducing the energy losses related to distribution compared to a single lumped system.

6. Conclusions

This work found a correlation between water supply and energy requirements. The attention to the topic of water-energy nexus is increasing due to the growing pressure on both resources. The general link within the resources is strong and summarized in figure 55.

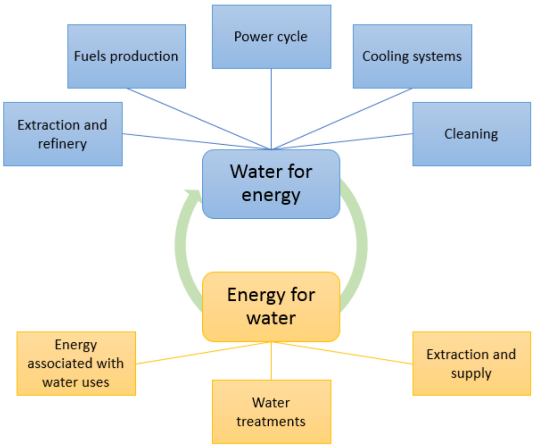

Figure 55 *Water-energy nexus*

Societies are evolving towards more sustainable and renewable solutions for their energy mix. The predictions to 2040 in the countries investigated in chapter four confirm an increase in the share of renewable energy technologies.

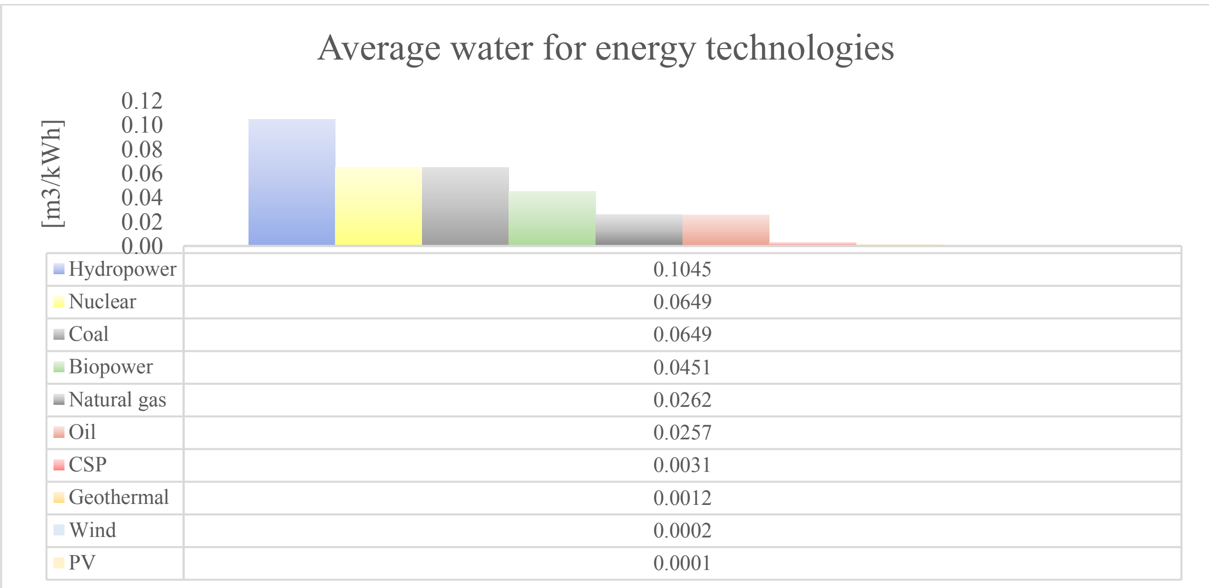

Figure 56 *Worldwide average withdrawn of water for energy technologies*

As shown in figure 56, renewables, with the only exception of hydropower and biomasses for fuels production, are a sensible choice also if considering the overall water withdrawn to produce electricity. In particular, in solar electric and wind power, water needs are respectively three and two orders of magnitude lower than those associated with nuclear and coal sources, which are on average the most water demanding non-renewable options. Hydropower seems the most water demanding, but it was stressed that the range of request can be significantly wide due to the very different amounts required according to each site and plant size.

From the calculation of the energy needed to treat and supply water and that of the water needed to produce energy, the amount of water relative to the energy required to supply water was calculated, providing an approximate figure of the water hidden in water. Comparing the scenarios of the reference case (2015) with the projection to 2040, the minimum reduction of this parameter will be 15, 23 and 0.8 % in United States of America, Italy and Morocco, respectively, while the maximum reduction is attested to 26, 24, and 18 %, respectively. The results suggest that major efforts should be taken especially in the regions where water scarcity is more problematic: the performance of Morocco is emblematic for its almost constant value of "water for water" demand even considering the predicted change in its energy mix. On the other hand, consumption trend will not follow the same decreasing route of withdrawal in all the countries.

Water crises are pushing to find alternative sources of water. Moreover, the general increase of water pollution will force stronger treatments associated with higher energy expenses. Nowadays, unconventional water sources like seawater or wastewater are considerably less used than traditional ones, such as surface water and groundwater, mostly because of technological simplicity and economic advantages in treating conventional sources. One of the most promising technologies is desalination. Without a radical change in the energy expense for the treatment of seawater, the desalination share projected for the future would more than double the water for water requirements, in case desalination would increase from 1% of the actual water mix to 10% (as shown in figures 35-37). Wastewater reuse may be fairly more attractive: the requirement for municipal wastewater treatment is around 0.2-0.8 kWh/m^3 and it varies according to locations, treatment nature, and quality of the effluent[80]. This requirement

[80] Energy efficiency drivers in wastewater treatment plants: a double bootstrap DEA analysis; A. Guerrini, G. Romano, A. Indipendenza

would increase between 1 and 2.5 kWh/m^3 if wastewater is to be reused for high-end applications.

The case study of greywater reuse for irrigation purposes within the urban water system was employed to test the effectiveness of the application of unconventional sources of water for a specific urban application. The outputs of the study are optimistic: in case of a well-designed system, the overall energy request would be low. Additionally, the economics of the system, albeit approximate, provided a confident quantification of the expenses and savings. An overall specific energy of 0.45 kWh/m^{3}and annual surface water savings of 175,150 m^3, but no economic benefits would be obtained within the considered lifetime.

The study was mainly based on the elaboration of data provided by the literature and an experimental investigation should be conducted. Several parameters could affect the outcome, like the characteristics of the greywater. Greywater reuse would not be a universal process, applicable everywhere and with the same performance. Also, to make its realization possible, the public would need to switch toward the employment of biodegradable detergents and soaps, to maximize the removal of organics during treatment and avoid complications in the operation of the system.

A multi-objective optimization (both at system and component levels) and exergy analyses may help further understand the way to improve the energy efficiency of water systems. By doing this, the sources of irreversibility can be detected, and interventions implemented. As energy plays a primary role in the costs of a water treatment plant, the limitation of its consumption can be also an economic incentive. A further interesting strategy to be introduced into a treatment plant could be moving from a condition of energy consumers to that of producers. It is a common action to install photovoltaic panels in this kind of plants in order to cover partially, or completely whenever possible, the energy demand. This specific technology has advantages and disadvantages when coupled with water treatment facilities. The positive points are the direct production of electricity, which is the main energy source consumed in this context and additionally it is a noble form of energy, convertible relatively easily in lower quality energy forms (e.g., mechanical). The disadvantage is related to the fluctuating nature of solar energy sources, which cannot guarantee a continuity of energy supply. Anaerobic digestion of the organic compounds, algae-feeding process and involvement of fuel cells are just some other technologies which could improve the coupling of energy and water advancements.

Another relevant aspect in the challenge of water-energy nexus is the recognition from the policy makers that this interaction should be faced as a single question. There is still a lack of communication between these two worlds especially concerning legal frameworks and subsidies which are generally left to the sensibility of the individual nations. Sometimes, the quality requirements are too strict for certain applications and prevent the use of recycled water without real scientific basis. An example of how there is no alignment about water reuse is provided by a situation happening in California. Here, a system called "laundry to landscape"[81] allows the direct use of laundry generated greywater for irrigation purposes, without any legal permits required. For this kind of application, a simple three-way valve is installed connecting the drain hose with the sewer pipe and the irrigation pipe, so that when no bleach or chlorine is used, the valve can close the sewer way. This system requires a fair level of consciousness from the user also due to of the requirement of eco-detergent not containing excessive salts, boron, etc.; in the absence of a regulatory framework, users need to be careful of their way of managing this system. However, even when legal bindings are available, the absence of awareness often leads to an improper use of wastewater: several cases of wrong use of untreated wastewater, especially for agriculture task, or direct discharge into water bodies are reported all over the World, leading to human health problems and environmental concerns.

6.1 Water-energy-food nexus

Finally, a further shade in the nexus definition should always be considered, including food in a water-energy-food security nexus. Food security is defined from FAO as "physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". Irrigation (for both edible and non-edible crops) is the major water demanding sector and considerable amounts of water are required to make or process almost any kind of food. Moreover, energy is required for food: transformation processes and transport are just two energy requiring stages of the typical food chain. One highly debated energy-food nexus is probably the cultivation of edible crops for energy use: biofuels production as well as oxidation or gasification of the biomasses has been under the

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[81] https://greywateraction.org/laundry-landscape/

radar for some time. The employment of non-edible crops for energy purposes is blamed of impacting the environment through land occupation as well as massive water use, as reported through this work.

By looking at FAO database, it is possible to quantify in first approximation (it means without considering all the climatic factors) the amount of water required by several edible crops during their growing phase. The district case study computed in this work produced an amount of usable resource equal to 520.7 m^3/day, which can be compared with the useful surface irrigable for some of the considered crops as reported in table 32.

***Table 302** Water needs for some crops and irrigable surface extension*

	Water needs [mm/day]			[m^3/ha-day]	Irrigable surface [ha]
	Min	Max	Average	Average	Average
Cotton	3.89	6.67	5.28	52.78	9.9
Maize	6.25	7.27	6.76	67.61	7.7
Onion	2.33	2.62	2.48	24.76	21.0
Pepper	5.00	4.29	4.64	46.43	11.2
Potato	4.76	4.83	4.79	47.95	10.9
Soybean	3.33	4.67	4.00	40.00	13.0
Sugarcane	5.56	6.85	6.20	62.02	8.4
Sunflower	4.80	7.69	6.25	62.46	8.3
Tomato	2.96	4.44	3.70	37.04	14.1

The values suggest that by recovering properly the greywater, a small-middle agricultural holding could be supported during the growing stage of one of the listed crops. However, a balance of the nutrients must be guaranteed. A small-scale application can be a valid alternative in the case that the restored water was employed in the urban garden, a trend which is surprisingly rising in the last years.

The issues around the availability of energy, safe water and food will not concern only the developing countries. The proper way to face it is to integrate these topics and develop an accurate management of the resources which minimize their use and simultaneously valorise the waste, led by policies that consider carefully this trilemma.