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Review

Water Energy Nexus and Energy Transition—A Review

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Abstract: The new perspectives of the water–energy nexus, water-for-energy and energy-for-water, emphasize the current and future need to find ways to produce as much energy with as low an amount of water as possible and to obtain as much water with as little energy as possible. In order to promote and implement the concept of sustainable development, the understanding of the dynamic and complex relationship between water and energy is crucial, especially in the context of energy transition. This paper presents a comprehensive analysis of the recent approaches regarding water and energy and the interlink during implementation, operation and servicing of various water and energy production systems. This endeavor is placed in the context of current energy transition from fossil fuels to renewable energy sources. A qualitative and quantitative analysis is performed with various literature solutions from water-for-energy and energy-for-water perspectives for a broader view of the impact of implementing novel technologies in terms of resource use. Technological and managerial innovations are discussed and placed in a transdisciplinary context with a focus on establishing key approaches for achieving sustainable development goals.

Keywords: water–energy nexus; energy-for-water; water-for-energy; energy transition; sustainable development goal; renewable energy; net zero emissions

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1. Introduction

Over the last few decades, a major concern of researchers, governments and international organizations was related to the intensification of climate change. It is proven that a primary source of anthropogenic greenhouse gas (GHG) emissions that cause climate change is the burning of fossil fuels. Thus, the viable proposal, accepted by the international community, was to find ways to transition to zero carbon energy systems, through energy mix changes in the energy production sector and through the electrification of end user sectors, such as transport and heating [1,2].

Studies in the literature have focused mostly on the prospective analysis of different energy mix schemes coupled with the introduction of renewable sources to meet net zero carbon energy goals. Most of the literature analysis efforts are directed toward comparative analyses related to the costs of different levels of decarbonization and the cost of the required infrastructure [3–5]. However, it was shown and proved that energy mixes with high penetration of renewables could lead to higher capital costs and a complex dynamic operation due to lower dispatchability and lower capacity factors than in conventional mixes which include fossil fuels. Thus, more research is necessary for a more in-depth investigation of the impact of energy transition from conventional mixes to energy systems in which the weight is placed on renewables.

The synergistic benefits of introducing renewable energy systems are not only related to the reduction of GHG emissions but also to the reduction of the impact on water resources. For example, by reducing or even eliminating thermoelectric plants, the consumption of cooling water is significantly reduced. Although these potentials are recognized and sometimes quantified [6–8], water use performance objectives are less often integrated into energy performance objectives, especially regarding the connection between water and energy supply systems and the impact of climate change on their evolution.

Considering that climate change will influence the availability of water resources and that in the coming period the electricity supply systems will be rebuilt with a mix consisting mainly of renewable sources, in addition to the current research on the modeling, simulation and optimal design of sustainable electricity supply systems, new research should also include water-related issues, i.e., the water needed to operate future zero carbon energy systems and the energy needed to ensure the proper water supply systems are operating. Thus, taking into account the targets for the Sustainable Development Goals (SDGs) [9], especially SDG6 and SDG7, a comprehensive treatment of the interactions between water and energy will generate solutions that accelerate the achievement of the goal of reaching net zero emissions after 2050.

In relation to the water–energy nexus (WEN) concept, the research literature has made numerous contributions for the in-depth knowledge of the multidimensional interactions between these elements; new methodologies have been developed, and new assessment and characterization tools have been developed [10–12]. However, there are still many gaps related to WEN characteristics during the energy transition that cause significant changes in all economic, social and political fields. Thus, in the conditions in which new challenges related to the energy transition have appeared, the development of review studies is useful in systematizing and assembling the data resulting from scientific research, highlighting the main challenges that would have an impact on the sustainability of water and energy.

The objectives of this study are to review comprehensively the links between water and energy, presenting a picture of the current state of knowledge in the context of energy transition. The main goal of this review paper is to promote and to improve the understanding of the dynamic and complex relationship between water and energy under the conditions of the energy transition.

In terms of the structure of this study, above, we briefly highlighted the requirements to consider the interconnections between water and energy in the context of the transition to zero carbon energy. Next, a Background of Knowledge is synthesized regarding the issue of reducing environmental pollution under the context of energy transition, taking into account a WEN perspective. In the Methodology and Data section, the approach and bibliometric method applied for searching and retrieving information on relevant papers and data obtained are described. In the Results and Discussion section, we consider the results of analysis made on the technological implications of the water–energy nexus, with its perspectives water-for-energy and energy-for-water, for accelerating the energy transition toward net zero carbon emissions. We identify and discuss key points that are expected to increase benefits and decrease the constraints of water–energy interrelations. Finally, the Conclusion section presents a summarization on the efficiency of various ways toward energy transition, such that the requirements of water sustainability are also met, whilst also taking into account climate change and socio-economic variability factors.

2. Background of Knowledge

2.1. Reducing Environmental Pollution—An Emergency

Greenhouse gases, out of which most is carbon dioxide (carbon emissions or CO_2 emissions), consist of gases in the atmosphere that absorb and emit infrared radiation. The balance between absorbed and emitted infrared radiation is the key element for the climate and the environment [13].

The process of the uncontrolled emission of greenhouse gases is the cause of the production of the greenhouse effect in the atmosphere that generates the phenomenon of global warming [14,15].

Changes in climatic conditions, notably the enhanced warming, lead to chain effects. Thus, in urban areas, the increasing warming leads to the "urban heat island effect", manifested by the increased accumulation of heat due to buildings, transport infrastructure and human activities. Climate change has consequences on the availability and security of the water and energy supply [16].

Today, it is proved that carbon emissions constitute the greatest threat to natural ecosystems, environmental sustainability and human development. The total amount of carbon dioxide emissions has continuously increased. Compared to CO_2 emissions in 1950 of 6 billion tons of CO_2, in 1990 the amount of carbon emissions reached 34 billion tons, and in 2020 the amount increased to 34.81 billion tons of CO_2 [17,18].

The last 30 years have seen historic meetings of representatives of the world's states to learn about, debate and take action to reduce polluting emissions and global warming, the most relevant being the Earth Summit in Rio de Janeiro in 1992, the Kyoto Protocol in 1997 and the United Nations Paris Agreement in 2015.

An action plan to limit global warming was initiated at the Paris Conference, with the long-term objective of keeping the global increase in average temperature below 2 °C and continuing efforts to achieve a limit to the increase in average temperature below 1.5 °C. The objective is to reach a state of climate neutrality where human activities no longer have a net effect on the climate system as a whole. Almost all countries of the world have proposed measures in accordance with the Paris Action Plan and specific road maps toward equity, sustainable development and carbon emission reduction, with a horizon set in 2030 [19]. Europe has acted as a global leader on this issue and set an ambitious plan toward net zero carbon emissions by 2050. The EU states have committed to reduce GHG emissions by at least 55% by 2030 compared to the 1990 level [20].

In order to achieve these objectives, optimal ways, methods and measures are needed that lead to the annihilation or reduction of pollution sources generated by human activities. Today, fossil fuels (coal, gas and oil) cover about 80% of the world's energy needs and emit an unprecedented amount of CO_2 [21]. According to the International Energy Agency (IEA) [22], power and heat plants based on fossil fuels cause 42% of energy-related GHG emissions, industry contributes with 24%, transport contributes with 22% and buildings cause 8% of energy-related GHG emissions [23].

The CO_2 reduction requirements to reach net zero decarbonization during 2021–2050 are illustrated by IRENA's 'Target Pathway to 1.5 °C' scenario, in which was stipulated the reduction of 13.0 $GtCO_2$ in the power and heat sector, 11.0 $GtCO_2$ in industry, 8.4 $GtCO_2$ in transport and 2.3 $GtCO_2$ in the buildings sector [24]. Thus, the responsibility for reducing carbon emissions falls on both energy producers and consumers.

Renewable energy sources (RESs) play an important role in the development of the sustainable energy, contributing to the achievement of sustainable socio-economic development and decarbonization. RES technologies can support the strategy proposed in the Paris Agreement to reduce global warming by 1.5 °C. However, this goal can only be achieved if, along with the introduction of RES technologies, the decarbonization process is introduced and intensified in all economic sectors, including transport, buildings and industry [23,25–27].

2.2. Water and Energy Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda for Sustainable Development, comprise 17 goals and the associated 169 targets as areas considered of critical importance for humanity [28]. Since the launch of the SDGs, the research community has intensified its activity in finding solutions to implement these goals, which are closely related to each other [6,29–33].

Although much progress has been made in understanding and applying the connections between different SDGs, as a result of the multiple societal, economic and environmental challenges, new clarifications are still needed. Related to the connections between the fundamental elements—food, water and energy—new research is also needed in order to accelerate the achievement of the established targets. Issues related to the growing demand for energy and water are considered central issues in the UN SDGs. There are two

SDGs directly involved in sustainable water and energy resources: SDG6—Clean water and sanitation and SDG7—Affordable and clean energy.

An integrated approach regarding the SDG6 and SDG7 goals is even more critical considering that even today a large proportion of the global population is still having difficult access to clean water for general use and sanitation services. This issue will be more prevalent in the future with the current predictions of global population increase, especially in areas where such issues are already prevalent. The measures to assure clean water and sanitation are an urgent requirement to assure sustainability [34–36]. Current research has been channeled towards these urgent needs: to identify other water resources that can be used; to improve water use efficiency, mainly in agriculture and energy generation; and to develop water infrastructure and water storage systems on a large scale [11,37,38].

2.3. Energy Transition and WEN Perspectives

In connection with SDG7, the concept of energy transition was introduced, referring to the process of moving from fossil fuel to non-fossil-fuel-based energy sources to create sustainable energy systems with zero or near-zero carbon emissions. The energy transition is a critical agenda item. Currently, efforts are biased toward increasing clean energy production and the electrification of all economic sectors, together with direct and indirect energy savings [39–42].

The energy transition brings many challenges in all economic sectors, resulting in a large complex interdependence between the SDGs. The sustainable development goal SDG6 has a target to provide universal access to drinking water for the world's population by 2030 [8,20]. However, this will have an impact on both water and energy consumption. In addition, the use of inefficient energy sources will have a negative impact on GHG emissions. Thus, it is imperative to implement new water and energy supply systems that are efficient, more robust and reliable in order to reduce greenhouse gas emissions in the long term [43,44].

For a long time, the concept of energy-for-water was used to evaluate the amount of energy required by the water supply system. In the same way, the water-for-energy concept was only applied to estimate the amount of water needed, especially for the cooling systems in power plants based on the combustion of fossil fuels. Over time, with the increase in the complexity of the interactions between water and energy, this concept has expanded, including the set of technological, economic and social processes in interaction that take place in the production, transport and use of both water and energy, in conjunction with other, essential elements for life on Earth [21,38].

Currently, the WEN concept has been extended to food, land and the environment, with different matrixes which allow better management of resource allocation decisions and reduce the negative impacts on society and the environment [45–47].

A deep understanding of the interrelations between water and energy and identifying the modalities in which technological, economic and social innovation can sustain and accelerate the energy transition is the objective of this review paper. Of great importance is also the cooperation between different actors [48–50], through which joint decisions are taken to ensure operational security, resilience and flexibility, as well as increase access across countries and sectors.

3. Methodology and Data

3.1. Approaching the Specialized Literature

This systemic literature review serves to investigate the knowledge gaps regarding the multidimensional interrelations between water and energy during the energy transition toward net zero pollution, obtaining a picture of the current state of knowledge regarding the complex WEN dynamics and illustrating their practical relevance [44,47].

To this end, three investigative parts have been conducted. Firstly, a mapping of the global and regional challenges on energy transition was performed, by utilizing conceptualizations and recent literature. Secondly, a review of the current knowledge on 'water-for-energy' and 'energy-for-water' was undertaken to identify new and appropriate approaches to enhance efforts to achieve the Sustainable Development Goals. Thirdly, the concept of the water–energy nexus was analyzed, in a systematic approach, in order to integrate the two elements, water and energy, with the energy transition issue in a synergistic approach, highlighting the ways of possible synergies and compromises. The review research uses the bibliometric methodology described in [44,51]. In addition to the data sets obtained through the bibliometric method, other works were used to describe the wider context of the dynamics of WEN interconnections during the energy transition [52–55].

3.2. Bibliometric Analysis and Data

In order to search and retrieve the information for obtaining the research landscape for the WEN and energy transition to net zero emissions, the steps recommended in [56] have been applied. To narrow the research base, several successive searches are necessary to address the interconnections between the water–energy interconnection and energy transition. Thus, the set of publications indexed in the databases focused on methods and technologies addressed in the WEN, studied in the "water-for-energy" and "energy-for-water" perspectives, and the impacts produced during the energy transition period to reach net zero emissions after 2050.

This analysis is based on publication and citation data from peer-reviewed research literature, obtained from Elsevier's Scopus database. The Scopus database search was chosen because it allows the systematic review of the literature and ensures the comparability of documents with the WEN topic, a very current topic, treated in different disciplines. Some other issues have been added from the IEEE database.

The strategy applied for information retrieval and meta-analysis included (a) record identification through a database search with specific keywords, (b) registration after removing duplicates and applying exclusion criteria, and (c) meta-analysis on the studies included in quantitative synthesis and case studies.

The search was performed with the specific keyword strings found in the title, abstract and keywords of the documents, limited to the English language and without limitations regarding the year of publication and geographic distribution.

A visual inspection was performed to eliminate duplicate documents and those lacking substantial evidence of the study objectives. After the textual analysis, the articles for which the qualitative and quantitative analysis was to be performed were established. The dataset was supplemented with some reports and publications from international organizations and from the IEEE database.

In Table 1, the number of documents retrieved for different keyword strings from the Scopus database (5 January 2023) are described, while Figure 1 shows the yearly distribution of published papers for C1, C2 and C3 search cases together with the distribution of the most prolific authors in the field.

Table 1. Search cases, keyword strings and number of documents retrieved in Scopus database (5 January 2023).

Search Case	Keyword String	Documents Retrieved
C1	"water for energy"	153
C2	"energy for water"	537
C3	"water energy nexus" and "energy transition" or "sustainable development goal"	53

By analyzing data from Figure 1, we can note that the number of papers published, based on the yearly distribution, has a similar pattern no matter the keyword string utilized, which reflects an increasing interest for the topic. Note that data for 2022 are not fully indexed, which explains the downward trend. The number of articles identified with the topic "energy for water" is much higher than the number with the topic "water for energy".

The number of documents with the topic "water energy nexus" and "energy transition" is low but has a growing tendency, which underlines future research directions.

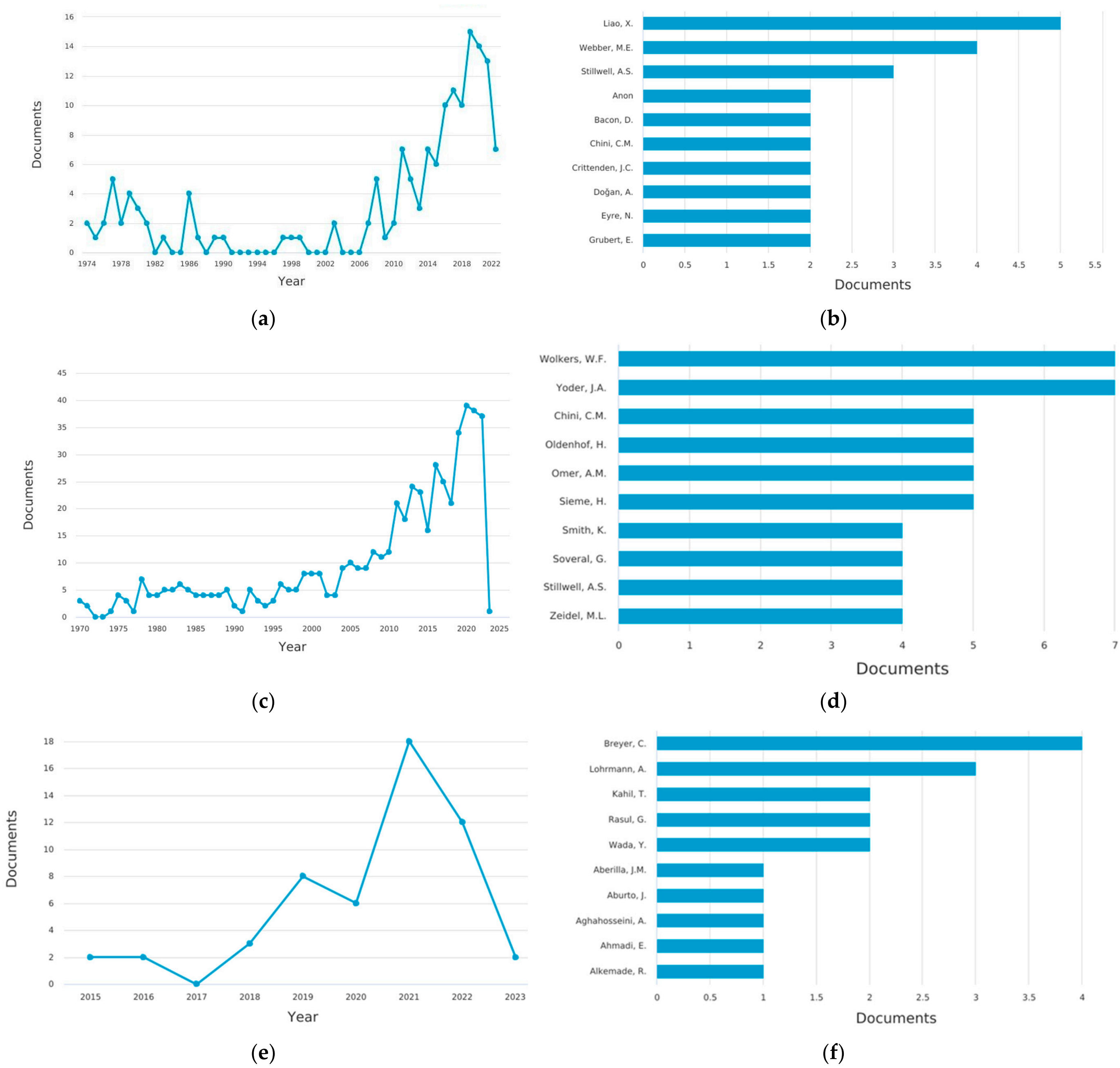

Figure 1. Yearly distribution of papers published, according to the Scopus database, for specific keyword strings (search cases C1, C2 and C3 from Table 1) and production of the most prolific authors in the field: (**a**,**b**) C1 search case (n = 153); (**c**,**d**) C2 search case (n = 537); (**e**,**f**) C3 search case (n = 53).

Figure 2 shows the distribution of research production by document type and subject area for C1, C2 and C3 search cases.

Figure 2. Distribution of research production by document type and subject area, according to Scopus database, for specific keyword strings (search cases C1, C2 and C3 from Table 1): (**a**,**c**,**e**) document type; (**b**,**d**,**f**) subject area.

The share of research articles, conference papers and review articles developed in the analyzed period is given in Table 2. The data show that interest for "energy for water", "water energy nexus" and "energy transition" is a popular topic. Moreover, the number of review papers is increasing.

Table 2. Share of research articles, conference papers and review articles developed in the analyzed period.

Search Case	Research Articles	Conference Papers	Review Papers
C1 (n = 153)	67.8%	11.8%	7.2%
C2 (n = 537)	82.7%	11.5%	2.8%
C3 (n = 53)	73.6%	3.7%	13.2%

An additional set of searches, which include the keyword "sustainability", was included in Table 3, which shows that there is still little research that integrates the topics related to the water–energy nexus and energy transition.

Table 3. Additional searches, keyword strings and documents retrieved in the Scopus database (5 January 2023).

Search Case	Keyword String	Documents Retrieved
C4	"water for energy" and "energy transition" or "sustainability" or "goals"	23
C5	"energy for water" and "energy transition" or "sustainability" or "goals"	32
C6	""water energy nexus" and "energy transition"	17

However, the number of studies that address interdisciplinary issues related to water, energy and sustainability is still low (Table 3).

In order to provide more cross-sectoral perspectives, in this review, articles that have put a wider focus on the development of tools, methods and technologies, and that propose solutions to accelerate the achievement of Sustainable Development Goals, especially SDG6 and SDG7, have been considered.

Even though the bibliometric analysis focused on articles from the Scopus database, for our systematic review, representative articles from the IEEE database were also considered. Thus, a synthesis of the performed analysis is presented in the following sections.

4. Results and Discussion

The performed bibliometric analysis on the research article dataset indicates that ever since 2011, many researchers have applied the WEN concept by considering two perspectives: water-for-energy and energy-for-water [57]. If the concept of water-for-energy was more accepted, the same did not happen with the concept of energy-for-water [58].

In some studies, energy-for-water has been estimated as the energy used for the capturing, pre-treatment and distribution of water and wastewater treatment. Other authors have also included water-related energy consumption in the residential, commercial and industrial sectors. However, the introduction of end user water into the water chain increases the share of the energy requirement for water compared to total energy demand. By including all processes where energy is applied to water, Sanders and Webber [59] classified 47% of total primary energy in the United States as energy-for-water.

Kyle et al. [60] propose as a solution the introduction of a third concept, "water and energy for other purposes", which could describe the consumption of energy and water in processes that take energy and water to produce a non-water output or service and would provide a broader approach to the WEN concept.

However, current approaches show that there is still a lack of understanding and knowledge at local, regional and global levels of data on energy and water consumption, which limits the assessment of the following feedbacks between water and energy systems.

In this context, approaches have been developed in the literature with the following targets: establishing opportunities to produce as much electricity as possible with low water consumption and with reduced CO_2 emissions; and establishing opportunities to produce as much water as possible with as little energy as possible and with low CO_2 emissions.

4.1. WEN Focused on Water-for-Energy

4.1.1. Context of WEN from a Water-for-Energy Perspective

Water is one of humanity's basic natural resources. Water is used for the general consumption of the population and to ensure the functioning of all economic sectors—domestic, commercial and industrial. Water is essential for energy production [21,61–63].

Energy production technologies such as nuclear, thermoelectric and hydropower require large quantities of water. An example is the U.S., where (Table 4) around 40% of the total freshwater extracted is used for power generation in thermal power plants [64]. Many studies and projects developed by world organizations recently forecast a more water-constrained future due to climate change and economic challenges [65–67]. This will have a significant impact in the energy sector and will drive up energy costs.

Table 4. Freshwater withdrawal and consumption in the U.S. in 2015 [64].

Sector	Water Withdrawal (341 bgd) [1]	Water Consumption (115 bgd)
Thermoelectric power	41%	4%
Agriculture	40%	83%
Residential and Commercial	12%	10%
Industrial	7%	3%

[1] Billion gallons per day.

The situation is dramatic especially in countries with arid areas, such as the Southern African Development Community's case where the index of the relative dryness—Climate Moisture Index (CMI)—is close to (−1.00) [37]. There are alarming signs that current electricity supply systems, dominated by power plants with large water requirements, will be heavily affected by likely future droughts and water shortages, especially in the summer months. Climate change, combined with the energy transition, has a significant impact on water resources [68–72]. Moreover, during the energy transition, the dynamic of the energy mix entails changes in the structure of demand and water consumption necessary for the functioning of the energy supply system [73]. In relation to this issue, several key points have been identified [8,74]:

- Availability of water resources to support transition to a green economy without compromising other services;
- Solutions for improving efficiency of water consumption for the energy sector;
- Modeling water for energy interaction for electricity generation.

The analysis and use of the WEN connection from the point of view of water for energy generation could allow the finding of solutions to improve the synergy between these two resources so that the affordability and operability of energy supply systems which deeply depend on water availability are ensured, together with the reduction of polluting emissions.

4.1.2. Evaluating Water Withdrawal and Consumption for Energy Generation

In order to properly characterize the water used for energy generation, several measuring tools have been introduced in the literature:

- Water withdrawal—refers to the gross amount of water abstracted from its groundwater or surface water source and used during electricity generation stages and then returned to the point of abstraction (return flows) [8];
- Water consumption—refers to water used in a process or incorporated into a product that cannot be returned to the source. Using this definition, water consumption becomes a subset of water withdrawals. For hydropower and bioenergy, water consumption includes only evaporated and transpired water, as well as water stored in crops and/or other products [8,21];
- Virtual water—is a measure of how much water is embedded in the production and distribution of a good or service [75]. The reduction of water imbedded in electricity generation can be achieved through less water-intensive electricity generation, such as renewable power generation, and more efficient use of electricity [76–79];
- Water footprint—refers to the total volume of water consumed by an individual or a group. At the level of human settlements and nations, the water footprint equals the aggregate quantity of domestic water resources consumed by all inhabitants, plus the

balance of virtual water they import and export through trade in various goods and services [32,80,81];
- Minimum water requirements—refers to the water required to fulfill basic human-needs and the functioning of critical ecosystems. In the light of sustainable water resource management, water requirements take into account social, economic and environmental needs [38].

The usefulness of these tools was confirmed by their application in multiple case studies [21,37,72,80,81] and by their use as criteria for selecting the most appropriate methods to reduce water withdrawal and consumption for energy generation.

This allowed the introduction of recommendations and regulations by international bodies. Thus, the minimum water requirements are specified in the International Energy Agency (IEA)'s documents, in which it is stated that the water requirements for fossil-fuel-based and nuclear power plants—the largest users of water in the energy sector—could be reduced significantly with advanced cooling systems [82].

A relevant case study in which an analysis of the water requirements for energy production is performed in [37] for regions of the Southern African Development Community (SADC). The water required at all stages of the energy production chain was taken into account: the extraction, processing and transportation of fuels, plant construction, operation, transmission of electricity and decommissioning of plant (Figure 3).

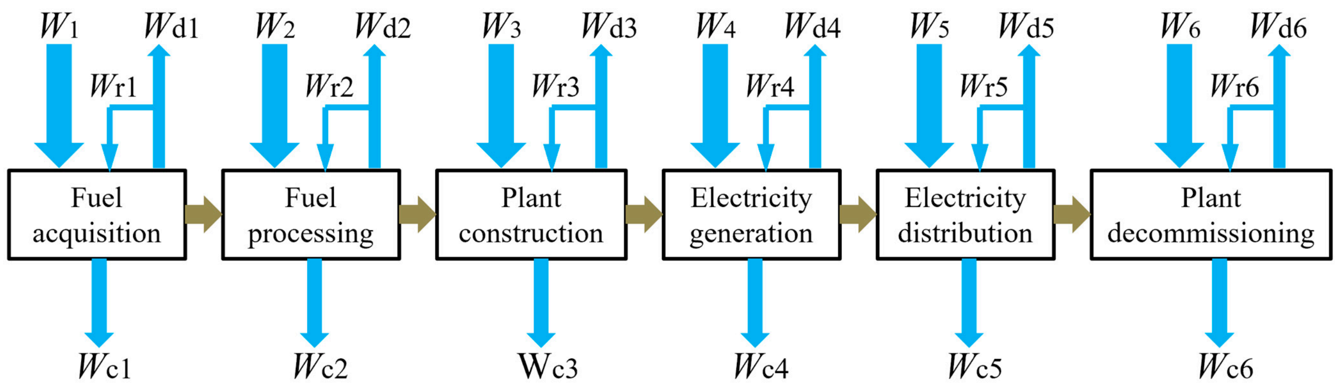

Figure 3. Water requirements in energy production chain (adapted after [37]).

The volume of water (W_i) that is withdrawn from a reservoir at each stage is partly consumed (Wc_i) and partly discharged (Wd_i) back into the water source. A part of the withdrawn water is recycled (Wr_i).

Understanding that the required quantity of water varies with the type of energy generation technology and the quantity of demanded and delivered energy, for assessing the efficiency of water use in the energy production chain, an overall tool was applied for estimating water withdrawal and consumption, water intensity WI, which corresponds to the volume of water required to produce a specific quantity of electricity, measured in m^3/MWh or L/kWh [37].

Thus, the withdrawn water intensity corresponding to each stage i, can be defined:

$$WI_i = \frac{W_i}{E_i} \tag{1}$$

where W_i is the input water, and E_i is the output energy, corresponding to stage, and the total water intensity WI_t is:

$$WI_t = \frac{\sum_i^n W_i}{E_{end-user}} \tag{2}$$

which corresponds to the total water withdrawn reported on the total energy obtained and available at the end–user input on a lifecycle or a predefined time.

The intensity of the consumed water is defined in the same way, taking into account the water consumption *Wc* from each stage (Figure 3).

In [37], for the SADC regions, the values for the estimated intensity of withdrawn water on a lifecycle basis are given, corresponding to the volume of water withdrawal required to produce one megawatt hour of electricity (Table 5). Note that initial values in L/kWh were transformed into m^3/MWh so that they could be easily compared with data obtained in other works.

Table 5. Water intensity based on a lifecycle basis according to Southern Africa Development Community (SADC), Regional Water Infrastructure Program; SADC: Gaborone, Botswana, 2010 [37].

Power Plant Type	Intensity of Withdrawn Water [m^3/MWh]
Coal-fired	1.28–194.42
Hydropower	0.08–440.00
Nuclear	4.51–119.4
Oil/gas/steam	1.48–86.9
Concentrated solar power (wet-cooled) (CSP)	0.5–5
Photovoltaic (PV)	0.27–1.95
Wind	0.17–0.32
Geothermal	12.8–344.7

From Table 5, it can be noted that the water intensity is higher for fossil fuel power plants due to the water used in cooling technologies and the upstream stages of electricity generation. Thus, the extraction and preparation of input fuels for electricity generation consume significant quantities of water and impact water quality [75,83–87]. The specific water withdrawal values taken in account are shown in Table 6.

Table 6. Specific water withdrawal for extraction and preparation of input fuels for electricity generation, adapted after [83].

Type of Fuels for Electricity Generation	Specific Water Withdrawal	
	[gallons/MMBtu] [1]	[m^3/MWh] [2]
Coal mining	1–6	0.0129–0.0775
Refinery petroleum	7–18	0.0904–0.2325
Oil extracted from shale	15–28	0.1937–0.3616
Oil extracted from sand	20–50	0.2583–0.6457

[1] 264.17 gallons = 1 cubic meter. [2] 1 gallon/1 MMBtu = 0.0129159 m^3/MWh.

A comparative analysis on the estimated overall water consumption intensity (in some works called "water factor") for the entire electricity generation chain is shown in Table 7 [75,88,89].

The data from Table 7, and from many other studies, allow ranking the power plants according to water requirements:

- The coal-fired thermal power plants withdraw a higher amount of water from the water source, which depends on the type of cooling system and the efficiency of the processes at each stage of the electricity generation technology [85–87,90].
- Hydropower plants exhibit the largest amount of water demand and have a wide range of water intensity, but in this case the water provides the driving force for hydropower plants. However, water scarcity poses a high risk to the production of hydro power [91,92].
- Renewable energy technologies like PVs and wind are the most water efficient over the considered stage of the lifecycle.
- The concentrated solar power (CSP) plants require more cooling water per unit of electricity generated compared to fossil and nuclear plants since CSP plants operate at lower temperatures with less steam efficiency [38,93].

- Geothermal power plants make use of convective hydrothermal resources inside hot rock beds. However, external water supplies are usually required given that many geothermal resources do not naturally contain enough water [94].

Table 7. Overall water consumption factors for electricity generation, after [75,88,89].

Power Plant Type	Water Consumption Factors [m^3/MWh]		
	Gleick (1994)	Macknick et al. (2011) Median Value	Wang et al. (2015)
Coal	1.9	1.8	1.9
Oil	1.85	–	1.85
Natural Gas	1.85	0.7	0.7
Nuclear	2.7	2.0	2.0
Hydroelectric	17	17	5.4
Wood	2.3	–	2.3
Solar	0.1	0.1	0.1
Wind	0	0	0
Bio-power	–	1.2	–
Geothermal	–	1.0	–
Concentrating Solar Power (CSP)	–	1.6	–

The high water consumption in thermoelectric power plants is due mainly to the use of water as the cooling fluid. The two types of wet-cooling technologies have different impacts on water consumption and water availability [75,85,89,95,96]:

- In the first type, called "once-through water cooling system", water from a source cools the steam in a condenser and then returned to the source to replenish the water abstraction, a process which increases the temperature of the water. In this case, overall net consumption of water is negligible, but this still affects water resource availability upstream, and ecological issues may arise.
- The second type, "closed-cycle water cooling system", is a recirculating, evaporative cooling system where water is circulated between a cooling tower and a condenser, but the warm water is evaporated into the atmosphere. Thus, in this case, much less water is withdrawn (~3%) for the same capacity of cooling, but the water consumption is overall higher due to evaporation and maintenance water replacement. Many investments have been planned to increase the share of thermal power plants with closed-cycle wet cooling. However, the share of thermoelectric plants with closed-cycle wet cooling systems is still small (in the U.S. it is about 42%, while another 43% of thermal power plants use once-through cooling).
- Other newly proposed cooling systems are dry cooling, which utilizes air for cooling instead of water and requires an air-cooled condenser where the steam passes through a bundle of tubes and ambient air absorbs the heat. Dry cooling systems withdraw and consume minimal water, but they have a high capital cost and have less overall power plant efficiency compared to closed-loop cooling systems [21,38,75].

A review on concentrating solar power (CSP) and storage was performed by Duvenhage et al. [38]. CSP with storage can overcome the supply intermittency experienced by many renewable sources. The most widespread CCSs are parabolic trough or central receiver technologies. At CSP plants, 90% of water is used for cooling, while the rest is predominantly used for cleaning the solar field and steam cycle make-up.

Since CSP efficiency is high in areas with high solar radiation, these power sources are installed in arid areas, which have a large water deficit, which will increase demand on water resources and limit CSP performance and security [97]. A comparison of water consumption factors for various CSP and cooling technologies compared to that of coal is given in Table 8 [38].

Table 8. Water consumption factors for CSP with various cooling technologies [38].

Cooling Type	Water Consumption Factors [m^3/MWh]		
	CSP Through	CSP Tower	Coal
Wet cooling	3.43	2.98	2.6
Dry cooling	0.3	0.1	0.13

The water use of a CSP plant is expected to be reduced by between 25% and 50%, through the recovery and recycling of water [98].

A complex study on water-for-energy was performed in [8], where the indicators regarding the performance of water usage levels by European energy systems are estimated. At the level of each EU country, the 14 types of power plants—coal-fired, gas-fired, oil-fired, nuclear, bio-power, concentrated solar power (CSP), solar photovoltaic (PV), wind, geothermal, hydro and ocean (tidal and wave)—and the related cooling systems are considered. Knowing the water intensity from the literature and the annual consumption of electricity, the water consumption was calculated, corresponding to each power plant in each country and then for all 28 countries in the EU. The analysis was performed for the period from 1980 to 2015 and the ensemble median/min/max as a predictor of water use is evaluated. The results, validated by EUROSTAT 2018, suggest that an "ensemble-based approach" is viable for robust estimates of yearly water use by energy systems for analyses at both the country and regional levels. Freshwater consumption for cooling systems of the power plants at the level of the EU was about 400 Mm^3 in the year 1980 and increased to about 800 Mm^3 in the year 2015.

From these analyses, several key points can be noted:

- The estimated water consumption related to specific energy production exhibits great local variations across natural, geographical, technological and hydro-climatic conditions and differences in definitions.
- The median estimate, based on the middle value in between the reported minimum and maximum spans, provides a skillful reproduction of historical yearly water use for the EU (EU28) as a whole. However, this may introduce a certain bias toward underestimation, as argued by [8,94].
- There is a significant source of uncertainty in the water consumption estimates as for many power generation technologies, much data remains unavailable. This is a key motivation for carrying out new studies to estimate the use of water in electricity production and the correct analysis of the water–energy link in qualitative and quantitative terms, as also highlighted by [8,75,81].
- The data should be open source, with wide (global) coverage and high temporal resolution to contain detailed information and be brought together in a single database for easy data processing. Examples of freely available water resource data relevant for global and regional scale water-for-energy studies are the Global Runoff Data Centre (GRDC), FRIEND (another river flow database operated by UNESCO), the European Water Archive (EWA) and EUROSTAT [8].

4.1.3. Opportunities and Water-for-Energy Solutions

The actual challenges for research are related to establishing the ways in which developing technologies could have a positive impact on the future of water-for-energy. To find the ways of innovation, the scientific context and modalities in which water is currently used in power generation have been analyzed.

The priority areas of new technologies that can be implemented on a large scale to reduce water consumption are as follows:

- Improving the heat capacity of water by adding new additives, named phase-change materials (PCMs), which are compounds with large latent heats to improve the properties of the cooling fluid for potentially reducing evaporation loss and saving water;
- Development of advanced fluids that can supplant the use of water as a coolant agent, having appropriate thermal properties and viscosities;
- Improving water recovery and water usage reduction in power plants by the implementation of water-free condensers. However, these depend on air convection, which limits the cooling efficiency and power output in the summer;
- Improving dry cooling technology, through which it is estimated that up to 25% of evaporated water can be saved.

Regarding reduction of water in fracturing technologies, waterless fracturing has been a known technology but scientific challenges led to limited scale implementation. Instead of water, another solution includes liquid propane or CO_2. CO_2 is especially promising since it is also a combustion byproduct and can be used from carbon capture and storage (CCS) sources [21].

In terms of CSP power plants, the identified solutions for CSP plants to reduce water consumption are to incorporate water resource management into the strategy, planning and deployment of CSP, to increase CSP performance by modeling the operation with respect to the seasonal and temporal water availability (also by restricting operation of the CSP) [97,98].

Furthermore, some studies are in view of water–for-energy in the energy transition period. In [74], the water requirements in the year 2040, in comparison with the year 2014, are analyzed regarding coal, oil, natural gas and uranium extraction, oil refining and thermal power generation (including new designs of nuclear plants). In addition, nuclear electricity generation is expected to have a significant impact on water resources. Significant stress factors already affect the water system due to the uneven distribution and inefficient or heavy use of water resources. Policy regulations have to be implemented for better management of water resources for sustainable development.

4.2. WEN Focused on Energy-for-Water

4.2.1. Water Sector Contribution to Energy Consumption and GHG Emissions

Water supply systems, included in the water sector, require a large amount of energy (currently 2–3% of the global energy consumption) that causes GHG emissions [39,99]. For example, in the U.K., this percentage is around 3% (responsible for 1% of annual GHG emissions), while in the U.S., the water supply system constitutes 13% of total energy usage (which constitutes 5% of all national GHG emissions annually) [100]. Compared to other sectors, the contribution of the water sector to energy consumption and associated GHG emissions is relatively low. However, the current trend of increasing water demand cannot be neglected because it would lead to a rapid increase in energy demand.

With the estimated global population size of 9.7 billion in 2050, and considering that 25% will live in regions exposed to extreme water shortages, large-scale implementation of drought-resistant technologies is therefore foreseeable. This means high energy consumption, with great impact on the environment [100]. In order to reduce energy consumption in water supply systems, new solutions will have to be found to increase the energy efficiency of water production and use and to reduce water consumption and water losses, which implicitly leads to a decrease in energy consumption [21].

It is therefore imperative to understand the nexus between water and energy, their availability and demand from the perspective of energy-for-water [58,99].

To establish the main opportunities regarding the energy-for-water issues, the WEN analysis is required in view that WEN describes the interdependence between energy and water at different levels of time and space boundaries [101–103]. By considering the water–energy nexus in the planning, design and operation of water supply systems, it will open the way for water system sustainability, saving energy and minimizing the related GHG emissions [100].

4.2.2. Energy Requirements for Water Production

Energy is required in all stages of the water production chain. In this regard, Mabhaudhi et al. [37] considered all stages of the water production chain, including both the construction and operation and maintenance of water supply facilities, in the processes of water abstraction, treatment (pretreatment, desalination and other), distribution, end user consumption and treatment of wastewater (Figure 4).

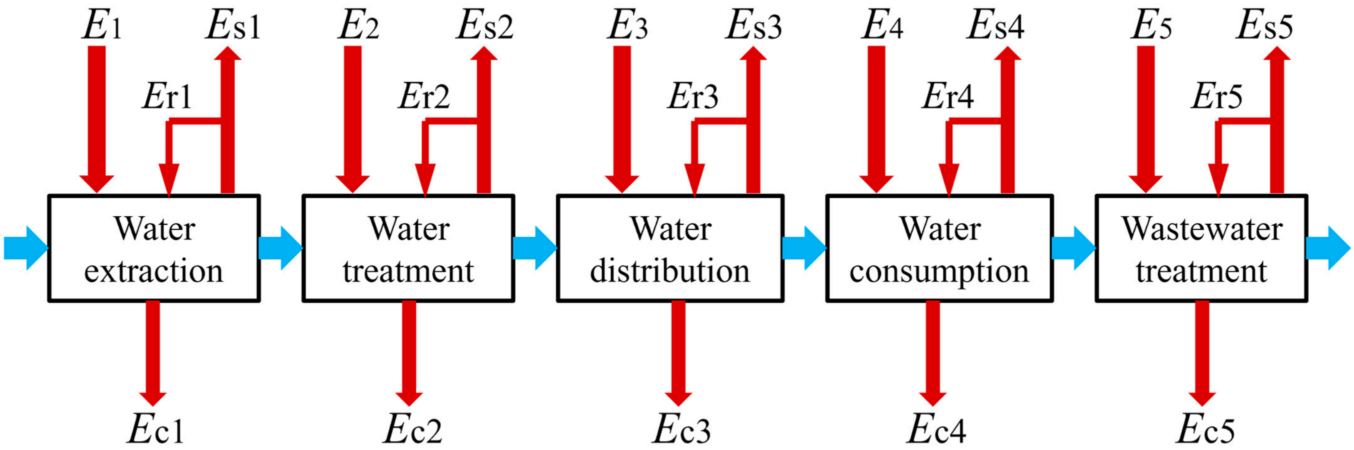

Figure 4. Energy requirement at different stages in the water supply system.

For each stage, there is specific energy flow, described by specific quantities: E_i—input energy, E_{ci}—consumed energy, E_{ri} is recovered energy used in water processing and E_{si} is stored energy and/or recovered energy introduced in the power system. For each stage, energy intensity EI_i can be defined:

$$EI_i = \frac{E_i}{W_i} \quad (3)$$

where E_i is input energy and W_i is the quantity of water output, corresponding to stage i.

The total energy consumed in the water production chain will be given by the sum of all corresponding stage energies. The total energy intensity EI_t of the produced water, available at the inlet to the end–user, defined as the total energy consumed E reported on total water W production on a lifecycle or a predefined time:

$$EI_t = \frac{\sum_i^n E_i}{W_{end-user}} \quad (4)$$

It is obvious that the energy efficiency of the water production process is reliant on the efficiency of each of the processes corresponding to the water production chain. Losses of energy and water should be reduced, and the ensemble of the water system should be optimized.

Using a hybrid Sankey diagram, Urban et al. [21] highlighted water flow and energy requirements for the United States (Table 9).

Table 9. Energy intensity for different stages in water production—U.S. case studies, after [21].

Process	Energy Intensity [kWh/m^3]
Brackish water desalinization	0.2–1.5
Sea water desalinization	2.5–4.0
Water transport and distribution	0.1–2.5
Water pre-treatment	0.2–1.5
Water post-treatment	0.2–2.5

The data in Table 9 indicate the high energy consumption required to obtain water, desalination technologies being the largest energy consumer, especially for sea water desalination.

A stage in the water production chain with a high degree of energy consumption is also wastewater treatment. The lower values for the energy intensity in this stage are given in [37], for the Middle East and North Africa region, with values of 0.1–0.3 kWh/m^3 and 0.272–0.59 kWh/m^3 for primary and secondary wastewater treatment (activated sludge).

Nair et al. [99] reviewed energy intensity values for various stages of water supply in different parts of the world. In Table 10, the maximum and minimum values of the energy intensities corresponding to the different stages of water supply, in different world regions, are shown. It can be noted that the large difference between the *EI* values mentioned in the literature is due to the influence of factors such as differences in topography, the distance to which the water must be supplied, the treatment levels and technologies adopted and the character of the end user.

Table 10. Maximum and minimum values of the energy intensities corresponding to the different stages of water supply, in different regions of the world; review adapted after [99].

Water Production Stage	Details	Energy Intensity [kWh/m^3]	Region
Ground water extraction	Groundwater pumping	0.14–0.79	U.S.
Surface water extraction	Water supply pumping	0.92	Australia
Water desalinization	Sea water desalination	3.0–4.0	Australia
Water treatment	Raw water treatment	0.1–4.32	Australia, U.S.
Water distribution	Water conveyance	0.04–2.4	U.S.
Wastewater treatment	Advanced wastewater treatment	0.38–1.5	Australia, U.S.
Recycled water	Recycling water	0.3–3.6	U.S.
Water end use	Residential heating	24.6–208.38	Canada, U.S.

Mabhaudhi et al. [37] showed that the desalination and groundwater pumping technologies are energy intensive. In the case of groundwater pumping, the values of energy intensities are influenced by the depth at which the groundwater aquifer is located. Thus, *EI* = 1.558 kWh/m^3 at a depth of 400–1200 m, and *EI* = 0.389 kWh/m^3 at a depth of 100–180 m.

The data in Table 10 also shows the importance of the water end user in increasing the energy efficiency and reduction in the energy intensity of water. Here, the case of the energy used for water heating in households is taken in account. Most of the time, in studies regarding the assessment of energy processes in water supply systems, the end use stage of water is not considered.

Today, efforts are directed toward the transition from electricity generated from fossil fuels to renewable energy sources for the operation of water supply systems, usually operating in stand-alone or off-grid configurations. These systems are typically designed to supply water for domestic use and irrigation. In regions with abundant solar energy, where water scarcity is high, the main focus has been on improving desalination plants powered by solar energy. In these system configurations, solar energy meets water-related energy demand in combination with other renewable energy sources [100].

4.2.3. Methods to Increase Water Production and to Reduce Energy Consumption

Vakilifard et al. [100] review the literature focused on the optimization techniques for techno-economic feasibility evaluation and for optimization of urban water supply systems, supplied with hybrid energy systems. Currently, cities hold more than 50% of the global population, which is predicted to increase to 67% by 2050. This situation is a challenge for cities to better manage resource consumption whilst also reducing GHG emissions, especially for water and energy.

There are two main technologies to increase water production: desalination and water recovery. However, each of these technologies requires large amounts of energy, with specific impacts, which requires detailed analysis.

A. Desalination methods

Desalination technologies are based on removing the salt content from sea water or brackish water [16,104–106].

Due to freshwater shortages and high population growth, desalinated water is used mostly in the Middle East and North Africa (MENA) regions—this amounts to 46.7% of the global desalination capacity [16]. Australia is also reliant on desalination for urban freshwater supplies with varying water supply amounts in main cities: Sydney (15%), Melbourne (30%) and in Adelaide, Brisbane and Perth (up to 50%) [104].

Today, desalination is becoming an increasing part of the water supply mix in the urban and industrial sectors. The global desalination capacity increased significantly from 8.09 million m^3/day in 1980 to 90.07 million m^3/day in 2014 [37].

Current desalination technologies are based on either thermal (multi-effect distillation or multi-stage flash) or mechanical/pressure-based (reverse osmosis) means, all of which being high energy consumers [16]:

- The mechanical-driven methods include mechanical vapor compression (MVC), microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO).
- The thermal-driven methods include multi-effect distillation (MED), multi-stage flash (MSF) and forward osmosis (FO).
- The combination of MF, UF and NF methods is often used as a pretreatment in the RO desalination method and also for water and wastewater treatment.

Current implementation of these desalination methods is limited by their energy consumption. Among these technologies, only RO and NF are used in desalination processes on an industrial scale. However, these methods are only effective for a salinity limit of NaCl up to 35%. For high-concentration saline water (especially in the case of brine), new desalination methods are developed, as electrodialysis (ED) and capacitive deionization (CDI). The operational energy requirement and associated pollution are the main issues in decisions on implementing the desalination technologies. This is a major factor impacting the extent and feasibility of desalination [104].

For evaluating the performance of a desalinization process, a reference indicator can be the minimum energy required to separate salt from pure water starting from thermodynamic considerations. This theoretical limit for the minimum amount of energy required to separate pure water from dissolved ions has the value of 1.06 kWh/m^3 for sea water containing 3.5 wt% (35,000 ppm) of NaCl; for the extraction of pure water from brine, whose salinity increases toward the maximum of 7 wt%, the theoretic specific energy is much higher [21,104].

In [105,107], for the energetic, economic and environmental assessment of brackish water and seawater desalination systems, the minimum energy requirements are taken in account. A comparative analysis of some specific energy consumption values for various desalination processes are presented in Table 11.

Table 11. Specific energy consumption for various desalination processes [108].

Desalination Technology	Energy Intensity [kWh/m^3]
Reverse osmosis (RO)	2.6–7.0
Multi-stage flash distillation (MSF)	3.0–5.0
Multi-effect distillation (MED)	1.5–2.5

The data in Table 11 indicate that the MED technology exhibits the lowest demand for energy per unit volume of freshwater produced. An optimum value of 3.7 kWh/m^3 for RO technology, applied at industrial scale, was mentioned [16].

A comparison between the specific energy of the desalination process by reverse osmosis (RO) and the capacity to purify by deionization (CDI) is given in Table 12 [21], while a global situation of the capacities of seawater desalinization technologies installed in 2014 is presented in Table 13 [104].

Table 12. Specific energy consumption required for RO and CDI desalination technologies as a function of water salinity, after [21].

Salinity [ppm NaCl]	Specific Energy Consumption [kWh/m^3]	
	Capacitive Deionization (CDI)	Reverse Osmosis (RO)
10^2	0.012	0.155
10^3	0.115	1.00
10^4	1.100	1.05

Table 13. Total worldwide installed desalination capacity by technology in 2014: after the data of the International Desalination Association, IDA desalination yearbook 2014–2015, Oxford, U.K.; Media Analytics Ltd., 2015 [104].

Desalinization Technology	Symbol	Global Installed Capacity [%]
Reverse osmosis	RO	65%
Multi-stage Flash Distillation	MSF	21%
Multi-effect Distillation	MED	7%
Electrodialysis	ED	3%
Nanofiltration	NF	2%
Other		2%

Data from Table 13 indicate that the most reliable membrane process for seawater desalination is RO, and it also has the largest share of global desalination. Still, the cost and performance of RO systems are affected by the membrane fouling process [104]. MSF, MED and RO are regularly used for seawater desalination, while ED and NF are usually applied for brackish water desalination.

Desalination costs have been reduced by a hybrid setup within thermal power plants, improving membrane properties, using high-efficiency pumps or by using energy recovery devices. However, the desalinating of one cubic meter of water still needs electricity at the range of 2–4 kWh [37].

Given that most desalination plants are powered by energy mix sources with a high share of electricity generated from fossil fuels (IRENA, 2015) [109], the operation of desalination causes a considerable amount of GHG emissions under current technical conditions [79].

Environmental impacts associated with inputs and outputs of conventional seawater desalination processes were pointed out by Li et al. [104]. There are different impacts associated with conventional seawater desalination processes: direct environmental impact on local marine ecosystems due to seawater intake and indirect environmental impact associated with chemical production and transportation, fossil fuel production and transportation, saline, chemical and thermal pollution of the ocean, greenhouse gas emission and air pollution.

B. Water Recovery

Wastewater recovery is a major alternative to produce water for various end uses. Usually, wastewater treatment has the role of removing biological and chemical pollutants from the water before it is released as clean water into the environment. However, in a circular economy, reclaimed water is seen as a crucial secondary source of water, solving both water pollution and water scarcity problems. Globally, only 7000 million m^3 of reclaimed water was utilized in 2011, comprising only 0.59% of total water use (EU, 2016) [35]. For water recovery from wastewater, the water quality criteria are important, as well as the energy consumption required for the reclamation. Energy use for this operation is expected to increase with stricter disposal and resource management policies.

Regarding environmental pollution in the wastewater treatment process, it should be noted that CO_2 is not the only polluting gas emitted. Other GHG emissions such as methane (CH_4) and nitrous oxide (N_2O) are generated from biological or chemical processes involved in the pollutant removal stage. In the case of wastewater treatment plants, energy use, the treatment process and chemical use are the major sources of GHG emissions.

Jin et al. [44] pointed out the works which reported the water footprint and impact-oriented water footprint of wastewater infrastructure. It was estimated that biogas energy production generated in the process lowered the energy and GHG footprint of wastewater infrastructure by 0.10 kWh/m^3 and 0.08 kgCO_2-eq/m^3, respectively.

A case study was performed in [110], where wastewater treatment plants (WWTPs) were chosen for the specific analysis, being considered one of the biggest GHG emitters in the water industry. In this research concerning the Canary Islands (Spain), different protocols and tools are used to analyze direct and indirect GHGs emissions. The results indicate that energy consumption generates the highest emissions, ranging from 165 to 2716 Tmeq CO_2/year for the smallest and largest size WWTPs, respectively. The proposed solutions are the introduction of renewable energies and the use of sludge as an internal energy resource (in anaerobic digestion), contributing to the circular technology and reducing emissions.

Fan et al. [35] show that the GHG footprint of wastewater infrastructure is 1.426 kg CO_2-eq/m^3 with biologically generated GHG emissions taken into account (i.e., CO_2, N_2O and CH_4). Other studies [111,112] also show that reclaimed energy can nearly meet the whole energy requirement of the water supply sector, with potential to even generate surplus energy from wastewater. These studies proved that an effective control of emissions in wastewater plants requires the development and implementation of integrated plans, which take into account the different resources and the specifics of GHG emissions.

Regarding the performance of wastewater treatment, the same dilemma as in the case of desalination technologies exists: to ensure an adequate protection of the environment that involves greater investments or to work in conditions of a lower dependence on the eco-environment, but this will make additional contributions to climate change. This dilemma can be managed through several approaches [79]. Firstly, energy efficiency optimizations should be performed for improving the energy use of wastewater treatment or utilizing energy from renewable energy sources for these processes. Secondly, optimization by stimulating the introduction of renewable energy sources in wastewater treatment plants through various economic incentives.

Finally, the mainly researched approaches to reduce the urban metabolic rate are resource utilization efficiency improvement, renewed resource adoption and water and energy reclamation. Despite the numerous scientific and technological challenges, there is also a massive financial burden for the implementation of these technologies.

4.3. Energy Transition—Strategies and Innovation

Global climate policy dialogues are increasingly discussing the sustainable energy transition, Goal 7 of the UN Sustainable Development Goals emphasizing the importance of clean and affordable energy. Many papers address this issue [8,39,113,114].

The current challenges are those related to expanding the infrastructure for renewable energy, finding new environmentally friendly energy carriers, creating reliable energy storage systems and a competitive international market [73,115–117].

In this section, an analysis on the characteristics and pathways to realize energy transition through renewables, taking into account the WEN.

4.3.1. Characteristics and Pathways

Energy transition refers to the process of moving from fossil fuel to non-fossil-fuel-based energy sources to create a sustainable energy system with zero or near-zero carbon emissions [8,20,31,40–44]. The energy transition includes all the technologies that ensure the passing from conventional fuels to non-conventional fuels and the acceleration of the electrification of production and service technologies.

The current energy transition is the main step in achieving climate neutrality, defined as that state towards which humanity will have to move to in the near future, where human activities no longer have a net effect on the climate system as a whole. Such transition involves the transformation of the entire economy into an electrified, ecological and energy-efficient economy, in which competitive prices for the energy consumed are ensured for all users. This desideratum is included in the energy trilemma and concretized in the United Nations Sustainable Development Goals (SDGs). The main approach in energy transition is to provide most of the electricity demand from renewable sources, which will gradually replace the power generation sources based on fossil fuels.

There are two main ways of energy transition to achieve the goal of 100% clean energy [50]:

- One way is the improvement of the existing processes and developing new energy conversion processes to produce near-zero carbon electricity. By lowering the price of electronic components involved in renewable technologies, conditions were created for the large-scale implementation of renewables in all regions of the globe.
- Another way is the general electrification of all areas of economy. Practically, this means the transition to sustainable technological processes, which will use almost entirely the electricity generated from non-fossil energy sources.

Worldwide, solar photovoltaics (PVs) and onshore wind turbines are the most widely implemented RESs. The costs of these technologies have decreased significantly, taking into account that specific costs of PVs and onshore wind having decreased by 70% and 50% since 2010 [38,109].

Existing hydropower and nuclear plants can also play an important role. As hydro capacities are already well developed, and other sources, such as biomass, are difficult to implement, an increasing share of RESs is expected to come from wind and solar.

The state of RESs in Europe is analyzed in [118]. The scenarios and the European Action Plan provide that the share of renewable energy for Europe will reach over 50% by 2030, increasing for wind and solar energy. The perspective of the energy mix structure for Europe is shown in Figure 5.

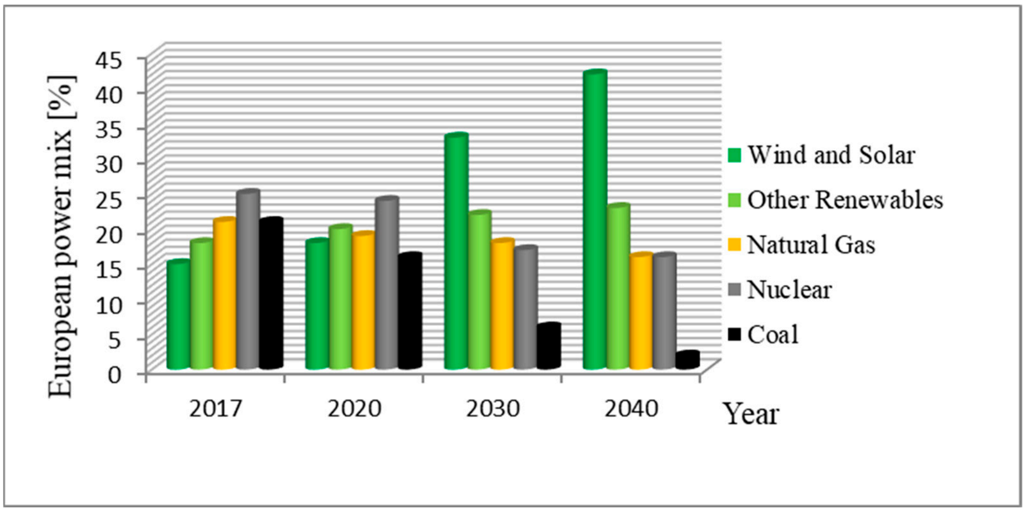

Figure 5. Dynamics of energy mix structure of European energy transition (2017–2050), based on [118].

The energy mix structure for Europe continuously changed (Figure 5), with a significant increase in the share of wind and solar power and a decrease below 5% of coal share, for the year 2040.

4.3.2. Flexibility Pathways in Energy Transition

Nowadays, many and various pathways have been proposed to reach a high implementation of RESs, with different methods to ensure the availability, accessibility, security and resilience of the electric energy supply systems. These pathways depend on the stage of implementation of the processes of direct electrification, where fuel combustion is replaced with renewable electricity generation [50]. The introduction of renewable energy sources has a major drawback, consisting of their intermittent operation and high dependence on environmental conditions.

For describing the prolonged periods of low wind and solar output, the term "renewable droughts" was introduced as a key reliability planning challenge in the designing of renewables. Different compensation methods to reduce renewable droughts are proposed through the introduction of additional sources (dispatchable sources) to realize adequacy and thus to ensure the ability of an electric power system to produce sufficient electricity to meet load needs at all hours through a broad range of weather and operating conditions. Currently, such adjustment sources are mostly coal-fired and natural-gas-fired power plants.

Until recently, studies of how to achieve 100% RES power systems addressed the mix power generation planning. However, presently there are many factors that complicate energy mixing, such as: climate change, uncertainty of water and energy systems, cybersecurity, intensification of economy-wide interactions and the focus beyond least-cost reliable planning (e.g., energy justice) [27].

The flexibility of the energy supply system is ensured by the coordination of the interactions between the systems and by the inclusion of different storage systems, having in view that more than 20% penetration from intermittent renewables can greatly destabilize the grid system, so the introduction of electrical energy storage helps to improve grid reliability, facilitate full integration of intermittent renewable sources and effectively manage power generation.

Thus, as the proportion of PV and wind energy in the energy supply mix increases, there is an increasing need for electricity storage and dispatch systems to meet peak energy demands and maintain network stability [23,38].

In Figure 4, a proposed block diagram of the energy flow during energy transition to interconnect among resources, energy systems and end users is shown.

The energy flow diagram in Figure 6 reflects the complex interdependence between energy resources, power system and end user, in which, to make the power system operation more flexible, reliable and stable, the introduction of energy storage systems is proposed.

Along with the increase in RES capacity, the need to introduce efficient energy storage systems also increased. However, only about 170 GW of installed storage capacity around the world was available in 2018, of which more than 96% was provided by pumped hydro, which is site-constrained and not available widely [119].

Much research has proposed solutions for a broad portfolio of storage technologies, as mechanical, thermal, electrochemical and chemical storage, to fully address the widely varying needs for large-scale electrical storage. However, these technologies are on different levels of maturity [120,121].

Each electrical storage technology has certain advantages and disadvantages that may be best suited for a particular application. For example, flywheels and supercapacitors can provide high power with fast response times but have low energy densities, whereas batteries offer high energy densities but slower response times [119].

Key ways of ensuring flexibility and electrification of the economic sectors are as follows [122]:

- Utilizing new non-fossil energy sources. Hydrogen and its derivatives have high potential for obtaining, storing and utilization in several sectors;
- Electrifying the heating system by incorporating heat pumps and energy storage;
- Using electric vehicle (EV) charging as storage systems for a flexible energy storage source;
- The process of industrial electrification should be accelerated and technological innovations introduced to achieve ambitious goals such as 100% clean energy;
- The directions to implement the transition to clean energy require increased technological innovation and system modifications, while also taking into account the vulnerabilities created by extreme temperatures, drought, sea-level rise and wildfires.

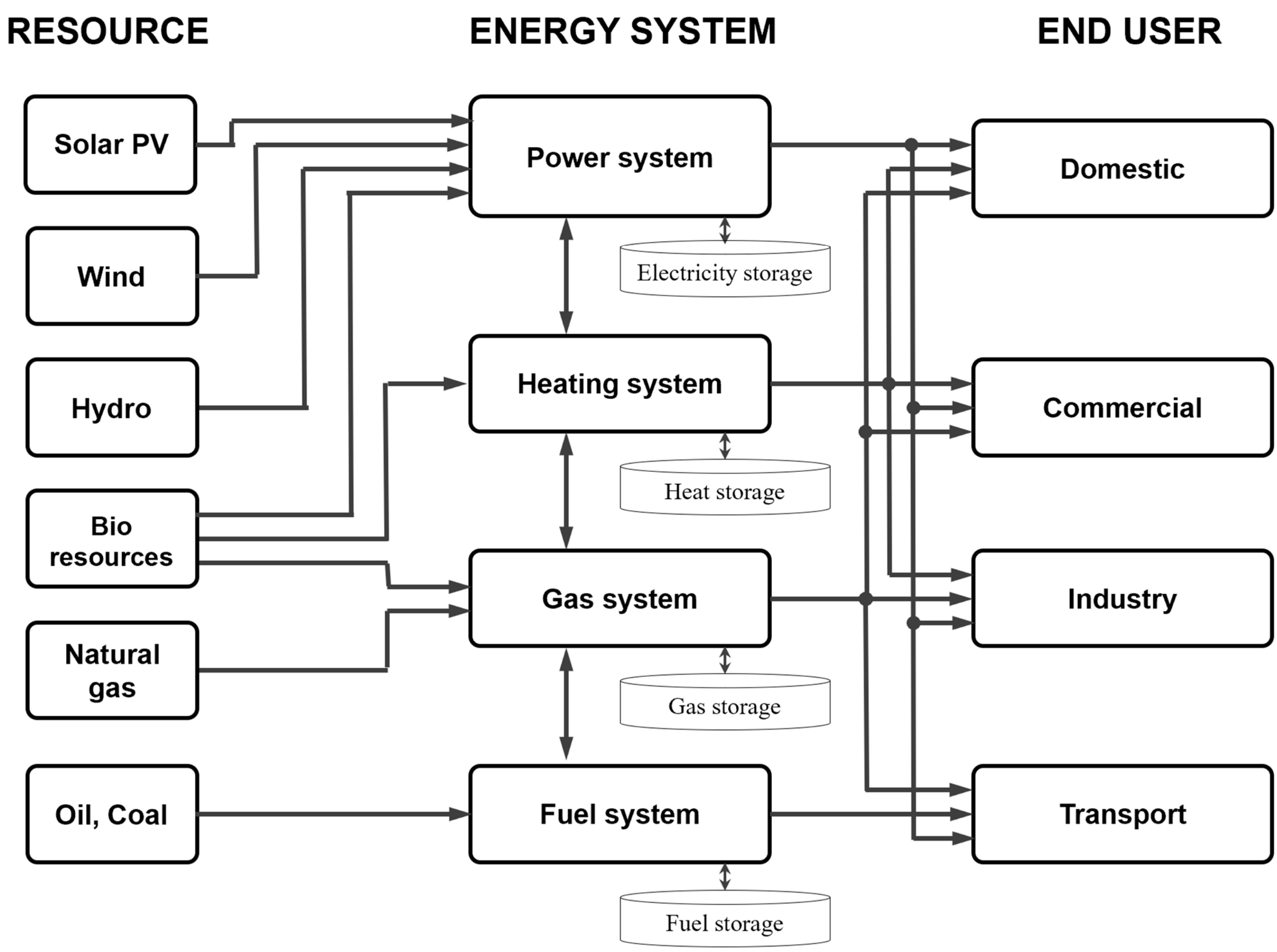

Figure 6. General block diagram of energy during energy transition to interconnect resources, energy system and end users (adapted after [23]).

4.4. Approaches of WEN Integration into Energy Transition

4.4.1. Innovations and Policies

The current period of energy transition towards net zero carbon is accompanied by significant changes in technological innovations, energy markets, regulatory structures and social pressures. The challenge is to find specific ways, methods and means for the optimal application of the WEN as a tool to accelerate the energy transition.

The results of the analysis developed in this review study illustrate the prominent trends that have occurred over the past two decades in connection with energy transition.

a. Trends in thermal power plants [69,86–89,95]:

- In electricity generation: passing from coal-fired steam to natural gas combined cycle units;
- In cooling systems: passing from once-through cooling to wet recirculating towers and dry cooling systems;
- In quality of water for cooling systems: passing from traditional fresh and saline surface cooling water to reclaimed water and groundwater sources;
- In withdrawal water technology: transition towards more water withdrawal efficient technologies.

b. Trends in energy mix structure [1,5,73]:

- Increases in the share of RESs and decreases in conventional fuels.

c. Trend in advanced energy technologies [69,89–91]:

- Introduction of renewable technologies, in particular PVs and wind, which will reduce water consumption for energy generation;
- Introduction of advanced carbon capture technologies, drilling and hydraulic fracturing, which have the least possible impact on the environment and water availability.

The study also reveals that, by applying the WEN concept and specific metrics, some pathways and innovations have been developed and applied in and between the water and energy sectors:

- Innovations for clean water generation [123–125];
- Innovations for integration of a wastewater treatment plant with a combined heat and power generation system [126–128];
- Introduction of new systems for energy and water storage [111,129–134];
- Innovation in green economy, in which the specific extensions of the water–energy nexus to other forms of nexus, i.e., food, land, pollution, etc., are applied [45,46,52,54], and new metrics are developed [123–125];
- Implementing Internet of Things (IoT) technologies and digitalization to sustain achieving SDG6 and SDG7, as a substantial step toward a Smart Green Planet [36,135].

However, there are still many unresolved points at the research level. The lack of a deep understanding of the connections between the water and energy sectors, as well as the lack of appropriate inter-sector coordination, reflects that water and energy resources are not yet used sustainably and SDG targets cannot be properly met [43,44,74,100,135].

Concerning the topic of energy transition, many critical points arise in the research community for identifying and developing:

- Most appropriate water and energy production technologies that support the objectives of sustainable development;
- Best methods for implementing decarbonization policies;
- Factors and innovation approaches that can accelerate the energy transition;

This analysis identifies critical points to be addressed in the water–energy nexus, some of which have been highlighted by the scientific community, international bodies and non-governmental associations:

- Utilizing the WEN concept to support sustainable energy transition;
- Water and energy conservation measures driven by the WEN concept;
- Development of water and energy studies through an integrated and interdisciplinary approach;
- Identifying barriers to decision-making related to water and energy issues during the energy transition period and solutions to overcome them.

The role of investors in energy transition and the achievement of SDGs is recognized, given their critical role in the market economy and innovation strategies. Thus, it is essential for research and regulatory bodies to develop appropriate methodologies and metrics systems in relation to the WEN, energy transition and to support investors towards the SDGs [136,137].

- Two representative papers also underlined the necessity to find ways of policy innovation in sustainable development goals on energy (SDG7) and water (SDG6).
- Urban et al. [21] highlighted that topics related to energy production and supply are dominant, and less attention is paid to demand management, energy efficiency and the effects of energy use. Moreover, the appropriate policy solutions for the energy transition are limited.
- Lohrmann et al. [87], applying a bottom-up approach, assessed the water footprint of the cooling systems of thermal power plants worldwide and obtained an estimation of water demand for power production at four different levels (global, regional, country and river). The projection for the energy transition period toward a net zero greenhouse gas emission economy by 2050 is obtained. However, the results are influences

by the limited availability of data on the cooling technologies and the water source (seawater or freshwater) used for cooling technologies.

- These documents underlined new and efficient pathways that should be followed for the integration of the WEN tool in the energy transition.

4.4.2. Transdisciplinary Approach

A transdisciplinary approach is allowing a better understanding and management of the interconnected water, energy and food systems for enduring local and global stability regarding the balance of nature and the quality of life.

Using the interdisciplinary qualitative and quantitative methods, Delafield et al. [138] proposed a conceptual framework for balancing society and nature in net zero energy transition. By taking into account the food–water–energy nexus (FWEN) concept, while establishing specific energy scenarios, is more likely to lead to a publicly acceptable and sustainable energy transition.

A research enterprise framework based on a transdisciplinary network is proposed in [49] to address the FWEN, through a transdisciplinary integration of research activities into a centralized business model that involves stakeholders, policymakers and non-research organizations. The proposed model shows the complex system network, with critical environmental influences on the individual components of the FWE system, feedbacks that affect the environment and consequences for social behavior, policy and technology (Figure 7).

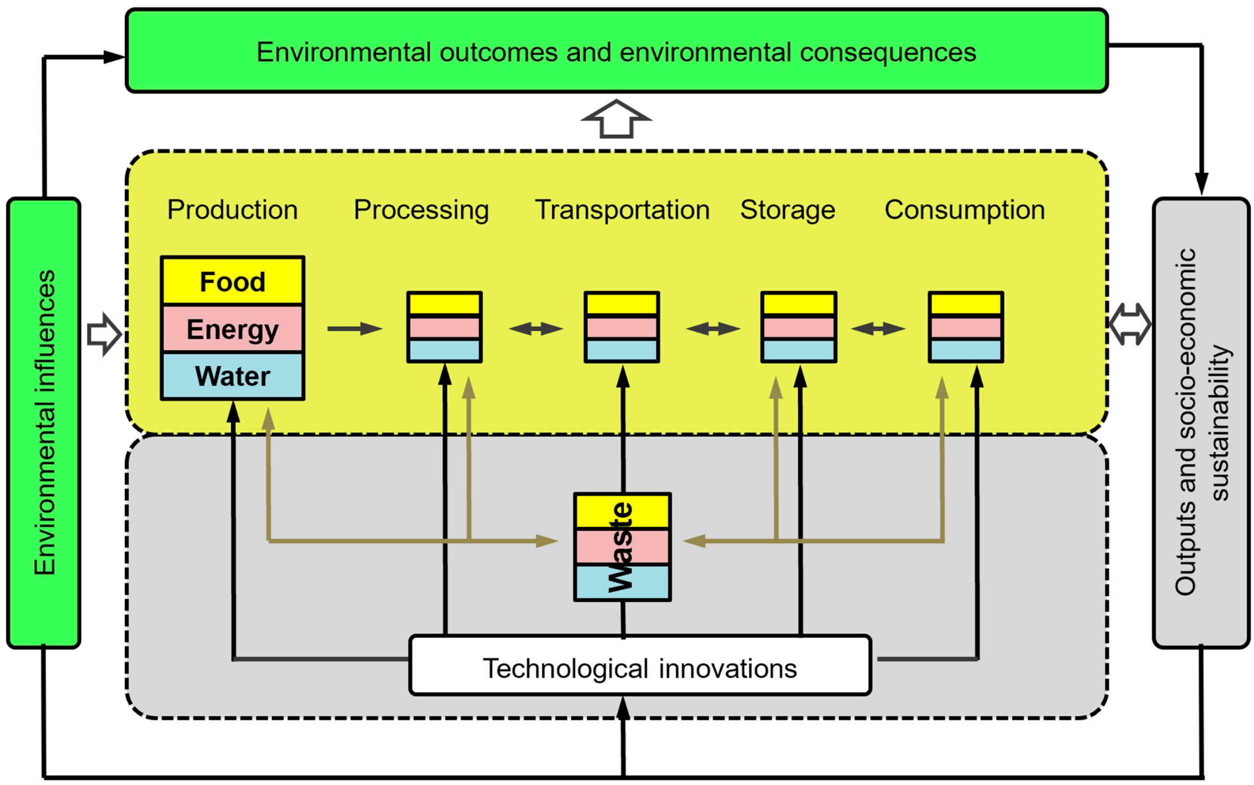

Figure 7. A research enterprise framework for prioritizing FEW interactions with environmental (green), economic (yellow) and societal (grey) systems (adapted after [49]).

The framework depicted in Figure 7 shows that a global research enterprise effort is required to obtain socio-economic sustainability through the development of systematic modeling and computation technologies, based on diverse inputs from experimentalists, technologists and behavioral scientists.

The development of new technologies (artificial intelligence, digitization, IoT, nanotechnologies) can greatly optimize the processes of wastewater treatment, water desalination and renewable energy generation, enabling food production in adverse environments. It is the role of transdisciplinary approach to unravel the unknown interactions within and without systems, based on known fundamental scientific principles that govern the unfolding and coupling of various physical, chemical, biological, economic and social processes [48,49,92,139–142].

The transdisciplinary approach is the incorporation of a wide range of scientific, social and political disciplines, including various actors, to address broad and complex issues, such as the WEN and energy transition. It focuses on extending scientific principles and technologies (concrete, abstract) to the less tangible philosophical and ethical norms of society. There may be different levels of collaboration in solving complex problems. One level of collaboration, which extends beyond disparate boundaries, is multidisciplinary collaboration between fields of knowledge, including, for example, the social sciences and the humanities. The multidisciplinary approach then extends further to become a transdisciplinary approach, incorporating higher levels of collaboration, building and disseminating knowledge.

The transdisciplinary perspective extends to areas beyond traditional disciplines and sub-disciplines to include contributions from practice and the influence of broader social systems. Thus, the integrative multi-level transdisciplinary schemes are required to integrate WEN and extended WEN tools in energy transitions to achieve the SDGs.

4.4.3. Citizen Involvement in Energy Transition

To understand how society can undertake energy transition taking into account WEN and more extended WEN concepts, the integrated energy models have to be developed to explore future energy scenarios. However, the actual models often focus only on the technical, technological and managerial solutions of the transition and overlook the long-term implications on both society and the natural environment [37,40,143,144]. Thus, without a holistic approach, it is virtually impossible to assess the trade-offs as well as the co-benefits of sustainable development goals.

Fan et al. [35] analyzed the WFE nexus tool and pointed out that the evaluation of energy transition normally depends on the perspective of policy-makers, and the degree of citizen involvement in the energy transition. In addition, in [145] it is underlined that many national, regional and world organizations advocate the participation of citizens and communities in the energy transition, to encourage a bottom-up approach in the implementation of sustainable energy initiatives. However, it seems that the energy of the community is not yet engaged.

Thus, the governance framework should be improved to include citizens as active participants in the energy transition [146].

5. Conclusions

The Sustainable Development Goals for water (SDG6) and energy (SDG7) serve as the basis for the energy transition strategy, which must take into account climate change and socio-economic variability factors.

Starting from the dynamic and complex relationship between water and energy under the conditions of the energy transition, this review paper analyzed the multidimensional interconnections regarding the water–energy nexus, from the water-for-energy and energy-for-water perspectives, during energy transition, to accelerate progress for achieving the sustainable development goals.

The following conclusions are reached:

- Relating to results of bibliometric analysis, the increased number of papers with topics "energy for water", "water for energy" and "energy transition" reflects the growing interest in this field of research. However, the number of studies that address interdisciplinary issues related to water, energy and sustainability is still low, even if it is a popular topic that outlines future research directions.

- Water-for-energy is a popular research topic, given that water is essential for all types of power plants; climate change and economic challenges induce many water constraints, with significant impacts on the energy sector and driving up energy costs. Moreover, during the energy transition period, the dynamics of the energy mix determine changes in the structure of demand and water consumption necessary for the operation of the energy supply system.
- In relation to this issue, several key points for research have been identified: finding solutions to ensure the availability of water resources to support the transition to a green economy without compromising other industries and services; improving the efficiency of water consumption for the energy sector; and developing new tools for measuring water withdrawal and consumption as bases for selecting the most appropriate methods and technologies of reducing water consumption for energy generation.
- The priorities for research related to the development and implementation of new technologies to reduce water consumption for power plants, with a positive impact on the environment, are new additives for improved water heating capacity and to improve the properties of cooling fluids, improving water recovery, improving dry cooling technologies and incorporating water resource management.
- Energy transition, as the process of moving from fossil fuel to non-fossil-fuel-based energy sources to create a sustainable energy system with zero or near-zero carbon emissions, includes two pathways for achieving sustainable development goals for water (SDG6) and energy (SDG7): One way is the improvement of the existing energy supply systems and developing new technologies to produce near-zero carbon electricity. Secondly, the general electrification of all areas of economy. These two developments mean the transition to sustainable energy.
- In these analyses, only the first way is addressed. Currently, worldwide, solar photovoltaics (PVs) and onshore wind turbines are the most deployed RESs. Existing hydropower and nuclear plants also play an important role.
- The analysis carried out showed that the planning of energy mix for the realization of energy systems 100% RES must take into account a number of factors: climate change and greater uncertainty, cybersecurity, economy-wide interactions and the focus beyond least-cost reliable planning. Some of these factors can be countered by making energy supply systems more flexible by coordinating interactions between systems, with the inclusion of different energy storage systems.
- Approaches to the integration of the WEN in the energy transition include the following syntheses. The analysis identifies the new innovation trends in thermal power plants, energy mix structure and advanced energy technologies. By applying the WEN concept and specific metrics, some pathways and innovations have been developed and applied in and between the water and energy sectors. However, there are still many unresolved issues, in particular, those related to the lack of adequate inter-sectoral coordination. A transdisciplinary approach will allow a better understanding and management of the interconnected water, energy and food variables as fundamental resources for achieving sustainable development.

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