*water*

*Review*

# The Water–Energy Nexus in 26 European Countries: A Review from a Hydrogeological Perspective

**Somayeh Rezaei Kalvani *, Riccardo Pinardi and Fulvio Celico**

Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area Delle Scienze 157/A, 43124 Parma, Italy; riccardo.pinardi@unipr.it (R.P.); fulvio.celico@unipr.it (F.C.)
* Correspondence: somayeh.rezaeikalvani@unipr.it

**Abstract:** The significance of the interconnection between water and energy, known as the water–energy (WE) nexus, is highly regarded in scientific publications. This study used a narrative review method to analyze the existing WE nexus studies performed before 2024 in 26 European countries. The aim of this study is to provide a comprehensive analysis of the existing WE nexus to identify research gaps and to report a conceptual overview of energy consumption related to groundwater use phases, ranging from the tapping to distribution. This information is valuable as a guideline for any future estimates in this field. The results indicate that the WE nexus in 26 European countries comprises a variety of topics, including the water supply system, wastewater treatment, hydropower, desalination, and biofuel production. Most of the focus has been on fossil fuel production, while water supply and desalination were considered rarely. Italy and Portugal had the largest WE nexus. It is highlighted that there have been no studies on the WE nexus focusing on the groundwater supply system that consider the conceptual hydrological model or hydrodynamic processes. In this work, a view of these aspects was provided by taking into account different hydrogeological and hydraulic scenarios that may affect the amount of energy required for groundwater exploitation. Most scientific publications have focused on quantitative analysis. In the future, it will be necessary for WE nexus models to place a greater emphasis on governance and the implications of the WE nexus approach.

**Keywords:** biofuel; water–energy security nexus; energy intensity; groundwater supply



**Citation:** Rezaei Kalvani, S.; Pinardi, R.; Celico, F. The Water–Energy Nexus in 26 European Countries: A Review from a Hydrogeological Perspective. *Water* **2024**, *16*, 2981. https://doi.org/10.3390/w16202981

Academic Editors: Christiana M. Papapostolou, Georgios Tzanes and Fanying Kong

Received: 12 September 2024
Revised: 11 October 2024
Accepted: 17 October 2024
Published: 19 October 2024



## 1. Introduction

Water and energy are two essential elements for human life and sustainable development that play essential roles in national security, poverty reduction, and economic sustainability [1]. The WE nexus is a novel approach for addressing the interlinkage between these two resources and sustainable resource management [2]. It is claimed that the WE nexus can enhance informed decision makers in water and energy planning and improve understanding of potential alternatives for both policy and technology. It can help resource coordinators and policy makers in energy and water conservation and sustainability [3]. Energy and water are basically interlinked [4]. It was evaluated that approximately 350 $bm^3$ of the water withdrawal was utilized for energy production, including hydropower and bioenergy production. Energy is also required for water production. For example, various stages of water treatment and distribution, including pumping, filtration, and desalination, consume significant amounts of energy [5]. Water scarcity can directly influence energy poverty and vice versa [6]. For example, one study [7] indicated that the reduction in the production of fossil fuel contributes the reduction in water stress in Germany.

The interconnections between water and energy have been initially acknowledged in the United States since at least 1994 [8]. However, over the past years, the interaction between water and energy as the WE nexus has been a hot topic among the scientific community and public [4]. A deep and comprehensive understanding of the WE nexus is crucial to achieve sustainable resource management [7]. There are so many literature reviews about the nexus topic, and most of the existing review papers analyzed the water–energy–food nexus (WEF nexus) at a global scale, such as [4–15]. However, only limited review papers focused on two these essential elements (WE nexus), such as [16–19]. There is one review paper focused on the nexus among water, energy, and food across 26 European countries [20] that demonstrated that water and energy security is a hot topic in European countries because of energy poverty. Thus, this study is significantly different from the previous review [20] because this review considered the interaction between water and energy in different sectors, including wastewater treatment, water supply, hydropower production, biofuel production, and desalination in European countries. In addition, a conceptual outline has been reported based on technical and scientific aspects that can expose the situation of energy consumption related to groundwater exploitation.

The aim of this review is to provide a holistic view on the WE nexus in 26 European countries because despite the high number of publications on the WE nexus, a holistic and comprehensive review on the WE nexus focusing only on European countries does not exist. Therefore, this study focuses exclusively on the WE nexus in European countries to identify the research gaps and provide insights into effective management strategies and policy recommendations with a focused insight into groundwater exploitation.

## 2. Materials and Methods

To analyze the existing WE nexus, this study used a narrative review approach because it is comprehensive and allows coverage of a different range of topics [21,22]. This study considered papers published before 2024. The following steps have been done:

1. Research was performed using variety of databases that cover all the relevant topics that addressed the interaction between water and energy (WE nexus). Unpublished papers are excluded. The selection criteria focused on published international and English language papers. In this study, Web of Science, Scopus, PubMed, Google Scholar, and Science Direct were used as secure databases.
2. In this step, suitable keywords that provide answers to the research questions were found.
3. All the relevant papers were selected, and non-relevant papers were omitted.
4. In this final step, all of the results and key findings were summarized and written.

In this study, the following keywords were used: water–energy nexus, water energy security, water–energy nexus and desalinate, water–energy nexus and biofuel, water–energy nexus and bioenergy, water–energy nexus and water supply, water–energy nexus and water treatment, water–energy nexus and hydropower, and water–energy nexus and groundwater pumping.

This review classified and analyzed the water–energy nexus based on geography and the types of sectors involved. The ArcGIS software was used to visualize the number of the WE nexus studies in each country and the different study sectors across European countries.

## 3. Results

### *3.1. Overview of WE Nexus Studies*

#### 3.1.1. The Number of Water–Energy Nexus Studies Across European Countries

Figure 1 illustrates the number of the WE nexus studies across the different European countries. It is indicated that the most WE nexus research has been conducted in Italy and Portugal with nine studies. Both countries rely considerably on hydropower for their electricity generation. This creates a direct interconnection between water availability and energy production and highlights the significance of studying the WE nexus. However, there is a lack of WE nexus studies in some countries like Bulgaria, Estonia, Latvia, and Lithuania. Moreover, it can be concluded that there is lack of studies in some countries characterized by energy poverty, like Bulgaria (the country with the highest level of energy poverty in Europe [23]), Latvia, and Lithuania [23]. Addressing energy security in countries with energy poverty is essential to promote sustainable development and economic growth.

It is important for these countries to efficiently manage their limited energy resources and increase resilience to climate change.

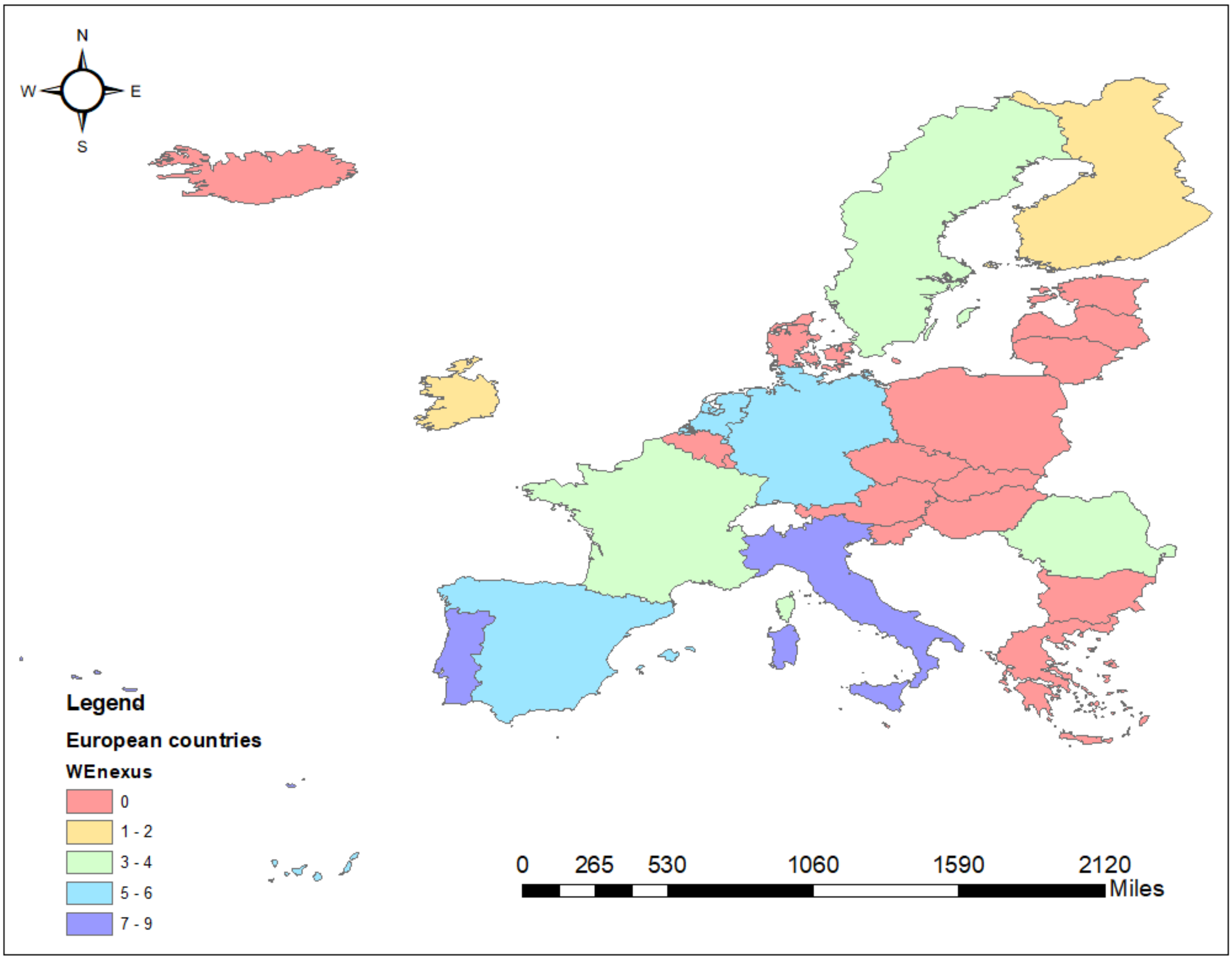


**Figure 1.** The number of WE nexus studies across the different European countries.

3.1.2. Sectors of Water–Energy Nexus Research Across European Countries

Figure 2 illustrates the water–energy nexus across various sectors in European countries. It demonstrates that the WE nexus is explored based on a range of topics, such as household water supply, bioenergy production, hydropower, water treatment, and water desalination. In each European country, the focus varies based on their specific needs. For example, in Italy, the WE nexus approach strongly emphasizes renewable energy sources, particularly hydropower production, to enhance energy efficiency and reduce carbon emissions. However, in other countries like Germany, Spain, and the Netherlands, studies are more focused on the bioenergy sector.

Figure 3 shows the number of WE nexus studies in different sectors in all of Europe. It is indicated that most of the WE nexus studies focused on bioenergy production. Next to bioenergy, the second largest number of studies was allocated to hydropower production. However, desalination has the lowest number of WE nexus publications with one publication in Portugal to overcome seasonal water scarcity and increase water efficiency. Ref. [24] used the WE nexus approach in Portugal to compare two different scenarios for desalination considering economic aspects. There is a lack of studies on the water supply in the context of the WE nexus for the domestic sector, specifically considering the hydrological conceptual model or the type of aquifer for pumping of groundwater. This is significant because pumping groundwater from aquifers with high permeability requires less energy since water moves readily, reducing the resistance against the pump. Understanding the type of aquifer is essential for sustainable groundwater management. Over-extraction from low permeability aquifers can lead to rapid depletion and land subsidence. Only one study in Romania [25] considered the WE nexus for drinking water purposes in the whole life cycle.

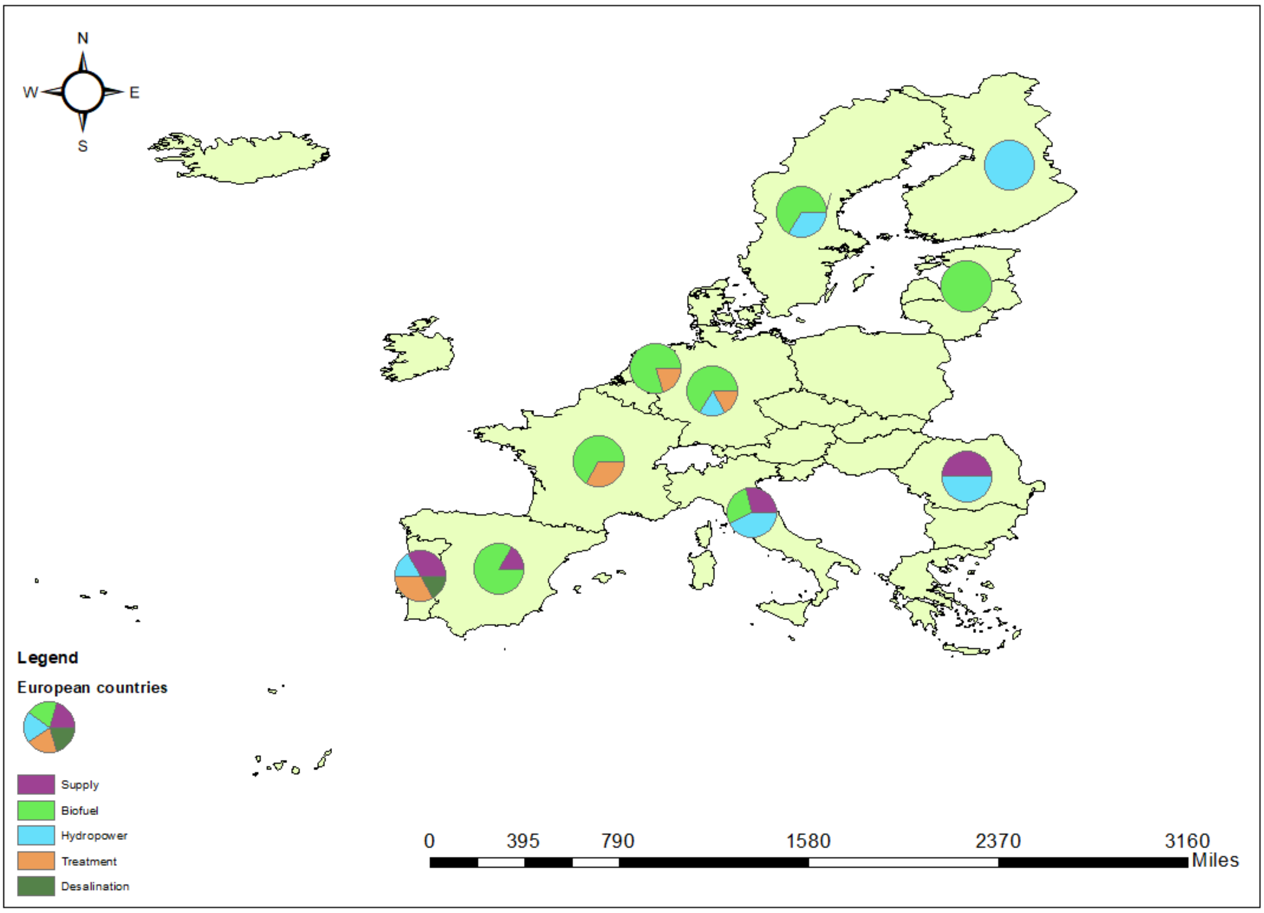


**Figure 2.** Sectors of water–energy nexus research across European countries.

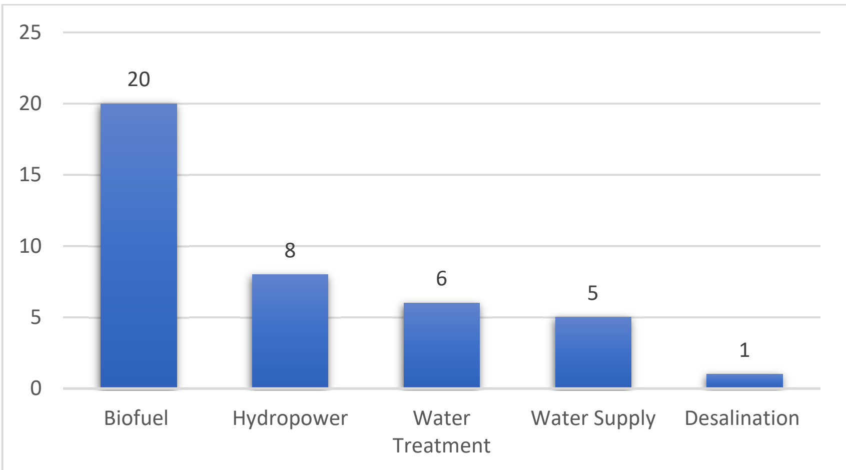


**Figure 3.** Number of WE nexus studies in different sectors.

#### 3.1.3. Overview of Existing Approaches for the Water–Energy Nexus

Table 1 provides a summary of the WE nexus studies in 26 European countries. It can be seen that during the past several decades, various approaches have been utilized to analyze the interaction between water and energy in various contexts. These approaches include life cycle assessment (LCA), optimization, statistical analysis, hydrological models and economic approaches. Some researchers used scenario analysis to discover the potential tradeoffs of the water–energy–food nexus for the future.

The optimization approach is a decision-making assistance method that helps to find the best possible appropriate solution for the water–energy nexus approach [26,27] by improving the energy efficiency and achieving sustainable water resource management across various scale [28–30].

Life cycle assessment integrated with the WE nexus has been used by various scholars, such as [25,31–35]. LCA is considered a standard approach to assess footprint indexes and energy performance [9]. Considering the LCA throughout the whole life cycle of water and energy systems contributes to an understanding of the interlinkage impacts of water and energy at different stages. Moreover, LCA can help to identify the environmental impacts (including greenhouse gas emission, water consumption, and resource depletion) across the different stages of water and energy production and consumption. This approach can help to recognize the stages with powerful negative impacts. This information is important for decision makers for sustainable prioritization. For example, a study by [31] identified that in biofuel production, the crop production stage has the largest environment impact in terms of water resource consumption. Another study by [32] demonstrated that groundwater abstraction for drinking water supply consumed high levels of energy compared to surface water abstraction. Moreover, another study by [36] used LCA to compare the environmental impacts of different alternatives for wastewater treatment technology to find more sustainable alternatives for water and energy use efficiency. However, it is challenging to choose a single functional unit that captures all these aspects because the WE nexus is a multi-functional unit.

Input–output analysis is a common and widely used approach in WE nexus studies to quantify the interlinkage between water and energy by evaluating the monetary and physical flow.

Hydrological models play an important role in the WE nexus by providing information about water availability and water demand. It helps to predict river flow and water revisors for hydropower management. For example, one study [37] used a semi-distributed (CWatM) model to simulate the future water withdrawal and streamflow under climate change scenarios for hydropower production. Another study [38] applied a conceptual semi-lumped hydrological model to assess the impact of climate change and seasonal streamflow on hydropower production. It can also help to predict some events like drought and floods in the future and evaluate the impact of these event on water and energy systems. For example, Refs. [39,40] used the watershed simulation and forecasting system (WSFS) to estimate the impact of severe drought on future hydropower production. Thus, considering hydrological models in the WE nexus benefits decision makers and planers to ensure the sustainable and efficient use of both water and energy resources.

Technological aspects are considered in WE nexus studies. For example, [41] compared different solar panels for freshwater production. However, economic dimensions are considered rarely. Political and social dimensions are not considered. The role of the behavior of the people and culture are not considered in WE studies.

**Table 1.** Summary of WE nexus studies in European countries.

| Method | Key Findings | Type of Water | Country | Reference |
|---|---|---|---|---|
| Water footprint + nexus + economic aspects | There is an essential need to produce a new integrated approach that can manage water for electricity production that considers economic aspects of the water–energy economic | Blue water | Italy | [42] |

**Table 1.** *Cont.*

| Method | Key Findings | Type of Water | Country | Reference |
|---|---|---|---|---|
| LCA + WE nexus | Environmental impacts of water for energy production and energy for water production (from water withdrawal, water treatment, and distribution) were considered. Moreover, the results demonstrated that water abstraction from surface water is less energy demanding than groundwater. | Surface water and groundwater | Italy | [32] |
| Semi-distributed hydrological model CWatM + optimization method Changes in future prices and climate on hydropower were considered. | An increase in temperature contributes to a slight increase in hydropower performance. | Surface water | Italy | [37] |
| Urban ecological infrastructure method | It provides energy for 600 households by improving land usability and environmental sustainability. This mini hydropower plant also reduces the risk of flood. | Surface water | Italy | [43] |
| Conceptual semi-lumped hydrological mode + bottom-up approach | The impact of change in climate, price, and seasonal streamflow on hydropower production was evaluated. | Surface water | Italy | [38] |
| WE nexus + LCA + water footprint | The crop cultivation step has the largest impact on water resources. Biogas production in terms of water consumption was unsustainable. | Blue water | Italy | [31] |
| Dynamic simulation tool TRNSYS Energy, economic and environmental model | Two different solar plants sources for freshwater production in domestic sector was compared | Surface water | Italy | [41] |
| Techno-economic assessment | Different scenarios were used to find the best solution to reduce water consumption. | Surface water | Germany, Portugal, United Kingdom, and Norway | [44] |
| LCA | Environmental impacts of different alternatives for wastewater treatment technology were compared to find more energy and water use efficiency alternatives. | Grey water (surface water) | Germany | [36] |
| Interview | Comparison of WE nexus studies in 8 cities | Grey water | Germany | [45] |
| Review | Considering the nexus between water and energy for bioenergy production contributes to poverty reduction and food security. | Blue water | Germany | [46] |
| Economic cost-benefit analysis | Using green roofs and a photovoltaic system can increase the PV yield by about 0.3%, reduce demand for heating (0.1%), and reduce runoff mitigation (30%). | Green water | Germany | [47] |
| Foreseer | Future water, energy, and land demands were estimated. | Blue water | Germany | [7] |
| Watershed simulation and forecasting system (WSFS) hydrological model + RCP | The impact of drought on water resources and hydropower production was analyzed. Severe drought can substantially impact on water resources and hydropower production. | Surface water | Finland | [39] |

**Table 1.** *Cont.*

| Method | Key Findings | Type of Water | Country | Reference |
|---|---|---|---|---|
| Hydrological model (WSFS) + Energy PLAN | The impact of severe drought on energy production in the future was assessed. The results indicate that stress on energy will be reduced by 2030 because of the development of nuclear energy. | Surface water | Nordic countries | [40] |
| Interview with water user associations | WUAs can play an important role in water management. | Blue water | Spain | [48] |
| Prospective approach | Biofuel production had a devastating impact on water resources. | Blue water and grey water | Spain | [49] |
| Irrigation efficiency and energy consumption using historical data | Irrigation for the agricultural sector required a high amount of energy in Spain. | Blue water | Spain | [50] |
| LCA | The environmental impact of carbonization in different energy scenarios was compared. | Surface water | Spain | [33] |
| Water footprint + different scenarios | The impact of virtual water imports on water and energy for biofuel production was evaluated. Importing raw materials from a country with abundant water resources can reduce water stress in Spain. | Blue water | Spain | [51] |
| Medium-term hydrothermal coordination (MTHC) + unit commitment and dispatch | Hydropower generation in different years was compared in terms of cost and the volume of production. | Surface water | Croatia | [52] |
| Statistical models, including the ordinary least squares (OLS) + the geographically weighted regressions (GWR) + GIS | The results indicated the trend and provided solutions to manage resources. | Grey water | France | [53] |
| Water–energy–carbon nexus + LCA | Reducing the use of herbicides and pesticides can improve water quality and reduce the demand for energy to treat raw water. | Grey water | Norway, France, Italy, Canada | [34] |
| Water balance + water impact assessment | The impact of bioenergy production was compared using different scenarios. | Blue water | France | [54] |
| Water–energy nexus | Different types of energy production were compared. The result indicated that it is essential to produce a national alternative that can ensure climate resilience in the energy and water sectors. | Grey water | Greece | [55] |
| Global macro-econometric model (E3ME) | A new model was produced that forecasts future energy demand and carbon emissions. | Surface water | The Netherlands and Latvia | [56] |
| Environmental input–output (EIO) model + water efficiency + energy efficiency + carbon emission index | The result indicated that all of these indicators have higher value compared with the global average. | Blue water | EU27 countries | [57] |
| Water footprint + carbon footprint + LCA | The water–energy–carbon nexus for wastewater treatment in different industrial sector was evaluated. | Grey water | Ireland | [35] |
| Statistical analysis (time series) | This study evaluates the role of North Atlantic Oscillation (NAO) and East Atlantic pattern (EA) on the WE nexus. | Surface water and groundwater | Portugal | [58] |
| EPANET 2.0 (simulation model) | Using renewable energy can increase social performance by increasing air quality and prompt eco-efficiency. | Surface water | Portugal | [59] |

**Table 1.** *Cont.*

| Method | Key Findings | Type of Water | Country | Reference |
|---|---|---|---|---|
| Comparison of three scenarios | Different scenarios were compared to find the best one for water reuse, including irrigating golf courses with reused water, municipal irrigation with reused water, and irrigating both locations with reused water. | Grey water | Portugal | [60] |
| Mathematical modeling Water–energy–greenhouse gas emissions nexus | Effect of flood on the WEG nexus | Surface water | Portugal | [61] |
| Optimization model + cost analysis | Two different strategies (centralized and decentralized) were compared. | Sea water | Portugal | [21] |
| Top-down and bottom-up approaches | The top-down approach is easy to apply because it does not need a lot of data. It is applicable with minimum data. It can provide accurate evaluation of energy inefficiency. The bottom-up approach can evaluate more details and provides more detail. It also enables the evaluation of disputed energy in pipes. | Groundwater and surface water | Portugal | [62] |
| Water and energy efficiency + statistical analysis | Higher energy consumption is related to the shower. A device is used to control water and energy consumption. | Blue water | Portugal | [63] |
| WAT + RCP WELC nexus | Under different forest scenario, no significant change in water flow. | Surface water | Romania | [64] |
| LCA | The main consumers of energy in drinking water treatment processes are pumping water and wastewater treatment. | Grey water | Romania | [22] |
| Water footprint + gross water consumption, net water consumption, and water balance | There is a need to provide a method that considers water evaporated from dams. | Surface water | Romania | [65] |
| Water–energy nexus using a water footprint approach | The impact of energy production on water resources in different Swedish countries was evaluated. | Blue water | Sweden | [66] |

## 4. Discussion and Conclusions

### *4.1. Guidelines for WE Nexus Application to Groundwater Resource Use*

In relation to the exploitation of groundwater, this work provides an overview of the energy consumption associated, ranging from the extraction to the distribution (see Figure 4). This information is capable of giving guidelines for future estimations in this specific sector. The following proposal scheme is based on technical and scientific knowledge derived from real case studies distinguishing variable scenarios depending on the hydrogeological and hydraulic local settings. The elements outlined in the following subchapters can be used as the basis for a solid analysis and models of energy consumption related to groundwater exploitation. The following case studies are mainly derived from works carried out in the Po Valley that, like many other areas of the world, is subject to an increasing demand for groundwater related to multiple uses like drinking, bottling, irrigation, livestock farming, and industry. This territory can be considered an excellent model for the application of the WE nexus as it has heterogeneous features [32] linked to different water-demanding contexts that vary according to geographical location, with lower pressure in the mountainous areas at the edge of the basin and higher pressure in the plain area where the main cities and water-demanding activities are located.

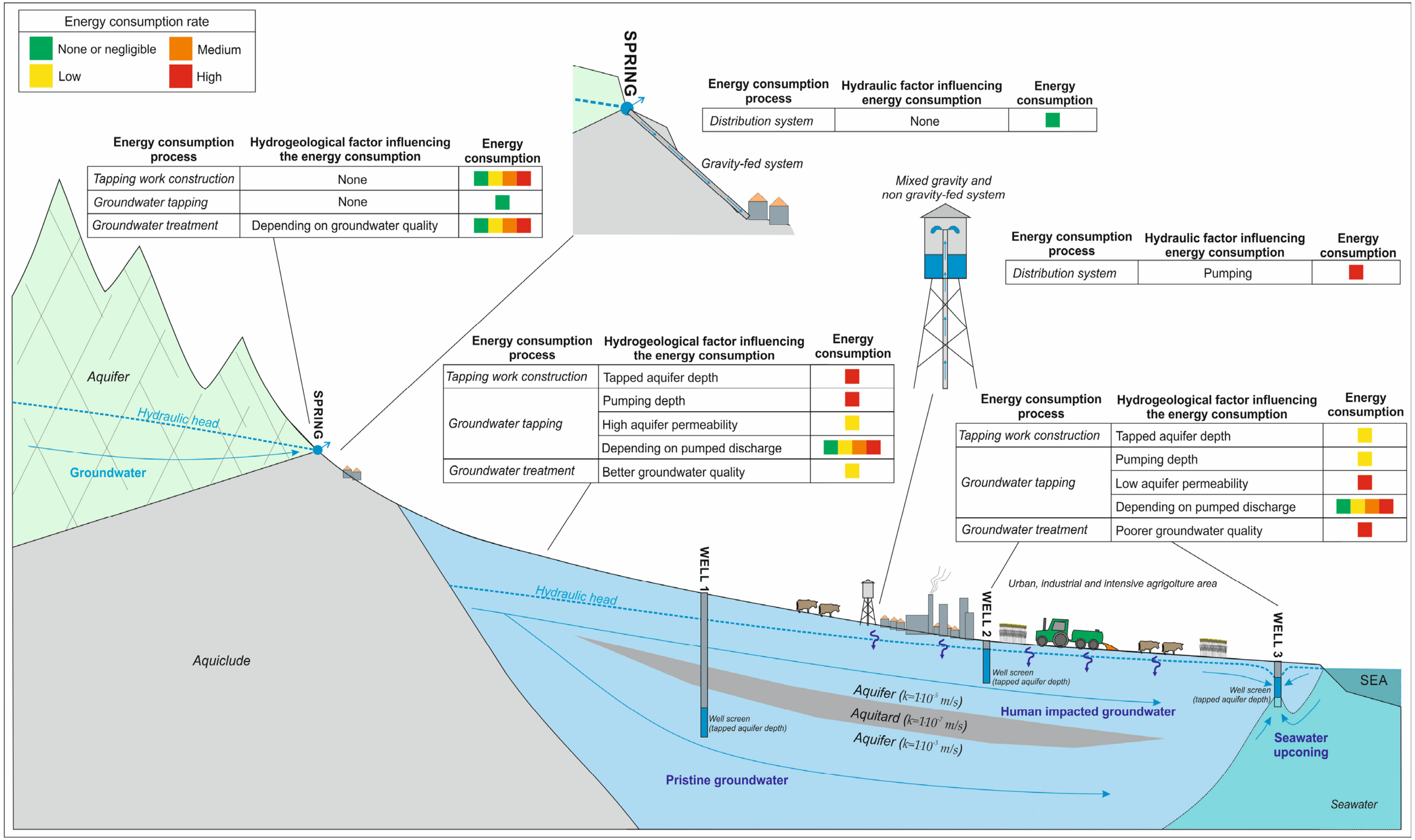


**Figure 4.** Ideal scheme of the energy consumption rate related to groundwater use and hydrogeological and hydraulic factors.

#### 4.1.1. Groundwater Tapping Work Construction

The first energy consumption to be taken into account comes from the implementation of groundwater exploitation works, which are variable depending on the hydrogeological context. With regard to spring tapping works, energy use is closely related to the size, the type of building, and the areal location of the operation. A large catchment work requires more material and thus energy use than a small one, and different types of intakes can be more or less energy-impactful elements (a drainage gallery or an infiltration gallery requires more energy for their construction than a simple artifact to convey outcropping groundwater). The location of the spring may also require higher or lower energy efforts, depending on the dynamics of access to the area. For example, the location of a spring along a slope inaccessible and covered with vegetation requires a high energy effort to build roads and to transport materials, compared to a location on the valley floor that is easily accessible and close to existing utilities. Stepping to contexts where groundwater does not outcrop, it is necessary to realize tapping work construction to drill the subsurface (overall wells [67]). The energy for their construction is directly proportional to the depth of the tapped aquifer (see the tapped depth of well 1 and well 2 in Figure 4) that can vary from a few meters to many hundreds of meters below the surface as observed in the context of the Po Plain [68] or across the entire Italian peninsula (ISPRA water well database [69]) in relation to the different geological settings. In addition, the borehole diameter at the same depth scenario could be an element of energy expenditure during the drilling phase in the same way as the lithology (and in particular mineralogy) of the geological medium greatly affects the energy required to drill the well, in relation to the hardness of the material of which the drilled subsoil is composed (Mohs scale is the main indicator of this character). The drilling rate could increase in an inversely proportional manner to the Mohs hardness, from cm/min to m/min as reported in Hoseinie et al. 2012 [70]. Other technical aspects specific to each well may alter the energy impact associated with their construction, such as the pipe material (the most common are PVC, concrete, and steel). In addition, the following general drilling methodologies could be considered: (i) less impactful methods, in cases of wells drilled by manual digging or with percussion systems; and (ii) more impactful methods, if excavators or well drilling rigs are employed.

#### 4.1.2. Groundwater Tapping

A second and important cause of energy consumption to report is certainly related to groundwater tapping. It could vary based on the function of the hydrogeological context, and it is strictly related to the eventual necessity to uplift groundwater through the use of pumps. Energy consumption related to tapping in the context of springs or for example in the Po Plain "fontanili" context *sensu* [71] can be considered null or negligible because of the natural outflow of groundwater from the aquifer (see the spring in Figure 4). In contrast, in wells, energy consumption is directly proportional to the installation depth of the pumping system, its flow rate and its efficiency. Groundwater tapping could occur using electric pumps or combustion engine pumps, like Power Take-Off models (PTO) for tractors. The well and the pump efficiency can decrease over time due to possible well clogging phenomena. It mainly depends on the infiltration water's origin and consequently physical, chemical, and/or biological processes that can deposit significant filling material and/or allow biofilm growth inside the well screen lights and the pumping equipment, decreasing the permeability and the efficiency of the supply system [72–74]. The original permeability of the exploited aquifer also affects energy consumption, facilitating withdrawal in locations with greater permeability (see differences in permeability between the shallow [well 2] and the deep [well 1] aquifers in Figure 4). This element is frequently heterogeneous depending on geological setting, for example, as shown in the context of the Parma city area [68], where [75,76] calculated a hydraulic conductivity varying from $1.2 \times 10^{-5}$ to $4.9 \times 10^{-5}$ m/s in coarse-grained horizons and from $9.3 \times 10^{-0}$ to $1.3 \times 10^{-0}$ m/s in fine-grained horizons.

#### 4.1.3. Groundwater Treatment

As observed in several of the above mentioned studies (see Table 1), a possible subsequent step after extraction that could require energy efforts is groundwater treatment. Its entity could depend on the original condition of the quality of the groundwater and its destination of use. Many aspects can affect water quality. These factors could be related to the natural hydrogeochemical characters of each aquifer, like mineral composition above all, as demonstrated in the Po Plain (e.g., [77]). As an example of these phenomena, numerous testimonies of hexavalent chromium remaining on the Po Valley and precisely in the Northern Apennine have been linked to the mineralogical nature of ophiolitic aquifers. In these cases, peridotites rocks are able to impart non-potable characteristics to groundwater (e.g., [78–80]).

To a greater extent, anthropogenic factors can make the aquifer polluted and thus necessitate groundwater treatment. As reported in several studies conducted in the Po Valley, it could be attributed to numerous possible origins, like industry [81–83], fertilization and livestock [84–86], sewage [87], landfills [88], pharmaceuticals [89], cosmetic products [90], and many others. Saltwater intrusion and upwelling are also human-induced hydrogeological phenomena that occur through pumping and can reduce water quality as schematized for Well 3 in Figure 4 (e.g., [91]). Water quality can be very different even at short distances within the same hydrogeological context, depending on the location of sources of contamination (see the lowland aquifer in Figure 4). Aqueduct or potable water systems may need more operations to purify groundwater considering the human supply, but they also can be extended to various entities for uses other than the tapped water. In cases of pristine groundwater, the treatments, and consequently the energy consumed for this purpose, may be negligible.

Even if characterized by lower consumption, it is also proper to include in this step the energy used for the qualitative and quantitative monitoring actions, which takes place through studies and analyses targeting the groundwater resource by the owners or the public agencies, according to regulations such as the Directive 2000/60/EC of the European Parliament (23 October 2000) and subsequent updates that establish a framework for community action in the field of water policy, including groundwater in the European Union.

#### 4.1.4. Groundwater Distribution System

The last field to be reported that may require energy consumption is that related to the distribution of groundwater resources. As exemplified in Figure 4, the energy to be used in different contexts is closely related to the necessity of contrasting gravity. In a mountain area or where a territory has sufficient topographic gradients, gravity could facilitate the distribution of the resource from origin to delivery without the use of additional energy. On the contrary, in flat settings or in conditions where it is necessary to impart pressure to the distribution network, energy consumption could be drastically higher and related to pumping systems. In these last contexts, there are infrastructural strategies that can reduce the energy used and combine it with gravity using artificial reservoirs or water towers. However, these strategies may still require great efforts in the construction phase. The design of these works is governed by hydraulic projects and principles that can vary substantially depending on a multitude of natural and anthropic factors. The most impactful factors are related to the pressure required to allow the distribution, such as altitude differences, an optimized design of the pipe network, and water losses from the pipe system. In Italy, the National Institute of Statistics (ISTAT, 21 March 2023) revealed that in 2020, 42.2% of pumped groundwater for aqueduct supply was lost due to leaky distribution systems. An exhaustive overview of the abovementioned themes was given by Vilanova and Balestrieri 2014 [92] and Coelho and Andrade-Campos 2014 [93]. Another energy expenditure related to water distribution can be associated with the transport of water resources where local conditions do not allow for a supply system, which often takes place by road, train, or ship. These conditions could be attributed to hydrogeological features combined with the climatic features of an area such as the absence of exploitable aquifers or the presence of drought periods.

#### 4.1.5. The Proposal of a New Application for Hydrogeological Modelling

The combination of the elements in the previous paragraphs influence the energy consumption related to groundwater use. As detailed in this work, they are closely linked to the hydrogeological and hydraulic context. Here, nexus analysis and life cycle assessment methodologies (e.g., for the Po Plain context [32]) are applied to evaluate and compare different process alternatives aimed to support the investigation of new solutions and reducing the energy intensity and the release of greenhouse gas (GHG) emissions while maintaining high-quality services under future pressures resulting from climate change. These methods are mainly focused on the analysis of past or present scenarios, and the use of future-oriented modelling and/or simulations could provide them with greater predictive utility. In environmental science, many kinds of predictive modelling exist. In this case, in relation to energy consumption, the points above have shown the importance of hydrogeology, which is a sector where numerical models are currently used for a variety of purposes. First, they are employed for hydrogeological balance analyses, where they constitute advanced tools useful for quantitative studies mainly aimed at the determination of exploitable groundwater volumes, for tapping work construction planning and for predict climate change scenarios (e.g., ref. [94] as an example for the Northern Apennine context). Numerical models are also employed for environmental hydrogeology that can be used for the prevention and/or remediation of areas contaminated by both soluble (like nitrates) and non-soluble (like hydrocarbon non-aqueous phase) contaminants in groundwater [75,76,95,96]. In conclusion, combining energy consumption data and hydrogeological information, this work offers a new use for numerical modelling of the WE nexus and thus to the evaluation of alternative scenarios useful for energy savings in the field of groundwater.

## 5. Conclusions

This current review analyzes the existing WE nexus in 26 European countries. It was remarked that the analysis of the WE nexus in European countries was conducted in different types of sectors, including water supply, water desalination, hydropower, and biofuel production. In each European country, the focus varies based on their specific needs. Among the WE studies in Europe, those focused on the interlinkage between water and energy in biofuel production represent 50% of scientific papers, showing the significance of this research topic in European countries. It is indicated that most of the WE nexus studies focused on surface water and blue water resources. The majority of the studies considered groundwater integrated with surface water as blue water. There is lack of studies that separately consider groundwater. Separate evaluations of groundwater would provide deeper insights into its role and vulnerabilities in the context of the WE nexus. Moreover, 7.5% of all studies involved groundwater resources.

The existing bibliography related to the WE nexus in Europe is illustrative of a still limited holistic approach to the field of water (and groundwater). For studies of the WE nexus, there are a variety of approaches that are currently used, but there is not a single and standard approach that can be utilized for the WE nexus globally. The first fundamental challenge for the evaluation of the interaction between water and energy is data availability at regional and global scales. For example, hydrogeological and hydraulic information related to withdrawal are often not made available by public agencies or private companies. Information on this critical theme is essential to standardize data collection approaches, which can facilitate a high degree of estimation accuracy. This work showed in detail how several hydrogeological and hydraulic factors could be extremely influential on energy consumption in the sector of groundwater exploitation. For this reason, a conclusive proposal is to use methods capable of incorporating all groundwater-related energy consumptions with a first step represented by the creation (or consultation) of conceptual and numerical models based on hydrological principles. Numerical models could support and guide the energetic consumption computations related to the entire groundwater use steps (see Section 4.1). From these insights, their application is proposed to be extended to WE nexus estimates to further support the results with scientifically based models and simulations and to make it even more of a useful tool for a predictive look at climate change and related socio-economic and energetic evolutions.

**Author Contributions:** Conceptualization: S.R.K., R.P. and F.C.; research design: F.C., S.R.K. and R.P.; supervision: F.C.; formal analysis: S.R.K. and R.P.; methodology: S.R.K. and R.P.; project administration: F.C.; writing—original draft preparation: S.R.K., R.P. and F.C.; editing: F.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data used in this analysis are publicly accessible at ISPRA https://www.isprambiente.gov.it/it (accessed on 24 August 2024) ISTAT https://www.istat.it (accessed on 24 August 2024).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Conway, D.; van Garderen, E.A.; Deryng, D.; Dorling, S.; Krueger, T.; Landman, W.; Lankford, B.; Lebek, K.; Osborn, T.; Ringler, C.; et al. Climate and Southern Africa's Water–Energy–Food Nexus. *Nat. Clim. Chang.* **2015**, *5*, 837–846. [CrossRef]
2. Rezaei Kalvani, S.; Celico, F. Analysis of Pros and Cons in Using the Water–Energy–Food Nexus Approach to Assess Resource Security: A Review. *Sustainability* **2024**, *16*, 2605. [CrossRef]
3. Healy, R.W.; Alley, W.M.; Engle, M.A.; McMahon, P.B.; Bales, J.D. *The Water-Energy Nexus: An Earth Science Perspective*; USGS: Reston, VA, USA, 2015. [CrossRef]
4. Hamiche, A.M.; Stambouli, A.B.; Flazi, S. A Review of the Water-Energy Nexus. *Renew. Sustain. Energy Rev.* **2016**, *65*, 319–331. [CrossRef]
5. IEA Water for Energy: Is Energy Becoming a Thirstier Resource? In *World Energy Outlook 2012*; International Energy Agency: Paris, France, 2012.
6. Bauer, D.; Philbrick, M.; Vallario, B.; Battey, H.; Clement, Z.; Fields, F. *The Water-Energy Nexus: Challenges and Opportunities*; US Department of Energy: Washington, DC, USA, 2014.
7. Heinrichs, H.U.; Mourao, Z.; Venghaus, S.; Konadu, D.; Gillessen, B.; Vögele, S.; Linssen, J.; Allwood, J.; Kuckshinrichs, W.; Robinius, M.; et al. Analysing the Water and Land System Impacts of Germany's Future Energy System. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111469. [CrossRef]
8. Gelick, P. Annual Review of Energy and Environment. **2016**, *19*, 1–23.
9. Gazal, A.A.; Jakrawatana, N.; Silalertruksa, T.; Gheewala, S.H. Water-Energy-Food Nexus Review for Biofuels Assessment. *Int. J. Renew. Energy Dev.* **2022**, *11*, 193–205. [CrossRef]
10. Moghadam, E.S.; Sadeghi, S.H.R.; Zarghami, M.; Delavar, M. Water-Energy-Food Nexus as a New Approach for Watershed Resources Management: A Review. *Environ. Resour. Res.* **2019**, *7*, 129.
11. Endo, A.; Tsurita, I.; Burnett, K.; Orencio, P.M. A review of the current state of research on the water, energy, and food nexus. *J. Hydrol. Reg. Stud.* **2017**, *11*, 20–30. [CrossRef]
12. Lee, M.; Keller, A.A.; Chiang, P.-C.; Den, W.; Wang, H.; Hou, C.-H.; Wu, J.; Wang, X.; Yan, J. Water-Energy Nexus for Urban Water Systems: A Comparative Review on Energy Intensity and Environmental Impacts in Relation to Global Water Risks. *Appl. Energy* **2017**, *205*, 589–601. [CrossRef]
13. Mannan, M.; Al-Ansari, T.; Mackey, H.R.; Al-Ghamdi, S.G. Quantifying the Energy, Water and Food Nexus: A Review of the Latest Developments Based on Life-Cycle Assessment. *J. Clean. Prod.* **2018**, *193*, 300–314. [CrossRef]
14. Purwanto, A.; Sušnik, J.; Suryadi, F.X.; de Fraiture, C. Water-Energy-Food Nexus: Critical Review, Practical Applications, and Prospects for Future Research. *Sustainability* **2021**, *13*, 1919. [CrossRef]
15. Simpson, G.B.; Jewitt, G.P.W. The Development of the Water-Energy-Food Nexus as a Framework for Achieving Resource Security: A Review. *Front. Environ. Sci.* **2019**, *7*, 8. [CrossRef]
16. Siddiqi, A.; Fletcher, S. Energy Intensity of Water End-Uses. *Curr. Sustain./Renew. Energy Rep.* **2015**, *2*, 25–31. [CrossRef]
17. Yoon, H. A Review on Water-Energy Nexus and Directions for Future Studies: From Supply to Demand End. *Doc. Anal. Geogr.* **2018**, *64*, 365–395. [CrossRef]
18. Wakeel, M.; Chen, B.; Hayat, T.; Alsaedi, A.; Ahmad, B. Energy Consumption for Water Use Cycles in Different Countries: A Review. *Appl. Energy* **2016**, *178*, 868–885. [CrossRef]
19. Nair, S.; George, B.; Malano, H.M.; Arora, M.; Nawarathna, B. Water–Energy–Greenhouse Gas Nexus of Urban Water Systems: Review of Concepts, State-of-Art and Methods. *Resour. Conserv. Recycl.* **2014**, *89*, 1–10. [CrossRef]

20. Rezaei Kalvani, S.; Celico, F. The Water–Energy–Food Nexus in European Countries: A Review and Future Perspectives. *Sustainability* **2023**, *15*, 4960. [CrossRef]
21. Rezaei Kalvani, S.; Sharaai, A.H.; Abdullahi, I.K. Social Consideration in Product Life Cycle for Product Social Sustainability. *Sustainability* **2021**, *13*, 11292. [CrossRef]
22. Collins, J.A.; Fauser, B.C.J.M. Balancing the Strengths of Systematic and Narrative Reviews. *Hum. Reprod. Update* **2005**, *11*, 103–104. [CrossRef]
23. Halkos, G.E.; Gkampoura, E.-C. Evaluating the Effect of Economic Crisis on Energy Poverty in Europe. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110981. [CrossRef]
24. Azinheira, G.; Segurado, R.; Costa, M. Is Renewable Energy-Powered Desalination a Viable Solution for Water Stressed Regions? A Case Study in Algarve, Portugal. *Energies* **2019**, *12*, 4651. [CrossRef]
25. Delcea, A.; Bitir-Istrate, I.; Pătraşcu, R.; Gheorghiu, C. Joint Energy and Water Management Scheme for Water Supply Systems in Romania. *E3S Web Conf.* **2019**, *85*, 6008. [CrossRef]
26. Liu, D.; Guo, S.; Liu, P.; Xiong, L.; Zou, H.; Tian, J.; Zeng, Y.; Shen, Y.; Zhang, J. Optimisation of Water-Energy Nexus Based on Its Diagram in Cascade Reservoir System. *J. Hydrol.* **2019**, *569*, 347–358. [CrossRef]
27. Si, Y.; Li, X.; Yin, D.; Li, T.; Cai, X.; Wei, J.; Wang, G. Revealing the Water-Energy-Food Nexus in the Upper Yellow River Basin through Multi-Objective Optimization for Reservoir System. *Sci. Total Environ.* **2019**, *682*, 1–18. [CrossRef]
28. Martin-Candilejo, A.; Santillán, D.; Garrote, L. Pump Efficiency Analysis for Proper Energy Assessment in Optimization of Water Supply Systems. *Water* **2019**, *12*, 132. [CrossRef]
29. Luna, T.; Ribau, J.; Figueiredo, D.; Alves, R. Improving Energy Efficiency in Water Supply Systems with Pump Scheduling Optimization. *J. Clean. Prod.* **2019**, *213*, 342–356. [CrossRef]
30. Ahmad, S.; Jia, H.; Chen, Z.; Li, Q.; Xu, C. Water-Energy Nexus and Energy Efficiency: A Systematic Analysis of Urban Water Systems. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110381. [CrossRef]
31. Pacetti, T.; Lombardi, L.; Federici, G. Water–Energy Nexus: A Case of Biogas Production from Energy Crops Evaluated by Water Footprint and Life Cycle Assessment (LCA) Methods. *J. Clean. Prod.* **2015**, *101*, 278–291. [CrossRef]
32. Arfelli, F.; Ciacci, L.; Vassura, I.; Passarini, F. Nexus Analysis and Life Cycle Assessment of Regional Water Supply Systems: A Case Study from Italy. *Resour. Conserv. Recycl.* **2022**, *185*, 106446. [CrossRef]
33. Lechón, Y.; De La Rúa, C.; Cabal, H. Impacts of Decarbonisation on the Water-Energy-Land (WEL) Nexus: A Case Study of the Spanish Electricity Sector. *Energies* **2018**, *11*, 1203. [CrossRef]
34. Venkatesh, G.; Chan, A.; Brattebø, H. Understanding the Water-Energy-Carbon Nexus in Urban Water Utilities: Comparison of Four City Case Studies and the Relevant Influencing Factors. *Energy* **2014**, *75*, 153–166. [CrossRef]
35. Trubetskaya, A.; Horan, W.; Conheady, P.; Stockil, K.; Moore, S. A Methodology for Industrial Water Footprint Assessment Using Energy-Water-Carbon Nexus. *Processes* **2021**, *9*, 393. [CrossRef]
36. Friedrich, J.; Poganietz, W.-R.; Lehn, H. Life-Cycle Assessment of System Alternatives for the Water-Energy-Waste Nexus in the Urban Building Stock. *Resour. Conserv. Recycl.* **2020**, *158*, 104808. [CrossRef]
37. Bonato, M.; Ranzani, A.; Patro, E.R.; Gaudard, L.; De Michele, C. Water-Energy Nexus for an Italian Storage Hydropower Plant under Multiple Drivers. *Water* **2019**, *11*, 1838. [CrossRef]
38. Gaudard, L.; Avanzi, F.; De Michele, C. Seasonal Aspects of the Energy-Water Nexus: The Case of a Run-of-the-River Hydropower Plant. *Appl. Energy* **2018**, *210*, 604–612. [CrossRef]
39. Veijalainen, N.; Ahopelto, L.; Marttunen, M.; Jääskeläinen, J.; Britschgi, R.; Orvomaa, M.; Belinskij, A.; Keskinen, M. Severe Drought in Finland: Modeling Effects on Water Resources and Assessing Climate Change Impacts. *Sustainability* **2019**, *11*, 2450. [CrossRef]
40. Jääskeläinen, J.; Veijalainen, N.; Syri, S.; Marttunen, M.; Zakeri, B. Energy Security Impacts of a Severe Drought on the Future Finnish Energy System. *J. Environ. Manag.* **2018**, *217*, 542–554. [CrossRef]
41. Calise, F.; Cappiello, F.L.; Vicidomini, M.; Petrakopoulou-Robinson, F. Water-Energy Nexus: A Thermoeconomic Analysis of Polygeneration Systems for Small Mediterranean Islands. *Energy Convers. Manag.* **2020**, *220*, 113043. [CrossRef]
42. Miglietta, P.P.; Morrone, D.; De Leo, F. The Water Footprint Assessment of Electricity Production: An Overview of the Economic-Water-Energy Nexus in Italy. *Sustainability* **2018**, *10*, 228. [CrossRef]
43. Comino, E.; Dominici, L.; Ambrogio, F.; Rosso, M. Mini-Hydro Power Plant for the Improvement of Urban Water-Energy Nexus toward Sustainability-A Case Study. *J. Clean. Prod.* **2020**, *249*, 119416. [CrossRef]
44. Oliveira, M.C.; Iten, M.; Matos, H.A.; Michels, J. Water–Energy Nexus in Typical Industrial Water Circuits. *Water* **2019**, *11*, 699. [CrossRef]
45. Moss, T.; Hüesker, F. Politicised Nexus Thinking in Practice: Integrating Urban Wastewater Utilities into Regional Energy Markets. *Urban Stud.* **2019**, *56*, 2225–2241. [CrossRef]
46. Mirzabaev, A.; Guta, D.; Goedecke, J.; Gaur, V.; Börner, J.; Virchow, D.; Denich, M.; von Braun, J. Bioenergy, Food Security and Poverty Reduction: Trade-Offs and Synergies along the Water–Energy–Food Security Nexus. In *Sustainability in the Water Energy Food Nexus*; Routledge: London, UK, 2018; pp. 60–78.
47. Bao, K.; Thrän, D.; Schröter, B. Simulation and Analysis of Urban Green Roofs with Photovoltaic in the Framework of Water-Energy Nexus. *CITIES* **2021**, 671–680.

48. Villamayor-Tomas, S. Polycentricity in the Water–Energy Nexus: A Comparison of Polycentric Governance Traits and Implications for Adaptive Capacity of Water User Associations in Spain. *Environ. Policy Gov.* **2018**, *28*, 252–268. [CrossRef]
49. Hardy, L.; Garrido, A.; Juana, L. Evaluation of Spain's Water-Energy Nexus. *Int. J. Water Resour. Dev.* **2012**, *28*, 151–170. [CrossRef]
50. Hardy, L.; Garrido, A.; Juana, L. Evaluation of Spain's Water-Energy Nexus. In *Water Policy and Management in Spain*; Routledge: London, UK, 2016; pp. 149–168.
51. Elena, G.-C.; Esther, V. From Water to Energy: The Virtual Water Content and Water Footprint of Biofuel Consumption in Spain. *Energy Policy* **2010**, *38*, 1345–1352. [CrossRef]
52. Stunjek, G.; Pfeifer, A.; Krajačić, G.; Duić, N. Analysis of the Water—Power Nexus of the Balkan Peninsula Power System. In *Proceedings of the Solar Energy Conversion in Communities: Proceedings of the Conference for Sustainable Energy (CSE) 2020*; Springer: Cham, Switzerland, 2020; pp. 235–257.
53. Al-Shaar, W.; Bonin, O.; de Gouvello, B.; Chatellier, P.; Hendel, M. Geographically Weighted Regression-Based Predictions of Water–Soil–Energy Nexus Solutions in Île-de-France. *Urban Sci.* **2022**, *6*, 81. [CrossRef]
54. Bonnet, J.F.; Lorne, D. Water Impact of French Biofuels Development at the 2030 Horizon. *Bioenergy Water* **2013**, 117.
55. Ziogou, I.; Zachariadis, T. Quantifying the Water–Energy Nexus in Greece. *Int. J. Sustain. Energy* **2017**, *36*, 972–982. [CrossRef]
56. Brouwer, F.; Vamvakeridou-Lyroudia, L.; Alexandri, E.; Bremere, I.; Griffey, M.; Linderhof, V. The Nexus Concept Integrating Energy and Resource Efficiency for Policy Assessments: A Comparative Approach from Three Cases. *Sustainability* **2018**, *10*, 4860. [CrossRef]
57. Wang, X.-C.; Klemeš, J.J.; Long, X.; Zhang, P.; Varbanov, P.S.; Fan, W.; Dong, X.; Wang, Y. Measuring the Environmental Performance of the EU27 from the Water-Energy-Carbon Nexus Perspective. *J. Clean. Prod.* **2020**, *265*, 121832. [CrossRef]
58. Neves, M.C.; Malmgren, K.; Neves, R.M. Climate-Driven Variability in the Context of the Water-Energy Nexus: A Case Study in Southern Portugal. *J. Clean. Prod.* **2021**, *320*, 128828. [CrossRef]
59. Ramos, H.M.; Morillo, J.G.; Diaz, J.A.R.; Carravetta, A.; McNabola, A. Sustainable Water-Energy Nexus towards Developing Countries' Water Sector Efficiency. *Energies* **2021**, *14*, 3525. [CrossRef]
60. Santos, C.; Taveira-Pinto, F.; Pereira, D.; Matos, C. Analysis of the Water–Energy Nexus of Treated Wastewater Reuse at a Municipal Scale. *Water* **2021**, *13*, 1911. [CrossRef]
61. Jorge, C.; Almeida, M.d.C.; Brito, R.S.; Covas, D. Water, Energy, and Emissions Nexus: Effect of Inflows in Urban Drainage Systems. *Water* **2022**, *14*, 868. [CrossRef]
62. Mamade, A.; Loureiro, D.; Alegre, H.; Covas, D. Top-down and Bottom-up Approaches for Water-Energy Balance in Portuguese Supply Systems. *Water* **2018**, *10*, 577. [CrossRef]
63. Pinto, A.; Afonso, A.S.; Santos, A.S.; Pimentel-Rodrigues, C.; Rodrigues, F. Nexus Water Energy for Hotel Sector Efficiency. *Energy Procedia* **2017**, *111*, 215–225. [CrossRef]
64. Tudose, N.C.; Cheval, S.; Ungurean, C.; Broekman, A.; Sanchez-Plaza, A.; Cremades, R.; Mitter, H.; Kropf, B.; Davidescu, S.O.; Dinca, L.; et al. Climate Services for Sustainable Resource Management: The Water—Energy—Land Nexus in the Tărlung River Basin (Romania). *Land Use Policy* **2022**, *119*, 106221. [CrossRef]
65. Robescu, L.D.; Bondrea, D.A. The Water Footprint from Hydroelectricity: A Case Study for a Hydropower Plant in Romania. *E3S Web Conf.* **2019**, *5*, 6012. [CrossRef]
66. Engström, R.E.; Howells, M.; Destouni, G. Water Impacts and Water-Climate Goal Conflicts of Local Energy Choices–Notes from a Swedish Perspective. *Proc. Int. Assoc. Hydrol. Sci.* **2018**, *376*, 25–33. [CrossRef]
67. Driscoll, F.G. *Groundwater and Wells*; Johnson Screens: St Paul, MN, USA, 1986; p. 1089.
68. Pinardi, R.; Feo, A.; Ruffini, A.; Celico, F. Purpose-Designed Hydrogeological Maps for Wide Interconnected Surface–Groundwater Systems: The Test Example of Parma Alluvial Aquifer and Taro River Basin (Northern Italy). *Hydrology* **2023**, *10*, 127. [CrossRef]
69. Pozzi ISPRA e Sito ISTAT. Available online: https://www.isprambiente.gov.it/it/banche-dati/banche-dati-folder/suolo-e-territorio/dati-geognostici-e-geofisici (accessed on 8 August 2024).
70. Hoseinie, S.H.; Ataei, M.; Mikaiel, R. Comparison of Some Rock Hardness Scales Applied in Drillability Studies. *Arab. J. Sci. Eng.* **2012**, *37*, 1451–1458. [CrossRef]
71. De Luca, D.A.; Destefanis, E.; Forno, M.G.; Lasagna, M.; Masciocco, L. The Genesis and the Hydrogeological Features of the Turin Po Plain Fontanili, Typical Lowland Springs in Northern Italy. *Bull. Eng. Geol. Environ.* **2014**, *73*, 409–427. [CrossRef]
72. Olsthoorn, T.N. *The Clogging of Recharge Wells, Main Subjects*; Keuringsinstituut voor Waterleiding Artikelen, KIWA, NV: Rijswijk, The Netherlands, 1982.
73. Kalwa, F.; Binder, M.; Händel, F.; Grüneberg, L.; Liedl, R. Biological and Physical Clogging in Infiltration Wells: Effects of Well Diameter and Gravel Pack. *Groundwater* **2021**, *59*, 819–828. [CrossRef]
74. Jeong, H.Y.; Jun, S.-C.; Cheon, J.-Y.; Park, M. A Review on Clogging Mechanisms and Managements in Aquifer Storage and Recovery (ASR) Applications. *Geosci. J.* **2018**, *22*, 667–679. [CrossRef]
75. Zanini, A.; Ghirardi, M.; Emiliani, R. A Multidisciplinary Approach to Evaluate the Effectiveness of Natural Attenuation at a Contaminated Site. *Hydrology* **2021**, *8*, 101. [CrossRef]
76. Zanini, A.; Petrella, E.; Sanangelantoni, A.M.; Angelo, L.; Ventosi, B.; Viani, L.; Rizzo, P.; Remelli, S.; Bartoli, M.; Bolpagni, R. Groundwater Characterization from an Ecological and Human Perspective: An Interdisciplinary Approach in the Functional Urban Area of Parma, Italy. *Rendiconti Lincei Scienze Fisiche e Naturali* **2019**, *30*, 93–108. [CrossRef]

77. Orecchia, C.; Giambastiani, B.M.S.; Greggio, N.; Campo, B.; Dinelli, E. Geochemical Characterization of Groundwater in the Confined and Unconfined Aquifers of the Northern Italy. *Appl. Sci.* **2022**, *12*, 7944. [CrossRef]
78. Fantoni, D.; Brozzo, G.; Canepa, M.; Cipolli, F.; Marini, L.; Ottonello, G.; Zuccolini, M. Natural Hexavalent Chromium in Groundwaters Interacting with Ophiolitic Rocks. *Environ. Geol.* **2002**, *42*, 871–882. [CrossRef]
79. Segadelli, S.; Filippini, M.; Monti, A.; Celico, F.; Gargini, A. Estimation of Recharge in Mountain Hard-Rock Aquifers Based on Discrete Spring Discharge Monitoring during Base-Flow Recession. *Hydrogeol. J.* **2021**, *29*, 949–961. [CrossRef]
80. Segadelli, S.; Vescovi, P.; Ogata, K.; Chelli, A.; Zanini, A.; Boschetti, T.; Petrella, E.; Toscani, L.; Gargini, A.; Celico, F. A Conceptual Hydrogeological Model of Ophiolitic Aquifers (Serpentinised Peridotite): The Test Example of Mt. Prinzera (Northern Italy). *Hydrol. Process.* **2017**, *31*, 1058–1073. [CrossRef]
81. Chelli, A.; Zanini, A.; Petrella, E.; Feo, A.; Celico, F. A Multidisciplinary Procedure to Evaluate and Optimize the Efficacy of Hydraulic Barriers in Contaminated Sites: A Case Study in Northern Italy. *Environ. Earth Sci.* **2018**, *77*, 246. [CrossRef]
82. Filippini, M.; Parker, B.L.; Dinelli, E.; Wanner, P.; Chapman, S.W.; Gargini, A. Assessing Aquitard Integrity in a Complex Aquifer–Aquitard System Contaminated by Chlorinated Hydrocarbons. *Water Res.* **2020**, *171*, 115388. [CrossRef] [PubMed]
83. Ciampi, P.; Esposito, C.; Petrangeli Papini, M. Hydrogeochemical Model Supporting the Remediation Strategy of a Highly Contaminated Industrial Site. *Water* **2019**, *11*, 1371. [CrossRef]
84. Severini, E.; Ducci, L.; Sutti, A.; Robottom, S.; Sutti, S.; Celico, F. River–Groundwater Interaction and Recharge Effects on Microplastics Contamination of Groundwater in Confined Alluvial Aquifers. *Water* **2022**, *14*, 1913. [CrossRef]
85. Severini, E.; Bartoli, M.; Pinardi, M.; Celico, F. Short-Term Effects of the EU Nitrate Directive Reintroduction: Reduced N Loads to River from an Alluvial Aquifer in Northern Italy. *Hydrology* **2022**, *9*, 44. [CrossRef]
86. Rotiroti, M.; Sacchi, E.; Caschetto, M.; Zanotti, C.; Fumagalli, L.; Biasibetti, M.; Bonomi, T.; Leoni, B. Groundwater and Surface Water Nitrate Pollution in an Intensively Irrigated System: Sources, Dynamics and Adaptation to Climate Change. *J. Hydrol.* **2023**, *623*, 129868. [CrossRef]
87. Ducci, L.; Rizzo, P.; Pinardi, R.; Solfrini, A.; Maggiali, A.; Pizzati, M.; Balsamo, F.; Celico, F. What Is the Impact of Leaky Sewers on Groundwater Contamination in Urban Semi-Confined Aquifers? A Test Study Related to Fecal Matter and Personal Care Products (PCPs). *Hydrology* **2022**, *10*, 3. [CrossRef]
88. Rapti-Caputo, D.; Vaccaro, C. Geochemical Evidences of Landfill Leachate in Groundwater. *Eng. Geol.* **2006**, *85*, 111–121. [CrossRef]
89. Meffe, R.; de Bustamante, I. Emerging Organic Contaminants in Surface Water and Groundwater: A First Overview of the Situation in Italy. *Sci. Total Environ.* **2014**, *481*, 280–295. [CrossRef]
90. Ducci, L.; Rizzo, P.; Bucci, A.; Pinardi, R.; Monaco, P.; Celico, F. The Challenge Posed by Emerging Environmental Contaminants: An Assessment of the Effectiveness of Phenoxyethanol Biological Removal from Groundwater through Mesocosm Experiments. *Sustainability* **2024**, *16*, 2183. [CrossRef]
91. Antonellini, M.; Mollema, P.; Giambastiani, B.; Bishop, K.; Caruso, L.; Minchio, A.; Pellegrini, L.; Sabia, M.; Ulazzi, E.; Gabbianelli, G. Salt Water Intrusion in the Coastal Aquifer of the Southern Po Plain, Italy. *Hydrogeol. J.* **2008**, *16*, 1541–1556. [CrossRef]
92. Vilanova, M.R.N.; Balestieri, J.A.P. Energy and Hydraulic Efficiency in Conventional Water Supply Systems. *Renew. Sustain. Energy Rev.* **2014**, *30*, 701–714. [CrossRef]
93. Coelho, B.; Andrade-Campos, A. Efficiency Achievement in Water Supply Systems—A Review. *Renew. Sustain. Energy Rev.* **2014**, *30*, 59–84. [CrossRef]
94. Petronici, F.; Pujades, E.; Jurado, A.; Marcaccio, M.; Borgatti, L. Numerical Modelling of the Mulino Delle Vene Aquifer (Northern Italy) as a Tool for Predicting the Hydrogeological System Behavior under Different Recharge Conditions. *Water* **2019**, *11*, 2505. [CrossRef]
95. Feo, A.; Pinardi, R.; Artoni, A.; Celico, F. Integrity of Fine-Grained Layers to DNAPL Migration in Multilayered Aquifers: Assessment in a Pce-Contaminated Alluvial System, Using High-Precision Simulations. *Ital. J. Eng. Geol. Environ.* **2024**, 127–134. [CrossRef]
96. Feo, A.; Pinardi, R.; Artoni, A.; Celico, F. Three-Dimensional High-Precision Numerical Simulations of Free-Product DNAPL Extraction in Potential Emergency Scenarios: A Test Study in a PCE-Contaminated Alluvial Aquifer (Parma, Northern Italy). *Sustainability* **2023**, *15*, 9166. [CrossRef]