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Implications of the Interrelations between the (Waste)Water Sector and Hydrogen Production for Arid Countries Using the Example of Jordan

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Abstract: In the energy sector, few topics, if any, are more hyped than hydrogen. Countries develop hydrogen strategies to provide a perspective for hydrogen production and use in order to meet climate-neutrality goals. However, in this topical field the role of water is less accentuated. Hence, in this study, we seek to map the interrelations between the water and wastewater sector on the one hand and the hydrogen sector on the other hand, before reflecting upon our findings in a country case study. We chose the Hashemite Kingdom of Jordan because (i) hydrogen is politically discussed not least due to its high potentials for solar PV, and (ii) Jordan is water stressed—definitely a bad precondition for water-splitting electrolyzers. This research is based on a project called the German-Jordanian Water-Hydrogen-Dialogue (GJWHD), which started with comprehensive desk research mostly to map the intersectoral relations and to scope the situation in Jordan. Then, we carried out two expert workshops in Wuppertal, Germany, and Amman, Jordan, in order to further discuss the nexus by inviting a diverse set of stakeholders. The mapping exercise shows various options for hydrogen production and opportunities for planning hydrogen projects in water-scarce contexts such as Jordan.

Keywords: hydrogen; water; wastewater; electrolysis; water scarcity; wastewater treatment plants; desalination; Jordan

Citation: Adisorn, T.; Venjakob, M.; Pössinger, J.; Ersoy, S.R.; Wagner, O.; Moser, R. Implications of the Interrelations between the (Waste)Water Sector and Hydrogen Production for Arid Countries Using the Example of Jordan. *Sustainability* **2023**, *15*, 5447. https://doi.org/10.3390/su15065447

Academic Editors: Oz Sahin and Russell Richards

Received: 3 February 2023
Revised: 10 March 2023
Accepted: 15 March 2023
Published: 20 March 2023

1. Introduction

This paper is based on input given at the SDEWES conference in 2022 [1].

The European Union and its Member States such as Germany have set ambitious goals for the decarbonization of their economy, their buildings, their transport, and their society as a whole [2,3]. In order to achieve these goals, governments rely heavily on climate-neutral or green hydrogen [4–6], whose production routes emit substantially less CO_2 into the atmosphere compared with the conventional production of hydrogen [7].

Today, approximately 100 megatons of such conventional hydrogen are produced worldwide associated with significant carbon dioxide (CO_2) emissions of approximately 100 megatons [8–10]. It is used in ammonia and methanol production or in refineries [10]. A substantial amount is produced from natural gas (or methane, CH_4) using steam reforming and water–gas shift processes [8,11] consuming approximately 6% of global natural gas use [8,9]. Even though hydrogen is a colorless gas, the political debate has labeled this type of hydrogen as "gray" [7,12]. Germany produces 60 TWh or 1.8 megatons of hydrogen, most of which is emission-intensive [9]. If CO_2 from reforming CH_4 is captured, stored, or utilized, "blue" hydrogen is harvested. If CH_4 is pyrolyzed, the resulting products are solid carbon and "turquoise" hydrogen. From a climate perspective, high hopes rest upon electrolysis, which splits water (H_2O) into hydrogen and oxygen (O_2). According to the Wuppertal Institute and DIW Econ, 5% of the hydrogen produced in Germany comes from electrolysis using water as a feedstock [13]; the global share is only 0.1% [8]. It is noteworthy that (sustainable) biomass including waste resources can also become part of the hydrogen economy through specific technologies/processes (e.g., thermochemical approaches, gasification, reformation, pyrolysis) [14,15].

As electrolyzers run on electricity, it is important to focus on electricity-related CO_2 emissions and, thus, how electricity is produced. If electricity comes from the grid or is from nuclear power stations, H_2O-based hydrogen is yellow or pink. If electricity is from renewables, electrolysis products are labeled as green [7,12]. The three main types of electrolyzer technologies differ, for instance, in technological maturity, costs, energy inputs, and efficiencies [8,13,14,16].

One of the great advantages is that hydrogen can be used in a variety of ways: in stationary or mobile fuel cells for producing electricity (and heat), to store excess electricity, or to manufacture steel [7,14,17–20]. Further processing hydrogen into other products (e.g., methane, kerosine, diesel, methanol, or ammonia) requires additional processes and technologies [7,18,21,22].

However, this flexible applicability in combination with its potential to reduce emissions creates a large interest in hydrogen in sectors that traditionally use hydrogen (e.g., chemistry, refineries) as well as in new sectors. These are, for example, the steel industry and transport, including air traffic. The growing interest of these sectors increases the expected global demand for hydrogen [5,12,20,23,24]. For them, low-carbon hydrogen is seen as a central option to become climate-neutral [7,22,25]. Moreover, in the energy sector, natural gas combustion plants can be retrofitted to use hydrogen for electricity generation. There are also proponents arguing for using hydrogen in other sectors such as heating in buildings [26]; however, direct electrification is almost always the (much) more efficient option [27,28]. Given this new demand for hydrogen, it is important that hydrogen production pathways help to tackle what Johan Rockström calls our planetary crisis [5,7,29].

Germany, for instance, will not be able to produce sufficient amounts of hydrogen on its own to serve domestic demand; henceforth, the country will rely on imports [5,7,13]. A key limiting factor in Germany (and other countries) is space restrictions for installing sufficient capacities of renewable energies in combination with less benign renewable potentials [7]. However, there are parts of the world where such constraints do not play a role, including countries in the Middle East and North Africa (MENA), which "receives 22–26% of all solar energy striking the earth" [30]. The MENA countries can be considered an attractive partner for Europe and Germany given their proximity, so that imports via ships or even pipelines are possible at (rather) lower costs while also offering opportunities for socio-economic development in the MENA countries [31].

However, despite the abundant potential of renewable energy resources in the MENA region, there is a substantial resource constraint: water. Research to address the immense water demand for green hydrogen production in water-scarce, arid regions is very limited. Potential hydrogen importing countries such as Germany do not have this problem (so far) and often underestimate the situation in potential exporting countries [32]. Jordan, for instance, belongs to those countries with the highest water stress in the world [33,34]. Structural issues such as poor planning as well as pressing dynamics including the intake of refugees and climate change exacerbate the situation [33,35,36]. Still, discussions about a future hydrogen economy in Jordan are taking off [37–39].

In the German context especially, energy-related challenges and potentials associated with hydrogen production have often been discussed from various angles [5,8,18,19,40–45]. For instance, hydrogen production and further downstream processes are energy-intensive and, thus, associated with energy losses [19]. In contrast, the debate on environmental impacts and the role of water is less advanced even though more and more publications focus on socio-ecological concerns. They aim to inform about unintended side effects that might occur, especially if hydrogen production is triggered by external actors including other European countries [7,46,47]. There are niche concerns about a global hydrogen uptake, in general, and hydrogen leakage, in particular, whereby reducing the availability of hydroxyl radicals in the atmosphere and increasing the lifespan of atmospheric methane [48,49]. Studies addressing water in the context of hydrogen often focus on water demand issues for electrolyzers [50–54] or other hydrogen processes [55–57]. The role of wastewater has been touched upon only very recently, especially by research from Australia [55,58–60]. However, German research has also investigated the different options of hydrogen production at wastewater treatment plants (WWTPs) [61–64]. Then, very often, the question is raised about how electrolysis-based oxygen can be used in wastewater treatment processes to also reduce the overall OPEX [58,63,64]. Although limited, just as important are the studies that investigate the water demand for equipment production and for the operation of auxiliary technologies, such as photovoltaic, to produce electricity to run electrolyzers or similar technologies [65,66]. Apart from the water needs for hydrogen production, there are studies that work on water recovery mostly when hydrogen is used in fuel cells [67–70]. It is noteworthy that Germany's Water Strategy acknowledges the impact of hydrogen on water resources seeking to establish safeguards to prevent negative effects on water [71].

This indicates that there is a limited number of publications on very specific relations between water and hydrogen production and that a systematic overview has been lacking thus far. Hence, the authors seek to systematically bring together and highlight the different relationships between the two sectors. Even though some innovative ideas such as the use of electrolysis-based oxygen for wastewater treatment were only tested in small-scale projects, it helped to structure and facilitate the discussion around hydrogen with stakeholders from Jordan to identify opportunities and challenges associated with hydrogen production in arid country contexts.

The paper builds on the assumptions that relevant relationships exist between the water and hydrogen sectors. It is generally assumed that water is used as the basis for green hydrogen. It can also be assumed that in arid countries there may be complications with hydrogen production, as fresh water is needed.

After this introduction and an insight into our methodology (Section 2), the first part of our results section (Section 3.1) compiles and structures the various threads of water-related hydrogen research. The second part of our results section (Section 3.2) will then tilt towards the case of Jordan, where we discuss the different connections between the water and wastewater sector on the one hand and the hydrogen sector on the other hand. Finally, a discussion (Section 4) is followed by concluding remarks (Section 5).

This paper is based on the project GJWHD—German-Jordanian Water-Hydrogen-Dialogue, funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) through the Export Initiative Environmental Technologies (EXI) [72]. We wish to express our gratitude for the funding of our project and would like to express our thanks to all the stakeholders involved in the GJWHD project. We also acknowledge financial support by Wuppertal Institut für Klima, Umwelt, Energie gGmbH within the funding programme Open Access Publishing.

2. Materials and Methods

As mentioned previously, this paper seeks initially to unveil the different threads of water-related hydrogen research and identify interconnections between the water and wastewater sector on the one hand and the hydrogen sector on the other hand. These findings will then be discussed for the case of Jordan, where policy makers are interested in developing the topic further despite the country's severe water restrictions.

In order to find answers to the research objectives, we applied two methods: (i) desk research, which was also a central preparatory step for (ii) two expert workshops conducted in Germany and Jordan.

The screening of the existing literature was firstly and predominantly used for identifying the interrelations between water, wastewater, and hydrogen. Secondly, the literature also helped to scope the situation in Jordan for the three individual sectors. Hence, in our search for information, we included scientific articles as well as gray literature. For the

German case, gray literature was mostly on recent or ongoing projects seeking to implement new technologies or processes. Media releases were also factored in, especially to learn about the latest developments in Jordan. Moreover, energy-related research projects funded by Federal Ministries in Germany are listed in a database called ENARGUS, which was also accessed for this project [73].

The screening of the literature, then, helped to structure and organize the two workshops and to identify relevant stakeholders as speakers and participants from the water, wastewater, energy, and hydrogen sectors. The overall aim of both workshops was to deliver knowledge to Jordanian and German stakeholders not only on the intersectoral relations between water, wastewater, and hydrogen but also on country-specific conditions. Within the framework of the German-Jordanian expert workshops, a community-based participatory research approach was chosen and carried out. The goal was to iteratively develop transferable and usable innovations in the water–hydrogen nexus. Experts from both countries were involved. The study design of the workshops is described in detail below.

2.1. Study Design of the Workshops

Methodologically, the study design followed the 4P framework of Gray et al. [74], as it has been used successfully in other nexus analyses [75]. The four Ps of the framework are: Purpose, processes, partnerships, and products. The 4P approach draws on frameworks identified in the literature that improve the practice of participatory processes [74]. It captures the essential questions starting with why, how, who, and what in a structured way.

- The purpose refers to the involvement of the different disciplines of energy, hydrogen, water, and wastewater of the two countries. The Why results from the necessity: It was necessary to be able to illuminate the problem from the different perspectives and to enable mutual problem awareness. This was the basis for the second P: partnerships.
- Partnerships describe the Who and include aspects of incorporating country-specific problems and approaches to solutions. The conceptualization of the workshops therefore involved careful selection of workshop participants based on their expertise.
- The process outlines How the dialogue process was conducted, its scope, and its objectives. Geographical specifics, technical capabilities, and cultural characteristics had to be taken into account.
- Products clarify the What and are outcomes, both in terms of technical solutions and social outcomes (e.g., in terms of the political regulatory framework or in terms of specific management tasks). Products can thus refer to the complete socio-technical regime [76].

2.1.1. Purpose

The aim of the workshops was to enable a practical networking of knowledge carriers and technology providers from Germany to support Jordanian stakeholders. The aim was to identify solution spaces for a sustainable use of the resource water in the context of current and future challenges. The overall objective of the project was to transfer experiences from the German wastewater sector to relevant Jordanian stakeholders.

2.1.2. Partnerships

The partnership, i.e., the selection of the experts involved, required an intensive research process in both countries. Here, on the one hand, the excellent networks of the Friedrich-Ebert-Stiftung in Jordan could be used, which had already led to the identification of important actors in a previous project. On the other hand, intensive research was required into technical solutions that have proven themselves in municipal practice. To this end, intensive preliminary discussions were held with associations. The German Association of Local Public Utilities was very helpful in identifying solutions that had been tried and tested in practice.

The network of stakeholders included academic, public, and non-profit partners with expertise in energy, water, and wastewater in urban as well as in rural areas. Some participants also had expertise in transportation, economics, and policy. Jordanian parliamentarians were also involved in the discussion process at times. The participants work almost equally in Germany and in Jordan.

2.1.3. Process

Two workshops lasting several days were held in Jordan and in Germany, framed by side events, excursions to technical facilities, and various expert inputs. The workshops themselves were intensively prepared and planned. The inputs and the visits to technical facilities required a detailed schedule. Interpreters were present throughout the program to minimize language barriers.

2.1.4. Products

The technical solutions visited during the excursions and the aspects of the regulatory framework, i.e., the laws and regulations in both countries, dealt with during the discussions can be described as products.

2.2. Organization of the Workshops

In line with the system described above, the workshops were organized as follows: The first workshop was held in Wuppertal, Germany, from 26 to 30 September 2022. Participants from Jordan came from the Jordan Valley Authority (JVA) under the Ministry of Water and Irrigation (MWI), the water and wastewater services sector in the Jordanian city of Aqaba, the Ministry of Energy and Mineral Resources (MEMR), and the National Electric Power Company (NEPCO), as well as from EDAMA, a Jordanian business association. For instance, the agenda included presentations by speakers from the Wuppertal Institute for Climate, Environment and Energy, the German Association of Local Public Municipalities, the water supplier of the city of Sonneberg, the Association of Machinery and Plant Engineering (VDMA), the National Organization of the Hydrogen and Fuel Cell Technology (NOW), and technology providers such as GRAFORCE. Field trips to wastewater treatment plants and hydrogen production sites were used to illustrate applied knowledge on the nexus.

The second workshop in Amman, Jordan, was held from 24 to 27 October 2022 and was supported by substantial efforts of the Jordanian Office of the Friedrich-Ebert-Stiftung. The delegation from Germany not only included representatives from academia such as the Wuppertal Institute, the Fraunhofer UMSICHT, the University of Applied Sciences in Saarbrücken, SRH University Heidelberg, and the German Institute of Development and Sustainability (IDOS) but also from Lower Saxony's Hydrogen Network and the Municipal Utility of the City of Aschaffenburg. Presentations from Jordanian stakeholders were given, for instance, by JVA, MEMR, NEPCO, EDAMA, the city of Aqaba's water and wastewater supplier, the Ministry of Transportation (MoT), and the Royal Scientific Society (RSS). In addition, researchers from the German-Jordanian University (GJU), the University of Jordan (UJ), and the Jordan University of Science and Technology (JUST) took part. In addition, representatives from the German Gesellschaft für Internationale Zusammenarbeit (GIZ) also participated in the workshop and provided interesting insights into the wastewater situation or the water–energy nexus in the country. In addition to presentations with discussions and a field trip to the WWTP close to the city of Irbid, interactive sessions were conducted based on the 6-3-5 brainwriting method [77]. For these sessions, we asked (i) what impacts need to be realized or avoided in a future Jordanian hydrogen economy and (ii) what steps are necessary to realize a sustainable future hydrogen economy in the country?

If putting it schematically, the workshop in Germany rather focused on the various connections between the three sectors of water, wastewater, and hydrogen, whereas the workshop in Jordan focused on the nexus' implications in Jordan. In real life, however, the participants from Jordan, especially, were asked to reflect upon their home country's situation in discussions immediately after presentations or field trips. Hence, the content of the discussions was very fluid. Given that the stakeholders were deliberately chosen from different sectors, the discussions were rich in content and seen as an important benefit of the project and workshops.

3. Results

3.1. Mapping Water- and Wastewater-Related Hydrogen Issues

3.1.1. Water as an Input for Electrolysis-Based Hydrogen

Hydrogen production through electrolysis (but also other hydrogen processes) requires demineralized water. For instance, the stoichiometric minimum requirement for the generation of 1 kgH_2 is 8.92 L of water [10,56,57,78].

However, water quality, cooling demand, and process losses also need to be taken into account. Already in the 2000s, Barbir reflected upon the advantages of a PEMEL in combination with variable renewable energy sources. As regards the stoichiometric water consumption, he found that the actual water consumption is about 25% higher due to process losses [51]. Later, Mehmeti et al. not only assessed the water footprint of different hydrogen production pathways including a PEMEL and a SOEC but also biomass gasification, reforming, and dark fermentation. Based on the available literature, he found water consumption for electrolysis to be between 9.1 kg/kgH_2 (SOEC) and 18.04 kg/kgH_2 (PEMEL), while hydrogen from biomass had a significantly higher water footprint [52]. Others state that it takes up to 30 L of water to produce 1 kg of hydrogen [53,54,58].

Saulnier et al. compared the water demand for available electrolyzers advertised on the market to be between 10 L/kgH_2 and 11.1 L/kgH_2. Due to the additional water demand needed to purify surface or tap water to deionized water, total water demand was assumed to be at approximately 15.5 L/kgH_2. In their paper, the authors conducted a thought experiment on how much water would be needed if 20% of the natural gas consumption in the Canadian province of Alberta would be substituted with hydrogen on an "equivalent energy basis". They found a daily water demand of 134,000 m^3 for hydrogen through electrolysis, whereas methane reforming would require 114,000 m^3 of water. The authors reflected upon the water situation in Alberta and believed that an expanded hydrogen production would be in conflict with the agricultural sector responsible for 67% of water consumption in the province. Moreover, in some parts of the region, the availability of surface water is negatively affected by climate change and permission for water extraction has been stopped since 2007 [79].

A substantially higher water demand for electrolysis-based hydrogen is provided by Coertzen et al. They expect the total water demand to be somewhere between 60 to 95 L/kgH_2 assuming, for instance, that 30 to 40 L of water is needed for cooling needs. Those estimates may increase due to a higher cooling demand during the lifetime of electrolyzer stacks. In a comparative perspective, Coertzen et al. show that, in order to produce other "colors" of hydrogen, both the stoichiometric water needs and the total water needs for, i.e., process cooling, are significantly lower for hydrogen production processes relying on natural gas as a feedstock [55].

Apart from fresh water, seawater may constitute another type of water from which to produce hydrogen. However, state-of-the-art electrolyzers would require auxiliary processes to desalinate seawater. Even though costs for operating a seawater desalination plant might be neglectable, desalination is an energy-intensive process and, based on today's electricity mixes, would increase emissions [50].

In a demonstration project called H2-Mare, several companies, including Siemens Gamesa, Siemens Energy, and ThyssenKrupp, seek to build an offshore wind turbine integrating an offshore electrolyzer. Green hydrogen will come from a PEMEL due to its quick start-up times. The facility will be without external power supply, which is why power consumption is sought to be reduced as much as possible. This also affects the seawater desalination process needed for purifying the water feedstock [80].

In contrast to H2-sMare, Tong et al. investigate opportunities for electrolysis with low-grade water, including seawater. While seawater is abundantly available, the authors highlight the downsides of desalination and purification processes adding investment and operational costs to the end product (hydrogen), which, in the longer run, could be avoided. In their paper, they review most recent developments in electrode materials or catalysts for electrolysis with saline and low-grade water [81]. Generally, seawater electrolysis has a relatively low technology readiness level, in part due to the problems caused by chloride corrosion [23,82]. However, Chinese researchers announced that they successfully operated a demonstrator to run for 3200 h [83].

Wastewater treatment plants (WWTPs) are considered to provide opportunities, especially for decentral hydrogen production in Germany [15]. Given that electrolyzers need highly purified water to protect the system from breakdown, using incoming wastewater will not be an option any time in the near future. However, according to Jacobs and Yarra Valley Water, treated or recycled wastewater combined with processes to purify the (already) treated wastewater further has several advantages. These advantages include consistent water supplies and less competition with domestic or industrial water needs as recycled water is normally discharged into the environment [58,84]. In Germany, a few electrolysis projects, mostly in a research and development stage, have been realized at WWTPs. Already in 2002/03, a PEMEL was installed at the WWTP Barth together with a PV system to run the electrolyzer. A more recent project was realized at the WWTP in the city of Sonneberg [85]. Apart from Australia and Germany, there are similar projects completed in the U. S. or in Oman [86,87].

3.1.2. Other Feedstocks from the Wastewater Sector for Hydrogen Production

Apart from H_2O, other feedstocks exist in the wastewater sector from which hydrogen can be produced. As regards sewage sludge, one can differentiate between thermochemical processes (e.g., pyrolysis, gasification) and biological processes (e.g., dark fermentation, photo-fermentation) to be applied for hydrogen production [64,88]. As of 2019, Liu et al. found that, generally, reaction rates are faster for thermochemical processes, resulting in higher hydrogen yields [60]. Researchers of the Sludge2P project aim at developing a novel process concept in which dried sewage sludge is processed into a product gas and a usable fertilizer. In the process, hydrogen is to be separated from the product gas. The remaining residual gas is used to heat the melting reactor. All process stages are considered to be, in principle, suitable for onsite operation by the WWTP operators; as a result, energy self-sufficiency can be achieved to a large extent [89]. Similar developments on hydrogen generation from wastewater sludge can also be found in Ukraine [90].

Another feedstock can be concentrated ammonium (NH_4) resulting from dewatering sewage sludge. Through plasmalysis, the German company GRAFORCE enables the recovery of hydrogen and other gases including, e.g., nitrogen or CH_4, which can then be stored individually. The overall advantage of this pathway is that water does not have to be purified; however, the concentration of NH_4 does have to be relatively high. Other products are (waste) heat and water with low NH_4 content. The energy demand is lower compared with electrolysis because the nitrogen–hydrogen bond is "looser" compared with water molecules. There are four hydrogen atoms per ammonium ion compared with two hydrogen atoms per water molecule [91,92].

Another innovative process is currently being developed at the Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT. Researchers have developed an electrochemical cleaning process for industrial wastewater using diamond electrodes. The novel approach is energy-intensive but is considered to be interesting for companies that produce electricity onsite; excess electricity could feed the cleaning process. In the cleaning process, a syngas is produced containing hydrogen with a share of up 60%. Researchers see an opportunity in applying this highly innovative water cleaning process in certain industries (e.g., in refineries for desulfurization of petroleum products by hydrogenation) [62].

Another hydrogen-based product is methanol (CH_3OH), which was produced at a WWTP in Dinslaken, Germany, in a research project. While biogas is often used in CHP at German WWTPs to deliver both electricity and heat for relevant processes, researchers converted biogas from the WWTP through methanol synthesis. Hydrogen was delivered through electrolysis. In particular, they assumed that it may make economic sense to produce an energy carrier, which is easy to store and transport, particularly in summer when there is excess grid electricity and minimal heat demand at WWTPs [61,93].

3.1.3. Water Needs for Operating Auxiliary Technologies

For producing hydrogen and green hydrogen, in particular, the technology set up will not only include electrolyzers but also auxiliary technologies including, for instance, power generation units running not only hydrogen processes but water-related processes as well (e.g., water desalination, pumping). In a project for the MENA region, researchers collected data on the water demand of renewable energy power plants [65]. For instance, electricity production through solar PV needs water for frequently cleaning the modules (from 0.01 m^3/MWh up to 0.1 m^3/MWh). However, in their study, the authors assume a higher water demand of 0.4 m^3/MWh for electricity production by solar PV in the MENA region, as high dust levels in the area would lead to significantly lower efficiencies. Others combine in their analysis the gross water demand of PV modules (1.500 h/a) with a PEMEL and expect a water demand of 19.1 L/kgH_2 [57]. Apart from solar PV, thermal concentrated solar power (CSP) plants also need water for cooling. While CSP plants lead to the highest energy generation, solar energy uses the least water, if PV technology is applied. Especially in regions with water scarcity, implementation of additional solar power plants can lead to further conflicts with other uses of water, such as agriculture [94]. For wind power combined with a PEMEL, a gross water demand of 11.0 L/kgH_2 is estimated. Pink hydrogen, based on nuclear electricity, "uses about 270 kg of cooling water per kg of hydrogen" [65]. Given these differences, decision makers should carefully choose between the different electricity generation options.

3.1.4. The Role of Water in Downstream and Co-Processes

There are several downstream processes to make use of hydrogen to produce ammonia or methanol. It was found that certain synthesis processes (e.g., methanization, Fischer–Tropsch synthesis) produce water as a byproduct [65]. However, it is unknown how this water can be used further.

A representative from the HTW Saar (Germany), who developed a process called bio-energy storage (BEST), explained that BEST does not only produce snythetic methane by using hydrogen from electrolysis and CO_2 from wastewater processes but also water as a by-product. He argued at the expert workshop that such water could be recovered and fed into the electrolyzers (even though purification will have to take place) [1].

Direct air capture (DAC) is a technology suitable for hydrogen-based products relying on CO_2 as an additional feedstock. DAC technology uses ambient air and filters CO_2, which can then be forwarded to Fischer–Tropsch synthesis or methanol production. While state-of-the-art DAC may need up to 50 t of water/tCO_2, recent developments promise up to 2 t of water can be extracted per tCO_2 [7]. Depending on the ambient air and humidity, other researchers point to processes that need approximately 4.7 l/tCO_2 [65].

Industrial point sources (including cement plants) could be an alternative source for producing CO_2 through carbon capture and use (CCU) for producing synthetic diesel or kerosene, for instance. However, the water demand is considered to be very high. Capturing CO_2 at power plants was found to result in an increasing water demand of 40% to 90%.

3.1.5. Indirect Water Needs for Equipment Production

Shi, Liao & Li assessed the impact of hydrogen production on water. Their paper establishes an approach to identify water footprints of hydrogen production from electrolysis factoring in "the geographical distribution of the footprints along the supply chain" and different types of electricity to run the electrolyzers. The authors find that hydrogen produced with Australian grid electricity has the highest water footprint compared with solar PV and wind. Since the PV panels were assumed to be built in China, which is associated with water demand, the largest proportion of water for Australian hydrogen is considered to be used in the Asian country. For grid electricity, the water is consumed locally. For the Australian case, the authors conclude that grid electricity is less an option from a water perspective [66].

3.1.6. End-Uses of Hydrogen and Hydrogen-Related Products

The use of hydrogen, in fact, offers the potential to recover water, e.g., used in fuel cells, for which there are mobile and stationary applications. In 2011, researchers found for a PEM- and molten carbonate fuel cell "approximately 8% of the theoretical amount of water generated" without any additional condensing system, even though a recovery rate of 40% would be necessary to serve the water needs of a typical U. S. American household [68]. Since then, several studies have been carried out verifying water recovery opportunities, even though recovery rates could theoretically be further improved [70]. Apart from hydrogen fuel cells, there are also fuel cells using methanol (DMFC). Apart from methanol and ambient oxygen, water is needed at the anode and produced at the cathode. In total, its water balance is considered to be positive [95]. Water recovery for drinking purposes has already taken place in aerospace [96].

3.1.7. Benefits of Hydrogen and Its By-Products Applied in the Water and Wastewater Sectors

In water supply services, hydrogen can be used to denitrify drinking groundwater. Fertilizers used in agriculture and transported to plants and soils may also pollute waters, which then have to be denitrified. For instance, water pollution with NH_3 takes place where groundwater resources—responsible for approximately 70% of Germany's potable water supply—are below intensively cultivated areas (e.g., for vegetables). In Germany, 27% of Germany's groundwater bodies exceed maximum thresholds of 50 mg nitrate/l. Such thresholds exist at the EU level because nitrogen can ultimately lead to limited oxygen uptake in infants between three and six months of age [97]. Groundwater resources can be treated biologically through autotrophic denitrification using hydrogen, which is an alternative to the heterotrophic path mostly applied to eliminate nitrogen [98]. For autotrophic denitrification of groundwater resources and potable water supply, the municipal public utility in the city of Aschaffenburg, for example, needs approximately 30 t of hydrogen per year. As of today, this is natural gas-based hydrogen, but the utility is planning for green hydrogen instead [99,100].

Apart from fresh water, wastewaters may include high loads of nitrate. Methanol, a hydrogen-based product, can and is used to denitrify wastewaters [101].

Apart from the role of hydrogen and derivates, oxygen as a by-product of electrolysis can also be used at WWTPs. In Germany, the WWTP in the city of Barth tested the use of pure oxygen in aeration tanks to deal with increased wastewater loads resulting from new camping grounds in the area [63]. In the project LocalHy, a small-scale test-WWTP was set up together with a PEMEL on a site of an operational WWTP in Sonneberg. Again, the focus was on making use of oxygen for wastewater treatment in the biological treatment stage [85]. Biological wastewater treatment consumes substantial electricity as turbo blowers need to blow ambient air into the aeration tank. As ambient air consists only of 21% oxygen, pure electrolysis-based oxygen could substitute for turbo blowers, at least partly. Electrolysis-based oxygen could also be further processed into ozone (O_3). In particular, for more advanced WWTP contexts, ozonation allows elimination of very specific pollutants. Ozonation in the context of WWTPs belongs to the so-called fourth treatment stage [102].

Waste heat of the hydrogen production process can also be made use of. For instance, electrolyzers produce waste heat, which students from Sweden analyzed for district heating [103]. In Germany, especially, the fouling for producing foul gas at WWTPs has a heat demand, which is currently often met by combined heat and power (CHP) [104].

3.1.8. Water-Related Impacts

In order to mitigate the impact of green hydrogen production, the German Advisory Council on the Environment recommends safeguards so that hydrogen production does not compete with other sectors such as agriculture/food security and with the well-being of the local population. Water-related safeguards could include that electrolyzers must not be built in areas with decreasing (ground)water levels and must not negatively affect local water supplies. As regards seawater desalination, the authors point to the risk that saline brine may destroy the coastal and maritime ecosystems and biodiversity if returned to the sea without any further measures [7]. Moreover, chemicals and metals may be in the discharge stream of desalination plants. Altgelt et al. point to zero-liquid-discharge technologies adding only little in costs [50].

According to the World Bank, hydrogen production will have to be accompanied by infrastructure works depending on how and where hydrogen is produced and consumed. Whether new roads, pipelines, or terminals are to be developed needs careful consideration factoring in environmental and social impacts including water-related effects. With respect to water, it is essential to analyze the impacts of large(r)-scaled hydrogen production on water availability and additional water infrastructure needs. This may include the modernization of the existing water network as well as its expansion. Authors also acknowledge that such additions come at a cost, and it needs to be clarified who pays for such investments [53]. Potentially, hydrogen production could result in an overall improvement of water supply in a region, if, for instance, inefficiencies (leaks) are tackled [7].

Depending on the energy situation of countries, the German Advisory Council on the Environment notes that water consumption could even decrease if conventional energy production and processing is substituted by green hydrogen production. In this respect, the authors mention the high water demand of coal and gas extraction and power plants [7]. Saulnier et al. also refer to factoring in water savings resulting from demand reductions in other sectors [79]. However, one needs to scrutinize the local peculiarities as water savings in one region are not automatically beneficial to other regions due to the distributional characteristics of water resources. Figure 1 summarizes the water needs and role of hydrogen and related products in the water and wastewater sector.

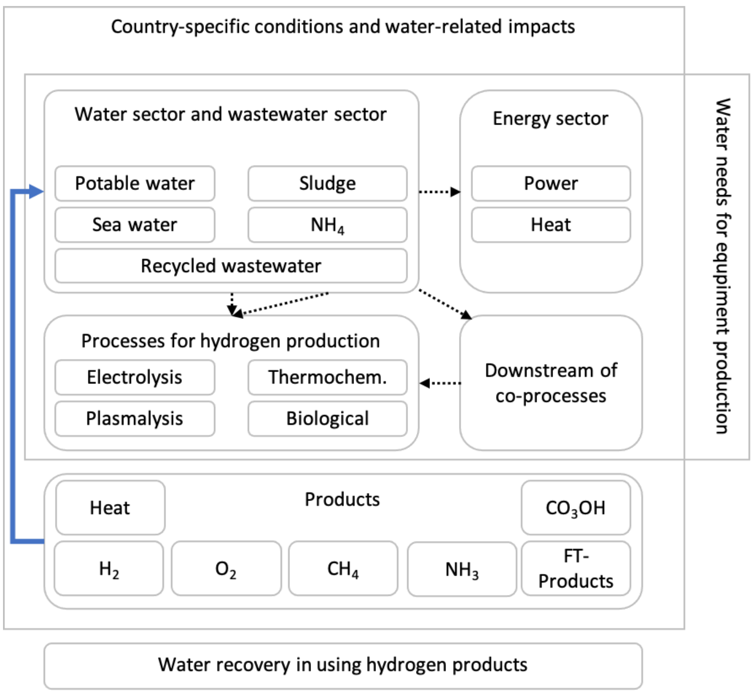

Figure 1. Schematic overview of the water–hydrogen nexus focusing on water needs (black arrows) and the role of hydrogen and related products in the water and wastewater sector (blue bold arrow).

3.2. Transferring Results to the Case of Jordan

Renewable water resources, which include "groundwater aquifers and surface water like rivers and lakes" [105], were 937 million m^3/year in 2014. Groundwater reserves totaled 540 million m^3, distributed among twelve aquifers of which the Disi aquifer is the largest. While the Jafer aquifer has both renewable and non-renewable water resources, key renewable groundwater resources are mainly located in the Yarmouk, Amman-Zarqa, and Dead Sea basins. Even though the safe yield of them is at 275.5 million m^3/year, static groundwater level drops between 1–20 m annually. Water scarcity is and will be a challenge for economic development of the country. Intense drought events were registered, for instance, in the years 2005, 2007, 2008, 2010, and 2011 [34]. Water stress is considered to have increased due to the influx of refugees, while so-called non-revenue water (NRW) has remained a problem for years. NRW is not billed either because its lost due to leakages/inefficient water networks or due to illegal connections [106]. In the end, feedback from the expert workshops was that fresh water resources must definitely not be used for hydrogen production.

Water use in Jordan is met by groundwater (52%), surface water (30%), and wastewater (17%). The dominant users are the agricultural sector (51%) and households (45%), followed by industry (4%). While being the major water consumer, agriculture only generates 3% to 4% of Jordan's GDP. The overwhelming amount of treated wastewater is facilitated to the agricultural sector, even though it needs further subtantial resources also from groundwater and surface water [107,108]. As treated wastewater is already re-used by approximately 90%, using this type of unconventional water resource for hydrogen production appears to be problematic due to tradeoffs with agricultural production. However, Jordan's population is growing and expected to rise by 24% by 2040 from 9.5 million to almost 12 million people [109], and the number of people connected to the sewage system is intended to increase from 63% to 80% between 2014 and 2030 [106]. These prospects would increase wastewater loads and, hence, additonal recycled water. This could be an opportunity to investigate the future use of recycled wastewaters for electrolyzers as well as of oxygen in Jordanian WWTPs.

Hence, the option to use desalinated water was brought up by participants of the expert workshops. In fact, Jordan has already initated plans together with USAID for a large-scale desalination plant at the Gulf of Aqaba. The project is expected to produce approximately 300 million m^3 of desalinated drinking water per year, of which 250 million m^3 will be supplied to Amman and other regions. The remaining 50 million m^3 is still to be decided or can be sold by the operator. The build-up of renewable energies for powering the plant, which will likely also require additional water, will have to be considered by the developer [110,111]. If used completely for the purposes of electrolysis, substantial amounts of hydrogen could be produced. However, participants voiced concerns that 250 million m^3 of additonal drinking water may not be enough to meet even today's demand sustainably. In the end, hydrogen production may fuel water conflicts.

The application of alternative pathways to hydrogen production through feedstocks provided by WWTPs (slugde, NH_4) was further discussed. For instance, even for (rather low-tech) CHPs at Jordanian WWTPs, it is difficult to have service personnel or operators to repair respective plants in time. This example, which can be transferred to all types of hydrogen processes, stresses the importance of having operation and maintenance staff trained to safeguard continous hydrogen production flows. Furthermore, 29 Jordanian WWTPs produce approximately 150,000 m^3 of semi-dry sludge and 357,000 m^3 of liquid sludge annually. According to GIZ, most of this sludge is stored onsite or is transported to unsanitary landfills, which, in turn, do not only produce emissions but also become a problem for groundwater resources [112]. In how far hydrogen produced from sewage sludge could offer a solution to this problem may deserve attention.

As regards the production of sufficient electricity, Jordan is home to solar-PV module producers. Given that Shi et al. voice concerns over water consumption associated with the production of solar-PV modules [66], new demand for renewable energies could also result in additional water demand by the solar-PV industry in Jordan. However, the experts argued that the number of PV panels, which are imported, is substantial, so that the domestic water demand for auxilliary technologies is and will be limited.

The application of hydrogen, especially, was discussed more concretely for the industry and the energy sector. For ammonia, being the 78th most imported product in Jordan, Saffouri (2022) explained that the country is the 27th largest importer of ammonia. In 2020, ammonia worth USD 56 million was imported. Domestic production of ammonia would reduce imports and increase domestic value creation [113]. In the energy sector, hydrogen could be an option to store excess electricity, which is an opportunity to further expand renewables without curtailment [114]. However, current projects to increase electricity system flexility focuses on battery energy storage and pumped storage facilities [115]. Even though Jordan produced almost 16,000 GWh of electricity from natural gas [116], the retrofitting of the existing plants has not been considerd in Jordan yet.

Regarding the next steps for a future hydrogen economy in Jordan, stakeholders highlighted the role of both pilot projects and capacity development. Given the good research conditions including GJU, JU and JUST, pilot projects at universities would help researchers and students to gain hands-on experience with the technologies.

4. Discussion

In the first part of our results section, we mapped the various connections between the water and wastewater sector on the one side and the hydrogen sector on the other side. Even though obvious for several researchers, we identified three different types of water to be used for electrolyzers: freshwater, seawater, and treated wastewater. Since most of the research has a rather narrow view on water focusing only on one or two types of water, e.g., [50,53], we widened the perspective, which is also relevant for policy makers strategically thinking about a future hydrogen economy and reflecting upon the different water resources that can potentially be used in electrolysis. However, it needs to be acknowledged that the different types of water may result in different hydrogen structures. For instance, while a desalination plant is a more central way to produce water for electrolysis, WWTPs are normally organized decentrally. Hence, a decision on the water resources to be used, has implications on the hydrogen structures to be developed.

We found large variations regarding the amount of water needed for producing 1 kgH_2 also depending on how broad the technology system is framed. While some only focus on the stoichiometric minimum of H_2O, others differentiate between different types of electrolysis and extend the system of analysis to cooling needs and the construction and operation of auxiliary technologies, e.g., [55,78]. In a water-scarce context such as Jordan, the analysis should cover the impacts on the national water situation as holistically as possible to identify all risks arising from hydrogen production.

These risks in arid countries include, for example, the conflicting goals of different sustainability approaches. With regard to a hydrogen economy to be established, aspects of social, ecological, and economic sustainability would have to be taken into account here, among other things. For example, it would be important for a socially sustainable hydrogen economy that the population's water supply is not negatively affected at any time. Accordingly, it would be relevant for an ecologically sustainable solution that the environment also does not suffer from the water requirements of the electrolysis processes. Last but not least, the development of a hydrogen industry must be profitable, so that it can also be economically sustainable. The national water situation should be analyzed to the effect that a functioning, green hydrogen economy can be expected to produce multi-layered, sustainable benefits.

One approach to prevent the mentioned conflicts would be to investigate the possibilities of a WWTP in more detail. Even though decentrally structured in most country contexts, WWTPs deserve special attention because, first, they can provide different feedstocks for hydrogen, for which different processes need to be considered [58,60]. Second, they can also use hydrogen-based products such as methanol or electrolysis-based oxygen for wastewater treatment [85,101]. Such opportunities or co-benefits of decentral hydrogen production should be taken into account when strategically planning a hydrogen economy. A driver for hydrogen production at WWTPs in Jordan could be the potential mitigation of challenges associated with sewage sludge disposal.

Opportunities for water recovery exist for different processes for the production and use of hydrogen or derivates [1,55,65]. Water can even be recovered from fuel cells [68,117]. Project planning in water-scarce contexts should pay particular attention to avoid leaks and inefficient water uses and consider water recovery where technically and economically feasible.

Hydrogen production and use can also help to substitute other forms of energy generation or consumption [79], which can be taken into account in a broader analysis, for instance, when fossil fuel extraction or use is to be substituted by green hydrogen. However, even then, a careful analysis of the hydrological situation in different areas is mandatory.

The results of this research are limited on the one hand by the fact that part of the chosen approach is a review of the literature. Here, the selected literature regarding the interaction of water and hydrogen is considered the core literature. Thus, the base of data was narrowed, and there is a possibility that important information in the literature was overlooked during the research. Additional information from the literature could, for example, provide further perspectives on the research question.

On the other hand, the format of the workshop represents a limitation of the research results. It should be noted here that the number of participants representing opinions and interests in the workshop was limited. Even though a multistakeholder approach was chosen to cover many topics, there is a possibility that geographical differences and demands, for example, were not sufficiently taken into account. Furthermore, when workshops of this type are held, there is a risk that individual contributions may be lost in the volume of information. To make the approach of conducting a workshop more representative, it would be useful to accompany the method with a quantitative survey. Another limitation of the workshop is the interest of the stakeholders. Here, interests from the technical and political fields are mainly represented. For extended research, it would be interesting to invite stakeholders with other interests (for example, primarily socio-ecological) to broaden the perspectives on the research question.

As regards the future research direction, we welcome feedback from other researchers to our concept on the water–hydrogen nexus. In fact, we provided an overview of the interplay between the sectors based on the existing literature, which was helpful to structure our expert workshops. In-depth and semi-structured interviews with planners of hydrogen projects and relevant stakeholders from the water sector could further provide insights into project realities.

Given that hydrogen technologies are mostly developed by manufacturers from industrialized countries, research apparently focuses mostly on the energy inputs. However, since the challenges related to energy are supposed to be outsourced to countries with good conditions for renewable electricity but questionable water situations, water-sensitive research and development of respective technologies and processes and innovative project planning need to be become a key theme.

Even though the role of WWTPs for hydrogen production really depends on the strategy for a green economy, such infrastructures may deserve further attention. Innovative processes at WWTPs could contribute to local value creation and green jobs in local or decentral areas. Furthermore, hydrogen and related products could contribute to improving wastewater treatment processes.

Our project has also sought to facilitate dialogue between the experts of energy and water sectors. For developing either a national- or export-oriented hydrogen economy, it appears to be essential to develop a common vision, identify challenges from both sector perspectives and work out solutions with minimal tradeoffs. In doing so, strategies and policies can be derived by policy makers from the water *and* the energy sector. This will most likely have a positive impact on acceptance by the population. The question on how such a process is to be initiated likely depends on country contexts and the stakeholders involved but needs proactive engagement from policy makers and practitioners, as well as applied research.

5. Conclusions

By presenting the interrelations between hydrogen and water in this article, we want to start to fill the gap of systematic research in this field and to highlight the importance of water as a resource in the potential export countries of hydrogen. We have focused mainly on the conditions of Jordan; however, it can be expected that water scarcity issues will also play an increasingly important role in other (arid) countries.

First, we worked on the different types of water that can be used for hydrogen through electrolysis. These include higher quality potable water, seawater, and recycled wastewater. WWTPs offer further feedstocks for hydrogen production, even though the use of non-H_2O feedstocks would not label the product as green hydrogen. In addition, water-sensitive hydrogen planning should also factor in the water needs of both auxiliary technologies (e.g., solar PV, desalination) and downstream or co-processes (e.g., synthesis, DAC). In addition, for hydrogen uses (e.g., in fuel cells) this can include technology or process operation and opportunities to recirculate water and to close water leaks in water-scarce contexts. Close attention should be paid to developing and enforcing water-related safeguards that help to avoid water conflicts and overuse induced by hydrogen production and a loss in maritime biodiversity as in the case of desalination plants.

The concept of the water–hydrogen nexus has been developed to structure the dialogue of the project called the German-Jordanian Water-Hydrogen-Dialogue. As Jordanian stakeholders discuss opportunities of future hydrogen production, a massive opportunity lies in the desalination plant commissioned by the end of the 2020s. Recycled water from WWTPs is at the moment used for agricultural purposes—so hydrogen production from treated water would also create tradeoffs if wastewater loads remain constant. However, since the population will likely increase, and it is supposed that more people will be connected to the sewage system, the amount of wastewater will likely increase. Given the challenging country conditions, a dialogue between relevant stakeholders of the water and energy sectors should be initiated with respect to the topic of hydrogen. Pilot projects would help to develop human capacities for a green hydrogen economy.

Supplementary Materials: A brochure with further information on the German-Jordanian Water-Hydrogen-Dialogue project will be available at www.wupperinst.org.

Author Contributions: Conceptualization, T.A.; methodology, T.A. and M.V.; validation, T.A., J.P. and M.V.; formal analysis, T.A.; investigation, T.A., M.V., S.R.E., R.M. and J.P.; writing—original draft preparation, T.A.; writing—review and editing, M.V. and J.P.; visualization, T.A.; supervision, T.A.; project administration, T.A. and M.V.; funding acquisition, T.A., M.V. and O.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), grant number 67EXI5503A. We acknowledge financial support by Wuppertal Institut für Klima, Umwelt, Energie gGmbH within the funding programme Open Access Publishing.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Acknowledgments: We would like to thank the National Organization for Hydrogen and Fuel Cell Technologies for exchanging ideas on the subject. Moreover, we would like to express our thanks to the speakers and participants in our expert workshops. Their thrilling presentations and fruitful discussions really brought the project to life. Moreover, the Jordanian Office of the Friedrich-Ebert-Foundation as well as the German Association of Local Municipalities really made great efforts to support our workshops.

Conflicts of Interest: The authors declare no conflict of interest.

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