ASSESSING THE ENERGY AND WATER IMPACTS OF SEAWATER ELECTROLYSIS FOR GREEN HYDROGEN PRODUCTION

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ABSTRACT

Green hydrogen from renewable energy sources is a promising energy carrier for a low-carbon future, with applications in energy, industry, transportation, and chemical sectors. In a scenario with high electrolyzer installed capacities, it is important to assess the impact of water consumption on freshwater resources. In fact, an annual water usage of about 20.7 Gt is expected for the predicted 2.3 Gt of hydrogen produced globally. In those areas where freshwater is a limited resource, high hydrogen production can deeply impact the local water system.

A promising solution for hydrogen production without freshwater consumption is represented by seawater electrolysis. The two approaches to hydrogen generation from seawater are indirect seawater electrolysis and direct seawater electrolysis. While indirect seawater electrolysis is a two-step process, in which seawater is first treated and purified in a desalination unit before electrolysis, direct seawater electrolysis is a novel technology that uses seawater directly as the electrolyzer feed.

Within this context, this study investigates the water and energy consumption of green hydrogen in the energy sector, with a focus on seawater electrolysis as a sustainable alternative to freshwater usage. The analysis was carried out considering the entire power-to-power process, involving renewable energy generation, water electrolysis, and electricity generation using solid oxide fuel cells. The water and energy impacts of both indirect and direct seawater electrolysis are assessed and compared across nine countries with varying levels of water stress and different energy mixes.

The findings of this study reveal that substituting fossil fuels such as coal, oil, and natural gas, with green hydrogen in the energy sector can significantly reduce water withdrawal. With respect to energy production from conventional fossil-fuelled generators, water withdrawal for the entire power-to-power process is reduced between 30% to 90% when electrolyzers are powered by photovoltaic systems, and between 37% to 91% when electrolyzers are powered by wind systems. The highest reductions are observed when substituting oil, particularly with wind energy coupled to alkaline electrolyzers. Moreover, seawater electrolysis represents a viable solution for regions with limited freshwater resources. Indirect seawater electrolysis, employing reverse osmosis desalination before water splitting, demonstrated a minimal energy consumption increase of 1.8% compared to direct seawater electrolysis. Consequently, direct seawater electrolysis is favourable only in specific applications.

1 INTRODUCTION

The energy sector is undergoing a transformation towards a more sustainable future, employing renewable energy solutions to reduce greenhouse gas emissions. This transformation calls for innovative approaches to exploit solar and wind resources, including the development of new energy storage technologies and energy carriers, among which hydrogen is seen as a promising option (Oliveira et al., 2021). Recently, numerous new projects were announced for low-emission hydrogen production, including blue and green hydrogen for applications in refining, industry, transport, buildings, and electricity generation sectors (IEA, 2023). Blue hydrogen is produced from fossil fuels where carbon emissions are captured and stored, while green hydrogen is obtained using only renewable sources (Dawood et al., 2020). However, currently, hydrogen is mainly generated from natural gas reforming

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(grey hydrogen) and coal gasification (brown hydrogen), which result in significant greenhouse gas emissions. By 2030, the European Union plans to produce about 10 Mt and import about 10 Mt of low-emission hydrogen (IEA, 2023). Globally, annual hydrogen production is expected to reach 2.3 Gt by 2030 (Oliveira et al., 2021), although this comes with high energy and water use.

Water use for hydrogen production should be taken into account when developing new plants, as suggested by IRENA and Bluerisk (2023). Water use is calculated based on water withdrawal and consumption. Water withdrawal is returned to the body of water from which it was extracted, while water consumption includes all water that cannot be returned. The impact of freshwater abstractions from the local network can be measured using the water stress indicator, a Sustainable Development Goal (SDG) of the 2023 Agenda program which determines the pressure on freshwater resources caused by abstractions (UN SDG, 2024).

On a global scale, the impact of water use for hydrogen production is low, but on a local scale, it can become a critical issue, especially in water-stressed areas (Dresp et al., 2019), as electrochemical water splitting is an energy-intensive process that requires about 9 kg of water per kg of hydrogen produced. Moreover, water is not only required for H_2 production but also for cooling needs. Future predictions indicate a global annual water consumption of about 20.7 Gt by 2040 and the water withdrawal share for hydrogen production in the energy sector will account for about 2.4% by 2040 (IRENA and Bluerisk, 2023).

Green hydrogen production is favourable in areas with high availability of Renewable Energy Sources (RES), such as North Africa or the southern regions of Europe. However, the water use associated with the electrolysis process may cause problems to the water network, where freshwater is scarce and water stress is high. To address these issues, some studies suggest the use of seawater electrolysis technologies in coastal and arid regions (Dresp et al., 2019). Two seawater electrolysis technologies exist: Direct Seawater Electrolysis (DSE) uses seawater as direct water feed, while Indirect Seawater Electrolysis (ISE) is a two-step process which requires water treatment and purification before electrolysis.

Recently, many researchers have focused their efforts towards investigating seawater electrolysis technologies, as demonstrated by the increased number of publications in the last few years (Farràs et al., 2021; Khan et al., 2021). Many studies compared the performance of direct and indirect water electrolysis systems. Khan et al. (2021) compared the performance of direct seawater electrolysis to a Proton Exchange Membrane (PEM) electrolyzer coupled with a Seawater Reverse Osmosis (SWRO) plant, evaluating energy consumption, costs, and environmental impact. They concluded that the indirect system using SWRO shows a minimal increase in the Levelized Cost Of Hydrogen (LCOH), energy consumption and CO_2 emissions. Specifically, they determined a 0.1% increase in energy consumption and a 0.6% increase in LCOH. Hausmann et al. (2021) analysed the energy consumption and costs of DSE compared to a two-step seawater purification and electrolysis process. In the study, DSE is proposed to reduce freshwater use, although the authors highlighted the challenges of this new technology. They concluded that DSE does not show significant benefits compared to ISE and suggested driving research efforts towards more advanced purification systems to increase water purity. In their study, the authors estimated that, if all energy was produced using hydrogen fuel cells, the freshwater required for electrolysis would constitute just 0.4% of global freshwater use and 2% for all primary energy. Dresp et al. (2019) conducted a thorough analysis of hydrogen production from renewable sources, particularly in arid and coastal areas. This paper analyses the electrochemical reactions and the challenges of DSE. Moreover, the energy consumption of reverse seawater electrolysis, using a fuel cell to generate electricity and freshwater, is calculated. They also compared DSE and ISE technologies, concluding that DSE may be implemented in offshore applications. Farràs et al. (2021) reviewed the scientific literature on the topic of hydrogen production from seawater. They conclude that currently, DSE is not competitive against ISE because of technical challenges that must first be addressed. However, future developments in this technology field are fundamental, as DSE is a promising solution in specific applications. The authors highlight the mismatch between the small scale of current commercial electrolyzers and SWRO plants which are usually large plants. Moreover, they point out the importance of assessing the footprint of these systems. Beswick et al. (2021) conducted a study to determine the water use of green hydrogen production. The study demonstrates that water use for electrolysis has a negligible impact on global resources. SWRO's increase in energy consumption is marginal, and so is the increase in LCOH. Moreover, the analysis suggests that substituting RES and

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hydrogen to fossil fuels for electricity production will result in water use reduction. The authors finally suggest increasing efforts to develop high efficiency electrolyzers.

The results of these studies indicate a minor difference in energy and costs between the two technologies, in favour of DSE. However, there is limited consideration of the impact of seawater electrolysis on local freshwater resources, focusing instead on broader-scale applications. Moreover, many studies lack a thorough assessment of the energy use of the two systems at the local scale, considering different electrolyzer and water purification systems. The size mismatch between commercial SWRO and water electrolyzers has not been addressed yet. Additionally, real data for energy production should be used. Moreover, the energy sector is currently dominated by fossil fuels, with renewable energy rising rapidly, especially in Europe. As increasing amounts of green hydrogen for electricity generation will increase water abstractions, the associated challenges must be evaluated and addressed.

To better understand the effects of hydrogen production on water resources, this paper is aimed at addressing the energy and water impact on the local scale in different regions. Ranging from the northern regions of Europe to North Africa, all 9 considered regions show different energy mix shares, RES penetrations, energy consumption, and water utilization levels. The analysis includes determining of the water withdrawal for green hydrogen production from RES, used to substitute increasing shares of fossil fuels in electricity generation. Lastly, water and energy requirements are evaluated for ISE and DSE technologies.

2 METHODS

This study conducts a comprehensive analysis of water and energy use for hydrogen production spanning across Northern Europe to North Africa regions. Specifically, the study focuses on nine regions such as Algeria (DZ), Denmark (DK), Germany (DE), Italy (IT), Libya (LY), Netherlands (NL), Norway (NO), Sweden (SE), and Tunisia (TN). Each region is characterized by different levels of water stress, water withdrawal, energy generation levels, energy generation shares by source, and RES penetration, but they all have direct access to seawater. In this section, the data used for the analysis is presented and discussed.

2.1 Water stress and withdrawal

Water stress is a Sustainable Development Goal indicator (SDG 6.4.2), defined by the United Nations as the "ratio between total freshwater withdrawn by all major sectors and total renewable freshwater resources, after taking into account environmental flow requirements" (UN SDG, 2024). Various degrees of water stress are categorized into five levels such as no stress (<25%), low (25-50%), medium (50-75%), high (75-100%), and critical (>100%) stress.

In this study, it is important to determine water stress levels to assess the impact of water use for hydrogen production at the local scale. Water stress data used for this analysis was obtained from the UN Water Organization database, which provides data for agricultural, industrial and service use (UN, 2024). While the latest available data refers to 2020, historical trends demonstrate minimal variations in water use over time.

Figure 1 shows the water stress levels (Figure 1a) and annual water withdrawal (Figure 1b) for the considered regions. Figure 1a shows a significant variability in water stress levels across the regions. Some regions like Norway, Sweden, and the Netherlands are characterised by very low levels of water stress, while others like Libya and Algeria have much higher levels. Regional patterns show that North African countries have higher water stress levels compared to European regions. Arid regions and countries with limited access to freshwater resources tend to have higher water stress levels. Specifically, Libya ranks fourth in the world for water stress (UN, 2024), with levels above 800%. Figure 1b illustrates the annual total withdrawal of water for the countries considered. Similarly to the water stress analysis, considerable differences can be observed across the regions, ranging from about 1 Gm^3/year to about 34 Gm^3/year. Countries like Italy and Germany have water withdrawals significantly higher than others like Denmark and Norway. Regional patterns can be identified, where European countries have generally higher water withdrawals compared to North African regions.

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Comparing water stress and withdrawal data, the disparities can be attributed to geographic factors like climate and freshwater availability, but also to the efficiency of the different water management strategies of the countries.

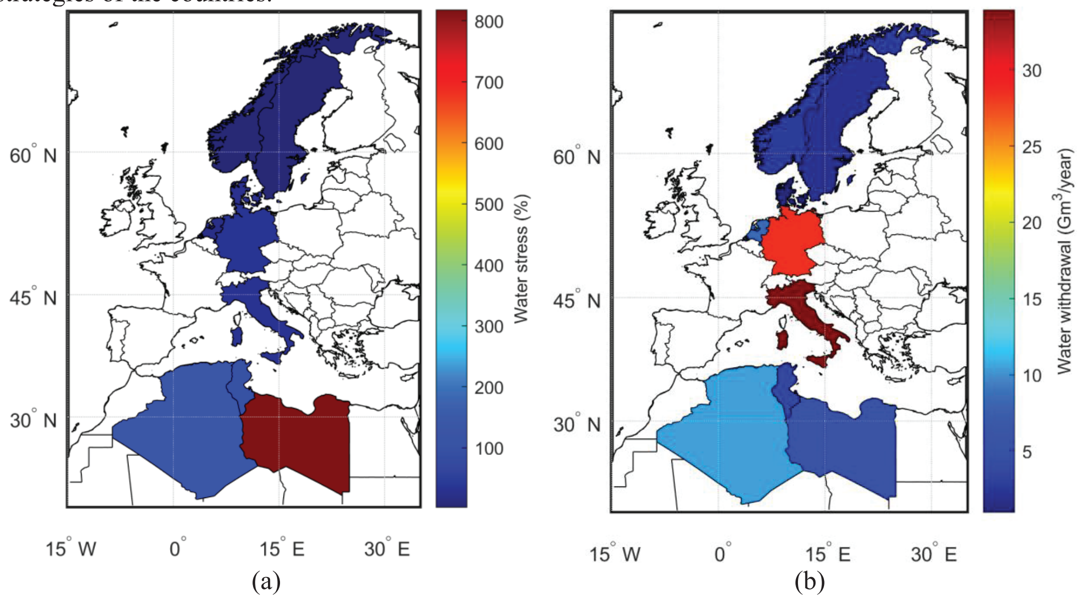

Figure 1: (a) Water stress levels and (b) water withdrawal for the countries analysed.

2.2 Energy generation

Figure 2 illustrates the electricity generation mix and the total energy generation for each region. The electricity generation mix data, divided by source, was derived from the IEA database (IEA, 2024) for the year 2020, to maintain consistency with the water data used in this analysis.
Analysing the data, it can be observed that most regions rely significantly on fossil fuels. Most countries rely heavily on natural gas, with Algeria, Libya and Tunisia being the primary consumers. Libya, in particular, shows notable reliance on oil. Germany, Italy, and the Netherlands also exhibit heavy dependence on coal, alongside some integration of renewable sources. Hydroelectric power is mostly predominant in Norway and Sweden and significantly contributes to the energy mix in Italy. Wind energy is integrated into the energy mix in Denmark, Germany, and other European countries, while PV contributes significantly to energy generation in Italy, Germany, and the Netherlands.
In summary, a distinct trend can be observed where northern regions rely on different sources including renewables, while southern regions and North African regions rely mostly on natural gas and oil.

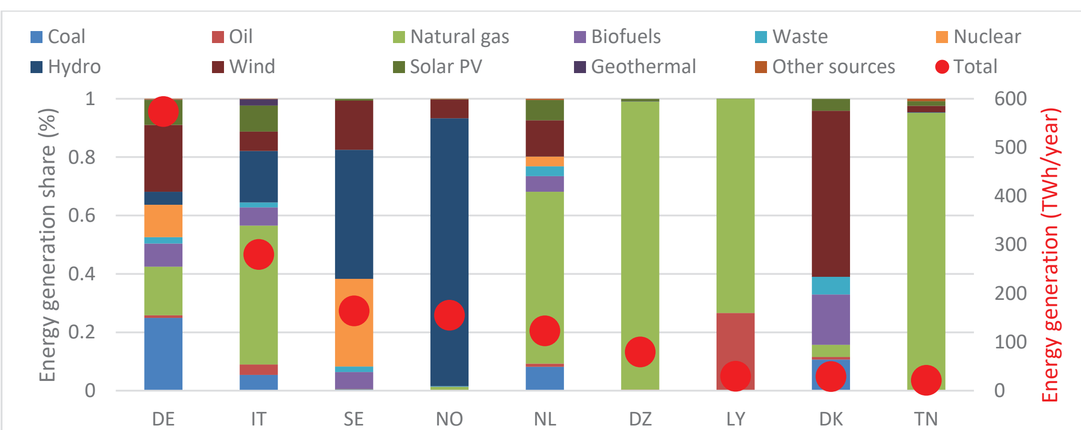

Figure 2. Energy generation share and total annual energy generation for each analysed region.

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Table 1 summarizes the data used in this study regarding water stress, annual water withdrawal and annual electricity generation for each country. All data refers to 2020. Overall, the data shows the diverse challenges regarding water resource utilization in hydrogen production for electricity generation across different regions.

Table 1: Summary of data regarding water stress, annual water withdrawal and annual electricity generation for each country.

	NO	SE	DK	DE	NL	IT	LY	TN	DZ
Water stress (%)	2.05	3.58	26.40	33.50	16.8	29.81	817.14	98.11	137.92
Water withdrawal (Gm^3/year)	2.69	2.07	0.98	28.48	8.31	33.89	5.83	3.59	10.46
Energy generation (TWh/year)	155.2	163.8	28.7	575.5	123.3	280.5	29.5	21.5	79.1

2.3 Water withdrawal for electricity generation

Extensive research has been conducted over the last decades to assess the water intensity of different technologies for electricity production (Gleick, 1994; Macknick et al., 2012; Meldrum et al., 2013), determining specific water withdrawal rates. In this study, the most recent data available (Jin et al., 2019) was selected for the analysis of the water withdrawal of different technologies. In their study, the authors analysed water use from surface or irrigation for different applications and considered different regions. Noticeably, water use depends on a variety of factors, including cooling technology and geographical location.

Figure 3 shows the water withdrawal of different technologies for electricity generation. Data analysis suggests that fossil fuel technologies require higher water withdrawals compared to renewable sources. Among conventional sources, natural gas stands out as the least water-intensive option. Among renewables, PV technology requires about 46 times less water than natural gas technologies. Wind turbines instead require no water whatsoever for electricity generation. Oil is instead the highest water-intensive source, at the most for wet cooling technologies. The very low water requirements of RES technologies constitute a significant advantage when transitioning from fossil fuels, in terms of optimizing water utilization for electricity generation.

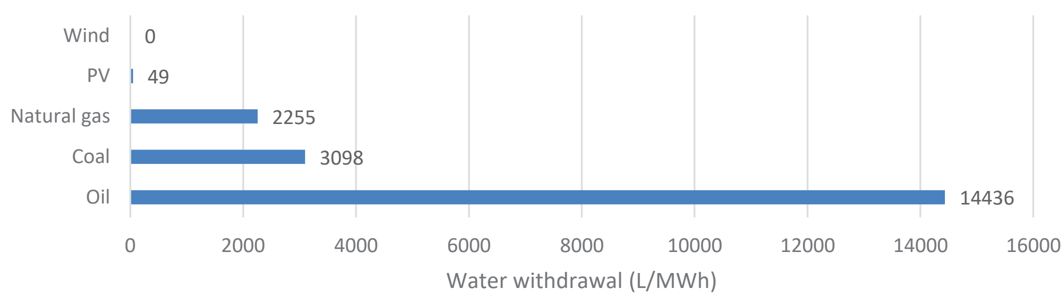

Figure 3. Water withdrawal for electricity generation from different sources.

2.4 Water withdrawal for hydrogen production

As previously described, reducing carbon emissions will involve the production of green hydrogen as an alternative to fossil fuels. However, hydrogen production requires significant quantities of water. Data on water intensity for hydrogen production processes was derived from the IRENA report "Water for hydrogen production" (IRENA and Bluerisk, 2023), which provides an analysis of the challenges of water use for hydrogen production.

The data includes water withdrawals for grey hydrogen from Steam Methane Reforming (SMR) and coal gasification, blue hydrogen from Carbon Capture Utilization and Storage (CCUS) technologies, and green hydrogen from electrolysis. Water withdrawal for blue hydrogen production from natural gas is examined both from SMR and Autothermal Reforming (ATR).

Figure 4 displays the water withdrawal required to produce 1 kg of hydrogen, using both fossil fuels and renewable energy sources. Considerable variation between different technologies can be observed,

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ranging from about 20 L/kg to about 80 L/kg. Coal gasification, both for brown and blue hydrogen production, is the most water-intensive process. Natural gas is instead a more water-efficient option, with water withdrawals comparable to those of electrolysis, but the process of grey hydrogen production involves carbon emissions. It can also be observed that CCUS for blue hydrogen production increases water requirements, compared to conventional systems. For this reason, blue hydrogen production can potentially increase water challenges in the future. In contrast, electrolysis technologies for green hydrogen production, both alkaline and PEM, generally require less water compared to fossil fuels. Among electrolysis technologies, PEM is the most water-efficient option.

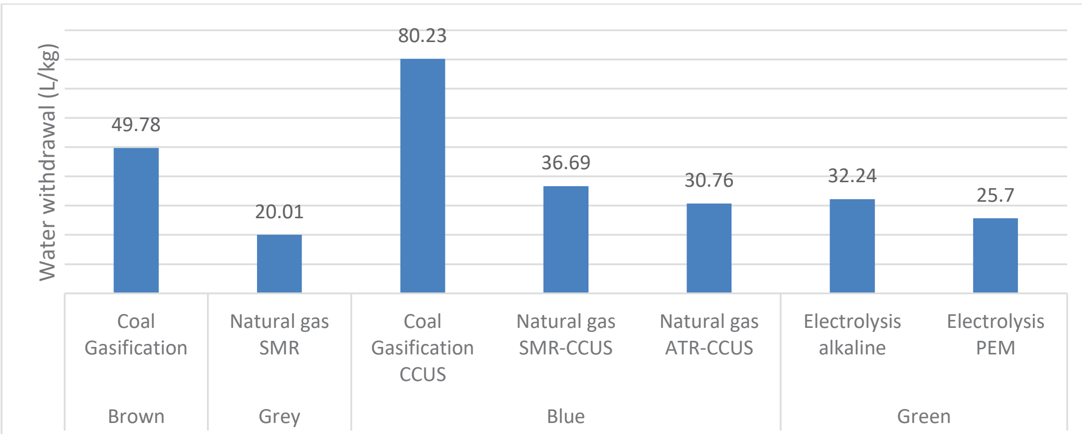

Figure 4. Water withdrawal for hydrogen production using different technologies.

2.5 Water withdrawal for green hydrogen from RES

The methodology herein presented aims to estimate the water withdrawal requirements for green hydrogen production using RES, to substitute fossil fuels in the energy sector.

The first step consists of generating the amount of hydrogen required. To match the real electricity generation for each country by source, hydrogen generation requires high amounts of RES power. This is calculated by dividing the energy generation per source with the PtP round-trip efficiency.

The total mass of hydrogen produced is then calculated as the ratio between the electricity generation for each country by source and the specific consumption of the electrolyzer.

Given the mass, water withdrawal for hydrogen generation is calculated considering the specific water withdrawal of the electrolyzer.

Additionally, the water withdrawal of the RES power plant for green hydrogen production is calculated as the product between the electricity generation for each country by source and the specific water requirements of either PV or wind. For wind generation, as the specific water withdrawal is zero (as shown in Figure 3), the total water withdrawal of the wind power plant is equal to zero.

3 RESULTS AND DISCUSSION

Future energy scenarios depend on the transition from fossil fuels to RES. In this analysis, the energy generation from fossil fuels for each country was substituted by green hydrogen, using RES. In fact, in the energy sector, the most carbon-emitting sources are coal, oil and natural gas (IEA, 2024). In this section, the results of the analysis are presented and discussed.

3.1 Current water withdrawal from fossil fuels

Based on the energy generation data for each country, the water withdrawal requirements for fossil fuel technologies are calculated and reported in Figure 5. Germany (DE) and Italy (IT), being mostly dependent on fossil fuels, show the highest annual water withdrawal among the considered countries. Specifically, Germany has the highest water withdrawal requirements, followed by Italy and the Netherlands (NL). Countries with high RES penetration, such as Sweden (SE) and Norway (NO), are characterized by very low total water withdrawal. Coal water requirements are relevant, especially in

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Germany, where it constitutes about 61% of the total water withdrawal for energy generation in the country. Natural gas water withdrawal is very relevant in most countries, especially in North African countries but also in Italy and the Netherlands. Oil technologies are instead the main cause of water withdrawal for energy generation in Libya (LY).

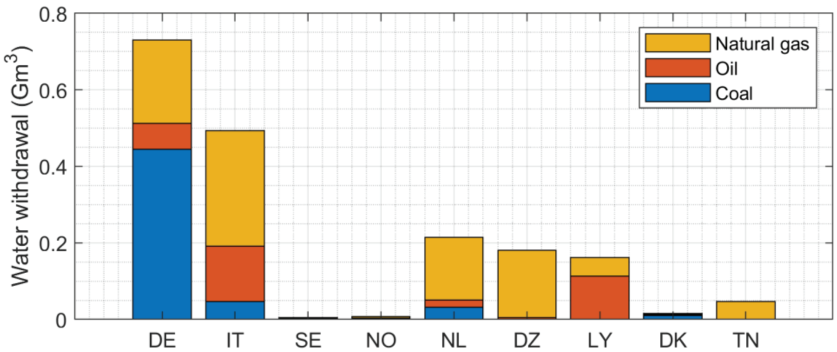

Figure 5. Water withdrawal for electricity generation from fossil fuel technologies.

3.2 Water withdrawal for RES and hydrogen in the energy sector

Green hydrogen is produced from RES and, in this study, solar PV and wind turbines are considered for the analysis. In fact, they are characterized by very low carbon emissions (IEA, 2024) and, as described before, very low water requirements compared to fossil fuels. In this analysis, two water electrolysis technologies are studied and analysed, i.e. alkaline and PEM electrolyzers. As demonstrated in Figure 4, they have very low water withdrawals, comparable with natural gas technologies. Hydrogen can be used for electricity generation in the Power-to-Power (PtP) process (Raimondi and Spazzafumo, 2023), where electrical energy is converted to hydrogen, which is an energy carrier, and then reconverted back to electricity. This way, excess renewable energy can be used to generate hydrogen, later used for electricity production (Migliari et al., 2024).

Various methods allow hydrogen to be used in electricity generation, mainly open-cycle gas turbines, combined-cycle, and Solid Oxide Fuel Cells (SOFC). Additionally, other technologies were developed to use hydrogen as a means for storing excess RES generation (Migliari et al., 2023). In this analysis, SOFC technology was used for energy generation, exploiting its capability to produce water as a byproduct when combining hydrogen and oxygen, thereby contributing to further decrease stress on freshwater resources.

The energy consumption of hydrogen production varies based on the technology and the efficiency of the process. However, the latest data shows that energy consumption for PEM electrolyzers amounts to about 57 kWh/kg and for alkaline electrolyzers to about 52 kWh/kg, as of 2020 (Glenk et al., 2023). Given the lower heating value of 120 MJ/kg (Dawood et al., 2020), the conversion efficiency of the PEM and alkaline electrolyzers are calculated to be about 58.5% and 64.1% respectively. For the efficiency of the SOFC, a conservative estimate of 55% is assumed (Fan et al., 2021).

Transitioning from fossil fuels in the energy sector necessitates increased capacity of RES hydrogen production. In this analysis, the effects on water withdrawal of increasing shares of RES and green hydrogen are analysed. While it's possible for energy generation to be entirely reliant on RES, their intermittent nature poses challenges to grid integration. For this reason, hydrogen is used as an energy storage solution. The study assesses the water usage across varying proportions of electricity generation directly from RES or using green hydrogen as energy storage, considering the entire PtP process to convert hydrogen back to electricity.

Figure 6 shows the total water withdrawal for different shares of RES and hydrogen-based electricity generation as a replacement for fossil fuels, focusing on Germany. Figure 6 refers to the use of PV for energy production and PEM electrolyzer for hydrogen generation. The graph highlights the significant water usage of hydrogen production. Notably, the two components exhibit comparable water withdrawal only for very low proportions of hydrogen generation. RES generation becomes more water-intensive only when its share exceeds about 97%. The same analysis was conducted for all considered regions, with all combinations of fossil fuels, and electrolyzers (PEM or alkaline). For the RES power

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plant, only PV was analysed, as the specific water withdrawal of wind turbines is zero. The results consistently reveal that, across all scenarios, the RES to H_2 share with comparable water withdrawal is about 97%, indicating that RES withdrawal is relatively low compared to electrolyzer water usage.

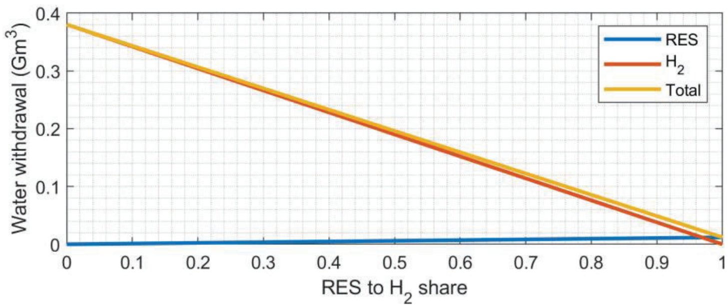

Figure 6. Water withdrawal for different shares of RES and hydrogen electricity generation.

3.3 Hydrogen water withdrawal in the energy sector

The future contribution of RES and hydrogen to power generation is very difficult to predict, as it depends on various technological factors such as the installed capacity of each renewable source and use of different energy storage systems, as well as the influence of policies and plans in individual countries. Therefore, the following analysis adopts a very conservative approach, considering the worst-case scenario in terms of water withdrawal, i.e. RES to hydrogen share equal to zero or, in other words, all energy generation from fossil fuels is substituted by green hydrogen generated from RES.

Figure 7 shows the results of the analysis, illustrating the water withdrawal of the entire PtP process using green hydrogen for electricity generation. Each graph displays the water withdrawal of current technologies for each considered country (in blue) and the potential withdrawal when substituting their energy production with a PtP process with hydrogen produced through PEM (a-c) and alkaline (d-f) electrolyzers, powered from PV and wind turbines. It can be observed that, in all cases, even for a complete substitution of fossil fuels, transitioning to green hydrogen leads to water savings.

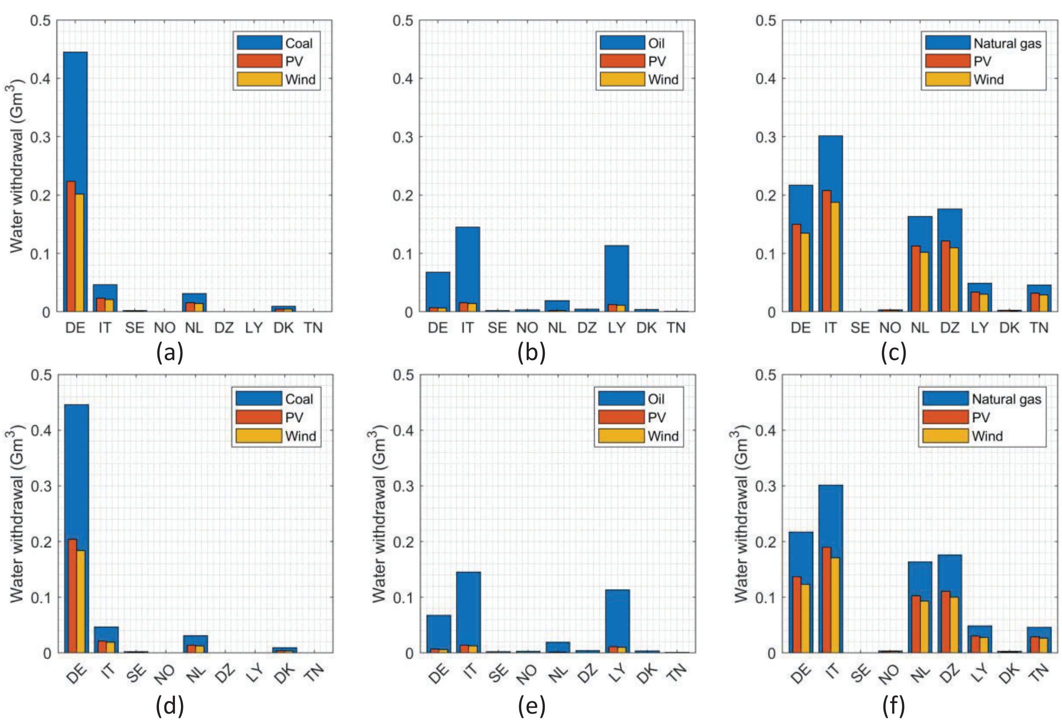

Figure 7. Water withdrawal substituting hydrogen from PEM electrolyzers to (a) coal (b) oil and (c) natural gas and from alkaline electrolyzers to (d) coal (e) oil and (f) natural gas.

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Table 2 shows the results of the analysis, expressed as a percentual reduction of water withdrawal when fossil fuel generation is substituted with PtP green hydrogen processes. A significant reduction in water withdrawal can be observed across all combinations. Generally, alkaline electrolysis achieves a slightly higher reduction in water withdrawal percentages compared to PEM electrolysis due to the fact that alkaline electrolyzer conversion efficiency is slightly higher, resulting in less energy consumption per kg of hydrogen produced and, consequently, less water requirements. Moreover, comparing PV and wind power sources, a consistent trend can be identified where wind results in slightly higher water withdrawal reductions compared to PV, both for PEM and alkaline electrolysis. In fact, the specific water withdrawal of wind plants is zero. Across fossil fuels, substituting oil results in the highest percentage reduction in water requirements, especially with wet-cooled technologies. Comparing the results summarized in Table 2 with the absolute values in Figure 7, even though oil shows the biggest percentage reductions, the total water withdrawal is low when compared to natural gas and coal. In fact, oil consumption is mostly relevant in some countries, as shown in Figure 2. In summary, regardless of the combination of electrolysis technology and power source, a considerable reduction in water withdrawal percentage can be achieved by substituting green hydrogen to fossil fuels in the energy sector.

Table 2: Water withdrawal reduction substituting energy generation from fossil fuels with PtP green hydrogen processes.

Electrolyzer technology	RES type	Primary energy source		
		Coal (%)	Oil (%)	Natural gas (%)
PEM	PV	-49,83	-89,23	-31,08
	Wind	-54,75	-90,29	-37,84
Alkaline	PV	-54,23	-90,18	-37,12
	Wind	-58,72	-91,14	-43,29

3.4 Seawater electrolysis energy consumption for green hydrogen production

The analysis discussed in Section 3.2 showed that the integration of green hydrogen from RES in the energy sector leads to a significant reduction in water withdrawal. However, some regions may still suffer from scarce freshwater availability. Additionally, the analysis focuses only on the energy sector, but for the agricultural and industrial sectors transition to renewable energies may be hard (IEA, 2024). For this reason, electrochemical splitting of seawater appears to be a promising solution to reduce water stress in regions with limited access to freshwater resources. This section discusses the energy and water implications of seawater electrolysis, comparing direct and indirect technologies.

The previous analysis, conducted over 9 different countries, proved that in some regions, especially in northern Europe, increasing RES penetration can lead to lower water stress. This is especially true in regions with high dependence on fossil fuels, such as Germany and Italy. However, other countries face tougher challenges because of critical water stress levels and limited access to freshwater. Among the analysed countries, water stress in North African regions exceeds 100%, reaching critical conditions. Although all of the considered countries have direct access to seawater, only some of them employ purification systems for freshwater production. Table 3 shows the total water desalinated per year. While most of the considered countries have zero or almost zero desalination production, Algeria is characterized by a production of about 0.631 Gm^3/year. However, it must be noted that this is a small quantity compared to the total annual water withdrawal of the country. Moreover, although Libya has direct access to seawater, the amount of seawater treated and purified is only about 0.07 Gm^3 (FAO AQUASTAT, 2024).

Table 3. Annual desalinated water production in the considered countries (FAO AQUASTAT, 2024).

	DZ	DK	DE	IT	LY	NL	NO	SE	TN
Desalinated water (Mm^3)	631,0	0,0	0,0	200,0	70,0	0,0	0,1	1,0	43,0

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As previously mentioned, seawater electrolysis can be achieved with ISE or DSE technologies. ISE requires, as a first step, seawater desalination and treatment which, at an industrial scale, is performed with reverse osmosis plants. The energy consumption of these systems has decreased significantly over the past few years to about 2.5 kWh/m^3. DSE, instead, allows the elimination of the need for water treatment and its specific energy consumption is about 53 kWh/kg.

Applying the same procedure discussed in Section 3.2, the water withdrawal for the two technologies was assessed. DSE performs similarly to conventional electrolyzers, as shown in Figure 8, where the total annual water withdrawal is calculated considering the specific energy consumption using both PV and wind sources. By applying the same procedure, it is calculated that for ISE systems, the seawater purification step increases energy consumption by only 0.1% for both PEM and alkaline electrolyzers, compared to using freshwater sources. However, the comparison between ISE and DSE should consider not only the energy consumption increase of the SWRO, but instead it should consider the entire PtP process. Therefore, the energy consumption of both DSE and ISE is calculated by employing the procedure previously discussed. Results show that the ISE system, using SWRO for seawater treatment, requires about 1.8% more energy than DSE, using both PV and wind sources.

In summary, because of the high energy consumption of the electrolysis process compared to SWRO, ISE and DSE offer comparable performance in terms of energy consumption. Their application should be intended mainly for arid and water stressed regions or where access to freshwater is limited. In these areas, however, ISE could provide services to the community. In fact, by oversizing the seawater treatment plant, purified water can be produced further reducing stress on freshwater resources.

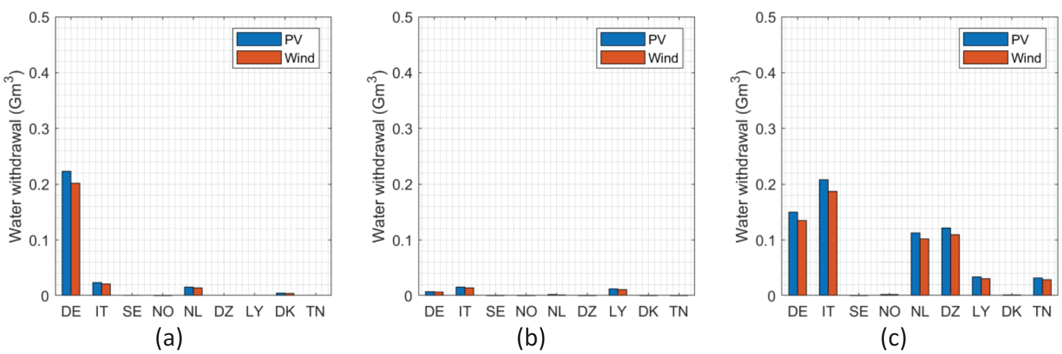

Figure 8. Water withdrawal for DSE from RES, substituting (a) coal, (b) oil and (c) natural gas with green hydrogen.

4 CONCLUSIONS

Green hydrogen from renewable energy sources is considered a key factor in the transition towards a low carbon emission future. In the near future, hydrogen production is expected to increase drastically, with applications in transport, industry, and electricity generation. However, as electrolysis is a very water-intensive process, thorough analyses must be conducted to address the impact on local freshwater sources.

This study provides a comprehensive analysis of the water and energy consumption of green hydrogen in the energy sector, as a potential sustainable alternative to fossil fuels. Direct and indirect seawater electrolysis are analysed as means to mitigate freshwater usage. The study considers nine countries spanning from Northern Europe to North Africa, each characterized by different water stress levels, water withdrawal intensities, and energy mixes. The analysis was carried out considering the water and energy consumption of the entire power-to-power process, in which electrical energy generated by renewable energy sources is provided to electrolyzers for hydrogen production, later converted back to electricity via solid oxide fuel cells.

The results show that substituting fossil fuels with green hydrogen results in a significant reduction in water withdrawal, across all analysed scenarios. Specifically, water withdrawal is reduced from a minimum of 30% to a maximum of 90% for photovoltaic-powered electrolyzers, and between 37% and

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91% for wind-powered electrolyzers. Moreover, fuel cells generate water as a byproduct of electricity generation, further reducing the water impact.

The comparison between indirect and direct seawater electrolysis shows minimal differences in energy consumption. Indirect seawater electrolysis exhibits only a slight increase in energy consumption (about 1.8%) compared to direct seawater electrolysis, due to the pre-treatment through reverse osmosis desalination. Therefore, direct seawater electrolysis holds promise in specific contexts where other operational benefits add to the slight decrease in energy consumption.

Further research will allow determining the water impact of different technologies, such as open-cycle and combined-cycle plants, and assessing future water stress levels, considering the water generated by fuel cells.

NOMENCLATURE

ATR	autothermal reforming	PtP	power to power
CCUS	carbon capture utilization and storage	RES	renewable energy sources
DSE	direct seawater electrolysis	SDG	sustainable development goal
ISE	indirect seawater electrolysis	SMR	steam methane reforming
LCOH	levelized cost of hydrogen	SOFC	solid oxide fuel cell
PEM	proton exchange membrane	SWRO	seawater reverse osmosis

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