Analysis of water resources for green hydrogen production in Europe

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Abstract:

Green hydrogen and its liquid and gaseous derivates can help decarbonize all sectors within the European energy system. Electricity from renewable sources and water are the inputs for green hydrogen production via electrolysis. Southern European countries with a high potential for renewable electricity are also subject to water scarcity. This paper analyzes relevant water resources and their locations for green hydrogen production. Analyzing the types of resources based on energy requirements for pretreatment shows the advantage of freshwater resources. On the European country level, we calculate potential green hydrogen production amounts solely considering freshwater availability and compare the results to local water stress data from the literature. Results indicate the sufficiency of freshwater resources on a European scale but show the necessity further to evaluate water limitations on a regional and seasonal level when siting electrolyzers.

Keywords: Hydrogen, Resources, Water Availability, Water electrolysis, Green hydrogen economy

1 Background and Motivation

With its Green Deal, the European Union aims to become the first climate-neutral continent by 2050 [1]. This requires substituting fossil fuels with renewable energy sources (RES) in all sectors. The most efficient way is the direct electrification of applications. For applications that are hard to electrify or electrification is not possible, hydrogen and its derivates, such as synthetic fuels, are suitable and promising solutions [2, 3]. Hydrogen can further serve as feedstock, fuel, or energy carrier and can be stored [3].To support the decarbonization of all sectors, the production of hydrogen, called electrolysis, must be carbon-neutral and thus based on electricity from RES, e.g., solar and wind. A further input of electrolysis is water. The resulting hydrogen is often referred to as green hydrogen [3].

The currently available technologies for water electrolysis are alkaline water electrolysis (AEC), polymer electrolyte membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC). AEC is the most mature and cost-efficient technology, with an efficiency of ~70%, expected to increase to ~80% by 2050 [4]. However, it struggles with dynamic production with fluctuating

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electricity feed-in from RES. PEM has been commercialized in the last years and offers the possibility of dynamic production in connection with fluctuating feed-in from RES. The efficiency of PEM is about 60%. Improvements are expected to increase efficiency to up to 74% by 2050. In terms of cost and lifetime, it lags behind the AEC. SOEC is the most recent water electrolysis technology which operates at higher temperatures. To date, there are only demonstration plants operated at accordingly high costs. The projected efficiencies of SOEC are the highest, at 81% today and up to 90% by 2050. The technologies differ in performance and, consequently, in specific water consumption. Stoichiometrically, it takes about 9 liters of water per 1 kg of hydrogen in the water electrolysis process. The gate-to-gate specific water consumption of the water electrolysis technologies provided by suppliers varies between 10.01 liters to 22.40 liters per kg of hydrogen, according to [5]. Experimental data provided in [6] show that the gate-to-gate water consumption of the three technologies is similar, with 10.0 liters for AEC, 10.7 liters for PEM, and 9.1 liters for SOEC. [5, 7]

Water electrolysis requires pure, deionized water as an input to produce hydrogen. Many types of water sources may need different kinds and amounts of treatment before being usable for electrolysis. Further, fresh water is already considered a scarce resource in many regions [8, 9], and due to climate change and the increasing frequency of droughts likely becoming even more scarce [10, 11]. Therefore, the question arises which water sources will be suitable for future green hydrogen production in Europe and to what extent they are available.

To this end, the authors combine different analyses for water stress and hydrogen production, considering spatial and temporal aspects. This paper first analyzes in section 2 relevant water sources and their necessary treatments before using them in electrolysis. In section 3, the authors compare today's water availabilities with the demand for producing predicted hydrogen amounts on a country scale. Section 4 elaborates on local water limits and seasonal variabilities in Europe. Finally, section 5 summarizes the previous findings and provides indications for siting of electrolyzers.

2 Water Sources

There are many different types of water sources conceivable for water electrolysis. The most discussed freshwater sources are surface water from rivers, streams, or lakes, and groundwater, rainwater, or wastewater. Besides, using seawater or direct air capture are further options. Water from these sources is mixed to different degrees with other minerals or metals and thus requires treatment before it can be used in electrolysis. The treatment differs for various water sources, but most share the process of reverse osmosis [5, 12].

Surface water, such as rivers and streams, often contains residues of nutrients, metals, chemicals, pesticides, and pharmaceutical ingredients [13–16]. Per liter of water, this can vary between 100 and 800mg of residues. The treatment to purify and deionize the water is called reverse osmosis and requires for rivers about 0.5 to 2.5 kWh_{el}/m^3 of water [17]. Most European lakes suffer from high pollutant concentrations due to excessive mercury and cadmium content caused by fertilizers and metal production [18]. Further, any interventions in the shore structure or a change in the water level may stress the ecological system of a lake [19]. Groundwater is accumulated water in the soil produced by seepage from precipitation or surface water. The minerals dissolved in groundwater depend strongly on the nature of the environment and the rock strata through which the seepage flows [20, 21]. The longer the groundwater remains in the soil, the less pretreatment is required for electrolysis [21]. The specific energy requirement for the treatment reflects this, as ~1.21 to 4 kWh_{el}/m^3 of water is required for reverse osmosis, depending on the plant size [12]. Locally, this can vary, e.g., for more acidic groundwater next to open-cast mining lakes. In this case, the energy requirement for groundwater approaches that of seawater. Rainwater, which can be collected in large storage facilities, is already of good quality and does not require reverse osmosis in all cases. The storage facilities' investment costs and the low availability reliability are disadvantages [5]. Similar considerations apply to industrial wastewater as these can be affected by weather and climate change, especially in the agri-food industry. Further, industrial wastewater can contain high concentrations of pollutants requiring more pretreatment to raise the water quality for water electrolysis. Reverse osmosis energy demands for industrial wastewater range from 4 to 16 kWh_{el}/m^3 of water [22, 23]. Seawater needs special treatment via reverse osmosis due to its high salt concentration. The energy consumption in the reverse osmosis process is about 3.7 kWh_{el}/m^3 of seawater up to 8 kWh_{el}/m^3. For smaller plants, the electricity consumption may increase to above 15 kWh_{el}/m^3 [24].

Figure 1 shows the specific energy requirements for pretreatment via reverse osmosis per water source. It can be noted that freshwater sources such as surface water, i.e., water from rivers, streams, and lakes, and groundwater require less electricity during the reverse osmosis process to pretreat and deionize the water for following electrolysis.

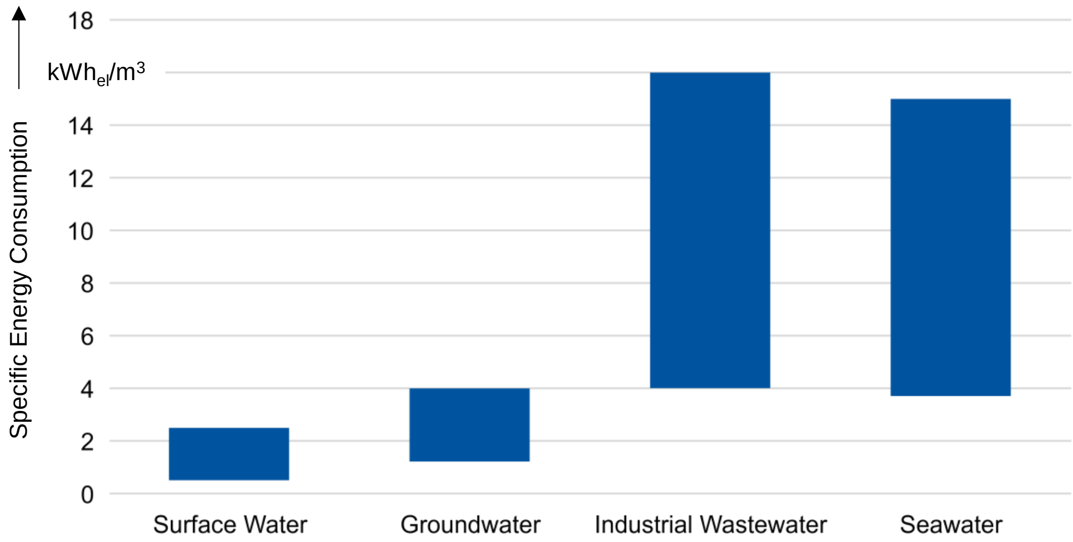

Figure 1: Specific energy consumption ranges for pretreatment via reverse osmosis

3 Water Availability for Hydrogen Production

To calculate the water availability for hydrogen production, the authors consider the water exploitation index (WEI), also often referred to as the withdrawal-to-availability ratio. This means the annual total abstraction of freshwater divided by the average freshwater resources [25, 26]. The WEI is commonly used to identify physical water stress. Water stress can indicate ecological damage and potential damage that may occur in the quantity and quality of available freshwater [27]. [26] defines water stress via WEI. A WEI below 10% signifies no water stress, between 10 and 20% low stress, and greater than 20% stress. Others, such as [10, 25], use different classifications. While [25] classifies low water scarcity (WEI <10%), moderate water scarcity (10-20%), water scarcity (20-40%), and severe water scarcity (>40%), [10] graduates in low water stress (<5%), low-medium (5-25%), medium-high (25-50%), high (50-75%), and extremely high (>75%).

The authors calculated the WEI, potential water withdrawals for hydrogen production without reaching 20% of WEI, and the resulting possible hydrogen amount on the European country level for 2018 based on data from [6, 28]. We assume the stoichiometric value of 9 liters per kg of hydrogen for the calculations. Figure 2 shows the resulting possible water withdrawals for selected countries. The complete table can be found in the Appendix. Countries in southern Europe like Bulgaria, Spain, and Turkey already suffered from water stress in 2018. Thus, further water withdrawal from freshwater sources in those countries only aggravates the water stress. Especially northern countries like Norway (~78bn m^3) and Sweden (~32.43bn m^3) have a massive amount of possible water withdrawals until reaching a WEI of 20%.

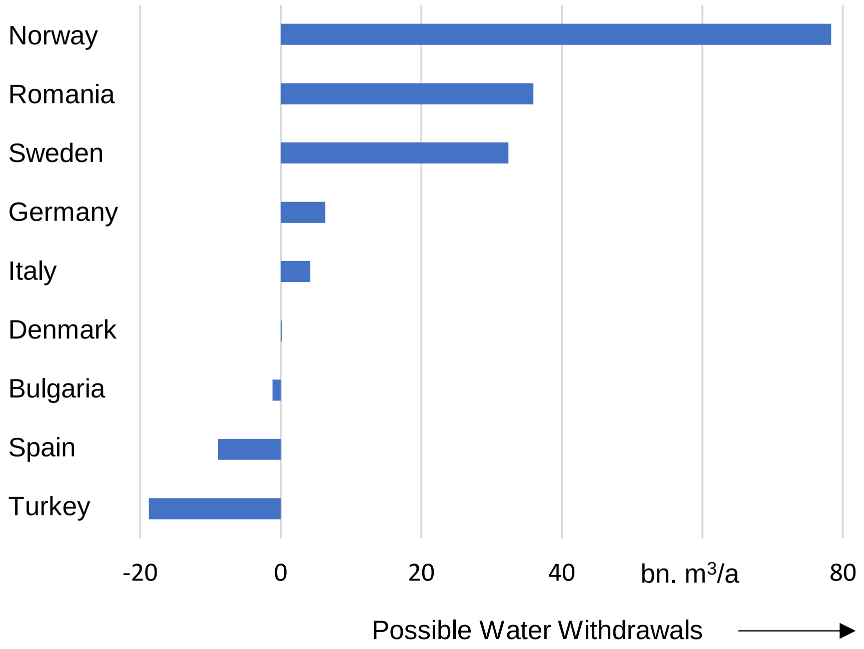

Figure 2: Possible water withdrawals for hydrogen production for selected countries

The total European hydrogen production potential based on water availability is about 44,778 Mt of hydrogen (cf. Appendix). Predictions from [29, 30] range from about 69 Mt to 100 Mt of hydrogen demand in Europe in 2050. On a European scale, the water availability exceeds the required water demands for predicted hydrogen amounts.

4 Limits of Water Availability

4.1 Local Limitation

In section 3, the authors have shown that some countries are already subject to physical water stress. Others may provide vast amounts of water for hydrogen production, and the overall water availability exceeds the required water demands. Using data from [10] for local water stress levels (cf. Figure 3) supports that predominantly southern European countries underly water stress in 2020. These data also show that for some countries, this holds true only for selected regions within the mentioned countries (cf. Figure 3).

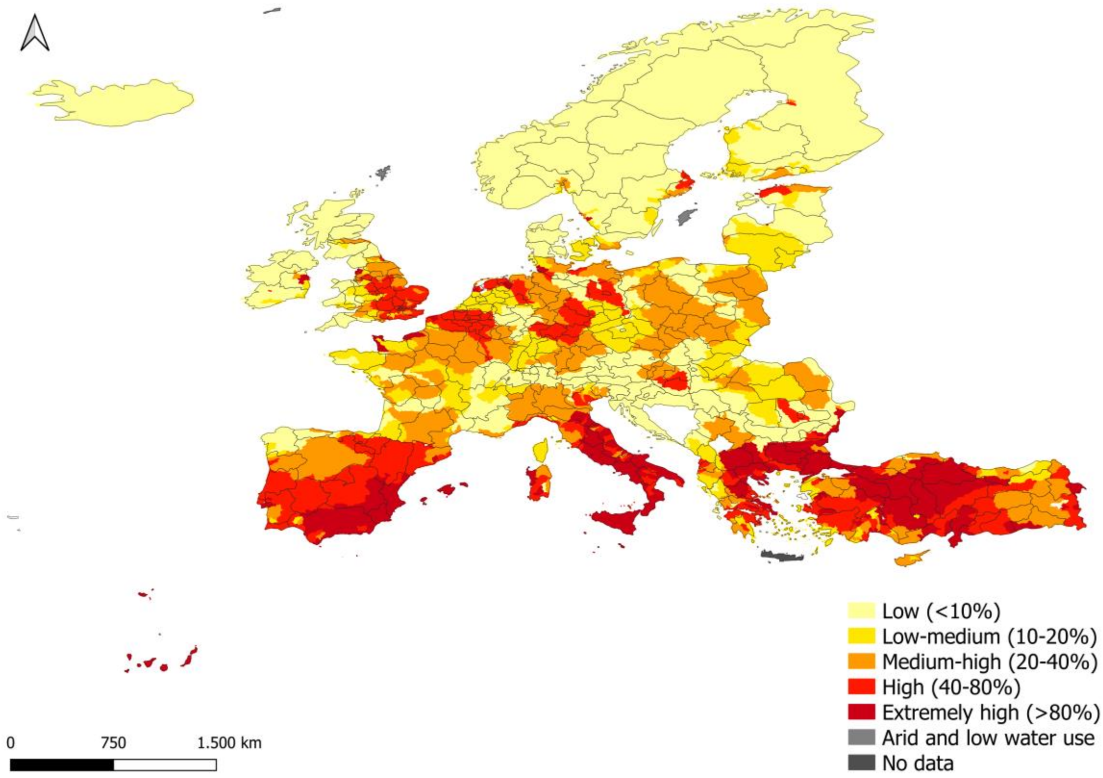

Figure 3: Water Stress in Europe 2020 [10]

Especially regions in southern Spain, southern Italy, Greece, and Turkey are subject to high to extremely high water stress. However, parts in northern Spain such as Galicia or in northern Italy can be classified into the low water stress category (cf. Figure 3).

Further, [10] provides data for water stress predictions in 2040 (cf. Figure 4). Accounting for these, Figure 4 shows that more regions will be subject to even higher water stress in 2040.

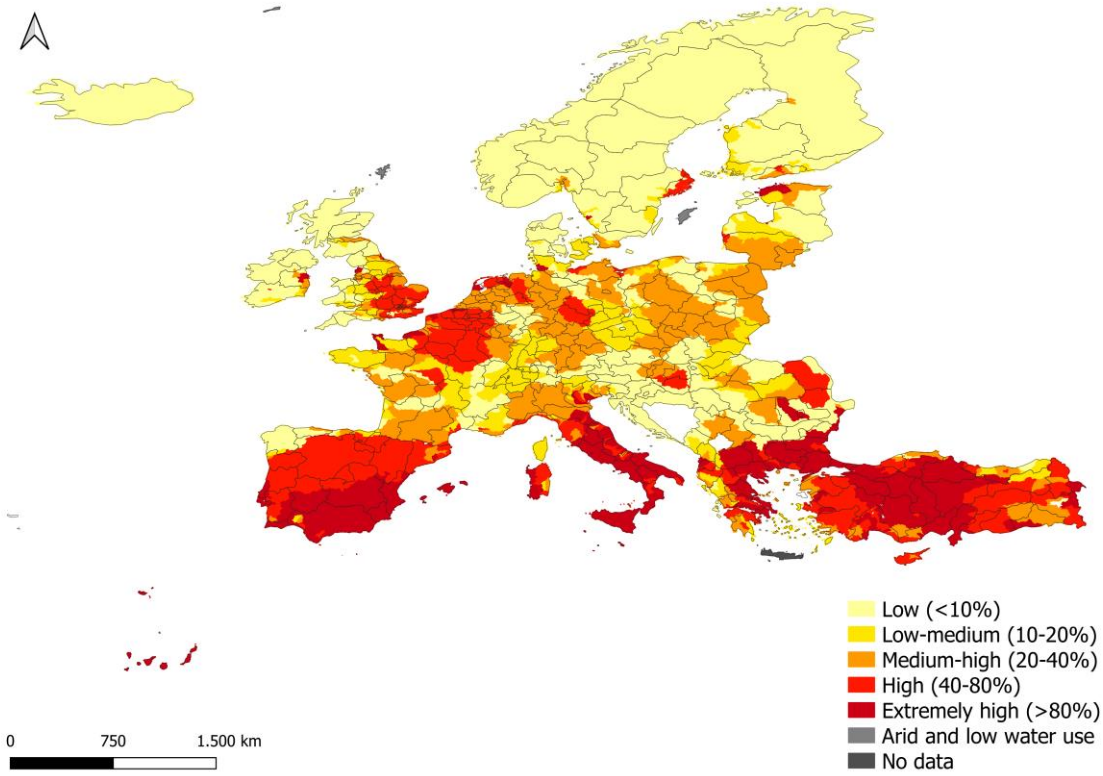

Figure 4: Water Stress in Europe 2040 [10]

In contrast, results from [31] show that countries with high solar irradiance, especially Spain, provide the lowest specific production costs for green hydrogen. Thus, suitable sites for hydrogen production, considering economic criteria, generally tend to have a risk for high water stress. Locations with high wind potential have slightly higher production costs for green hydrogen than locations with high solar irradiance. However, these locations are significantly much less subject to water stress risk. These results are contradictory regarding water availability. Thus, site planning for hydrogen production requires much more detailed and specific geographical investigations.

4.2 Seasonal Limitation

Figure 5 shows the seasonal variability of water availability in Europe. The variability is calculated by the standard deviation of average available water amounts in Europe from 1960 to 2014 divided by their respective mean value.

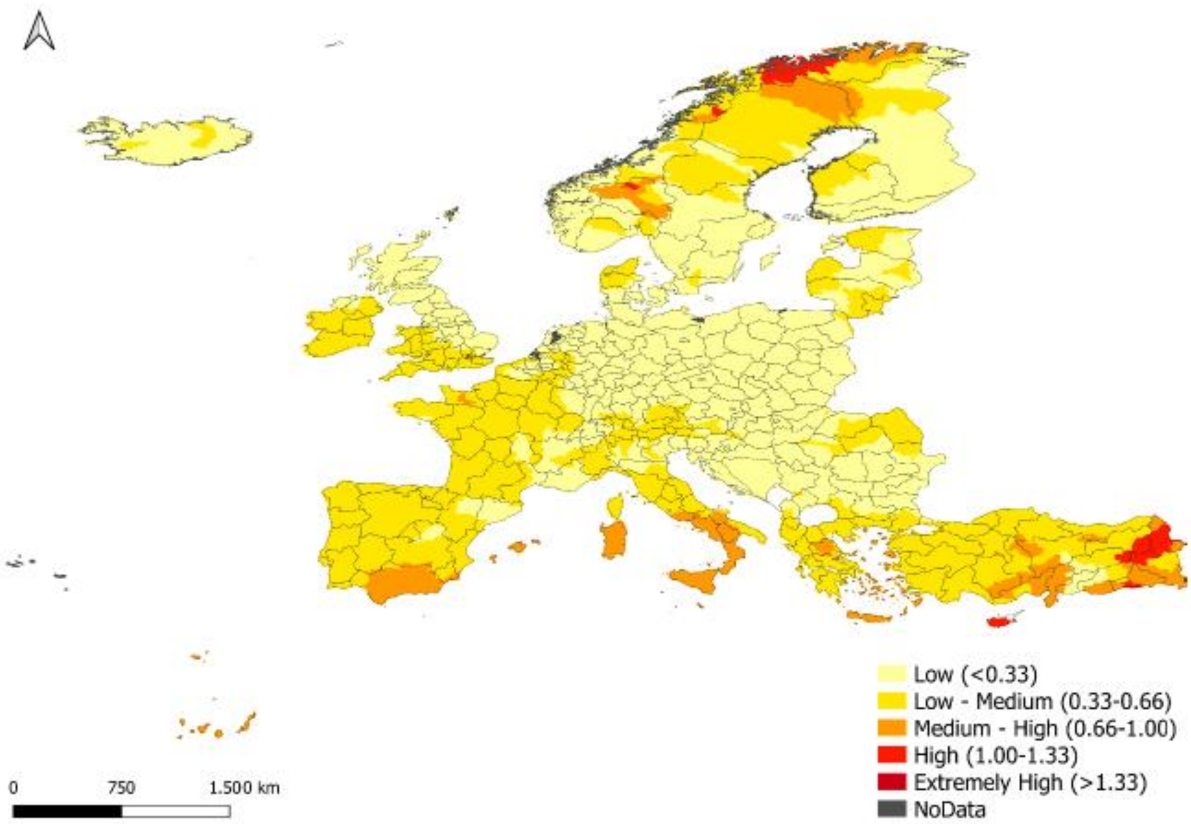

Figure 5: Seasonal variability of water availability in Europe [10]

High deviations in water availability in southern regions such as Spain and Italy result from higher temperatures in summer. Hence, hydrogen production may underly additional seasonal limitations. In northern countries, there is lower water availability in winter due to freezing. However, the water stress risk in these regions remains low [10].

Not only the water availability is subject to seasonal effects but also the availability of cheap renewable energy for hydrogen production. From an energy systems perspective, electricity from RES should especially be converted to hydrogen if it cannot be integrated directly into the power system. Integration limitations can result from network congestion and balancing issues due to RES surplus in the power system. To consider these limitations, [32] conducts a dispatch simulation that models the European power and hydrogen system in 2040 in hourly resolution and with high spatial granularity. The results indicate that optimal hydrogen production occurs primarily during summer due to the high availability of electricity from PV and wind at low electricity demand (cf. Figure 6). In contrast, hydrogen production potentials in the winter are lower due to high electricity demand and lower PV feed-in.

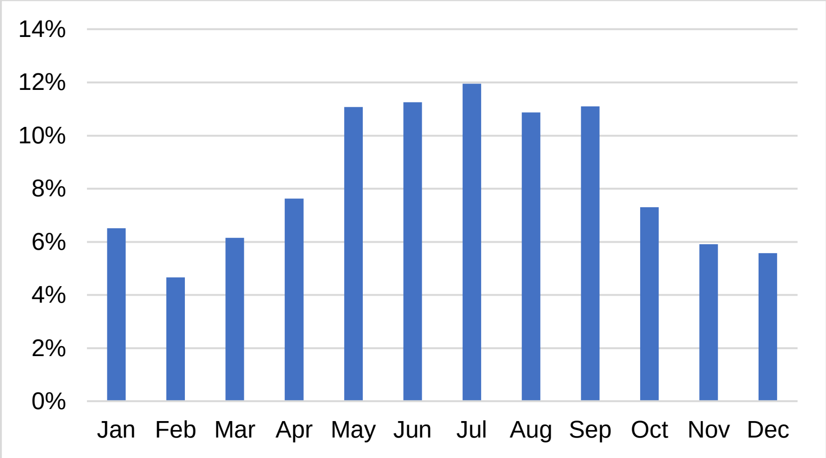

Figure 6: Monthly shares of hydrogen production [32]

Again, the analysis shows a potential conflict between water availability and hydrogen production. While from a systems perspective, hydrogen should be produced primarily in summer, water availability may be lower in southern European countries at this time (cf. Figure 4 and 6).

5 Conclusion

The analysis shows that on the European level, the water availability exceeds the predicted water demands for hydrogen production by far. Nevertheless, there are regions in Europe that are already subject to water stress. Due to climate change, even more regions will be subject to water stress, and the level of water stress will generally increase. Notably, this will affect regions with economically beneficial locations for hydrogen production. Further, water stress risk will increase in periods beneficial for hydrogen production from an energy system's point of view. This results in spatial and seasonal limitations for hydrogen production, which need to be considered when siting production plants for renewable gases and fuels. Besides, in the lack of freshwater resources, e.g., in regions in the Mediterranean Sea, seawater can represent an alternative associated with higher economic efforts.

Acknowledgment

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Appendix

Country	Freshwater Resources 2018 [bn. m^3]	WEI 2018 [%]	Water Withdrawals 2018 [bn. m^3]	Potential water withdrawals for H_2-Production [bn. m^3]	Potential H_2 Amounts [Mt]
Albania	30.20	3.17	0.96	5.08	564.74
Austria	77.70	4.49	3.49	12.05	1,339.03
Belgium	18.30	21.83	3.99	-	-
Bosnia-Herzegovina	37.50	1.07	0.40	7.10	788.75
Bulgaria	21.30	25.47	5.43	-	-
Croatia	105.50	0.64	0.68	20.32	2,258.31
Cyprus	0.78	26.54	0.21	-	-
Czech Republic	13.15	12.10	1.59	1.04	115.43
Denmark	6.00	17.83	1.07	0.13	14.47

Estonia	12.81	12.56	1.61	0.95	105.86
Finland	110.00	5.97	6.57	15.43	1,714.78
France	211.00	12.80	27.01	15.19	1,688.00
Germany	154.00	15.87	24.44	6.36	706.69
Greece	68.40	14.80	10.12	3.56	395.20
Hungary	104.00	4.26	4.43	16.37	1,818.84
Iceland	170.00	0.17	0.29	33.71	3,745.67
Ireland	52.00	2.74	1.42	8.98	997.22
Italy	191.30	17.80	34.05	4.21	467.66
Latvia	34.94	0.52	0.18	6.81	756.26
Lithuania	24.50	1.04	0.25	4.65	516.13
Luxemburg	3.50	1.49	0.052	0.65	71.98
Malta	0.051	81.74	0.041	-	-
Netherlands	91.00	8.90	8.10	10.10	1,122.33
Norway	393.00	0.07	0.28	78.32	8,702.77
Poland	60.50	15.86	9.60	2.50	278.30
Portugal	77.40	7.92	6.13	9.35	1,038.88
Romania	212.01	3.03	6.42	35.98	3,997.57
Serbia	162.20	3.43	5.56	26.88	2,986.28
Slovakia	50.10	1.11	0.56	9.46	1,051.54
Slovania	31.87	3.02	0.96	5.41	601.28
Spain	111.50	28.00	31.22	-	-
Sweden	174.00	1.36	2.37	32.43	3,603.73
Switzerland	53.50	3.19	1.71	8.99	999.26
Turkey	211.60	28.87	61.09	-	-
UK	147.00	5.73	8.42	20.98	2,330.77