Water Consumption of Powerfuels

Demand, supply, and policy recommendations to foster environmental sustainability

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Deutsche Energie-Agentur GmbH (dena)
German Energy Agency
Chausseestraße 128 a
10115 Berlin, Germany
Tel.: + 49 (0)30 66 777-0
Fax: + 49 (0)30 66 777-699
E-mail: info@dena.de
www.dena.de

Authors:
dena: Friederike Altgelt, Matteo Micheli, Katharina Sailer, Kilian Crone

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1 Water demand

Water consumption is gaining more interest in the discussion on the environmental sustainability of powerfuels, i.e. renewable hydrogen and its derivatives. The stoichiometric amount of water required to extract one kilogram of hydrogen via water electrolysis amounts to 8.92 litres, however, in practice, this quantity is usually about 25% higher (Barbir 2005). Experimental data for PEM, AEL and SOEC[1] electrolysis depicted in Figure 1 show that the three technologies consume similar amounts of water, gate-to-gate[2]. However, a more holistic quantification of water consumption requires wider product system boundaries. Expanding the product system boundary of water electrolysis, as well as expanding the product system itself by also considering further process steps needed to produce hydrogen derivatives increases the variability of the data on water consumption, thereby also increasing the complexity of the topic.

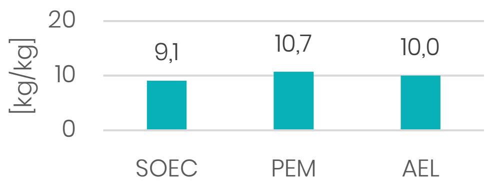

Figure 1: Water consumption, hydrogen, Gate-to-Gate

Water Quantity

To gain a clear understanding of the quantities of water employed in powerfuels production, it is pivotal to distinguish between *water use* and *water consumption*. First, it is crucial to note that water use and consumption refer to freshwater only in the definitions used herein, and so do the reported figures. Other water sources such as desalinated water or recycled water therefore do not contribute to water use and water consumption. Hence, they hold the potential to reduce water use and consumption to zero, as they do not diminish the amount of freshwater that is available to the ecosystem and for downstream users. However, using non-freshwater sources can be linked to additional challenges, e.g. regarding the water quality and the degree of water treatment needed (Simoes et al. 2021).

Water use equals the freshwater intake from surface or ground water.

Water consumption is defined in this report according to lifecycle assessment (LCA) practice as freshwater losses on a watershed level, which are caused by evaporation, freshwater integration into products, and release of freshwater into sea. Consumed water thus represents the share of used water that is not available to the ecosystem and for downstream users any longer (Koehler and Thylmann 2012).

$$Water\ consumption = Water\ use - Water\ discharge$$

Second, additional water consumption compared to a gate-to-gate boundary may result, among others, from water required for cooling in the individual processes in fuel production and possibly also from cleaning of installations for solar power generation (Heinemann and Kasten 2019).

Third, while gate-to-gate water consumption is a practical measure to quantify the water requirements of electrolysis operation, it does not capture the water consumed over the entire lifecycle of hydrogen production, which would require a cradle-to-grave[3] lifecycle analysis. (Shi et al. 2020) performed such a cradle-to-grave LCA of hydrogen produced via PEM electrolysis in Australia. According to the authors, prior to mid-2020, no rigorous analysis of the nexus of hydrogen and its associated water use, consumption, and impact had been performed.

[1] Polymer Electrolyte Membrane electrolyzers (PEM), Solid Oxide Cell electrolyzers (SOEC) and alkaline water electrolyzers (AEL) are the common technologies for the production of renewable hydrogen and its derivatives
[2] The term "gate-to-gate" describes the system boundary pertinent to the presented data. The gate-to-gate boundary includes one sole value-added process of the production chain. In this case, the electrolysis reaction alone.
[3] I.e. a system boundary including the whole product system lifecycle from the extraction of raw materials to its end of life.

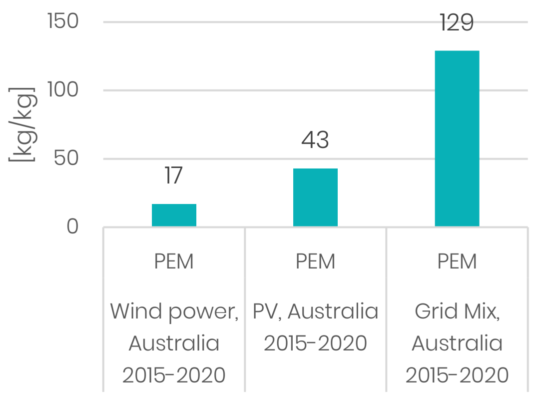

Figure 3: Water consumption, hydrogen, Cradle-to-Grave

Their results are reported in Figure 2, which shows that the water consumed over the lifecycle of hydrogen can be several factors higher than the water employed for electrolysis alone. Lifecycle analysis does not necessarily provide a clear assessment of the local impact on water consumption at the production site, yet it delivers a holistic quantification of the amount of water consumed over the energy carrier's lifetime.[4]

In conclusion, the water consumption of green hydrogen itself varies widely and contributes significantly to the amount of water consumed over the lifecycle of green hydrogen-based products such as PtL-diesel and PtL-kerosene.

When hydrogen is processed further to a Power-to-Liquid (PtL) fuel, additional sources of water consumption need to be considered. It is particularly interesting to note that some Direct Air Capture (DAC) plants[5] can extract water from the air during operation to amounts high enough to exceed the operational water needs of the PtL process (including electrolysis), implying that at the PtL production facility itself, water can be produced, and not consumed. This is true, e.g., for the low-temperature DAC plants operated by Climeworks. According to the company,, their technology can extract about 1,000 litres of water from air per tonne of CO_2 captured (Viebahn et al. 2019).

To quantify the magnitude of the water consumption of green hydrogen and its derivatives, it is helpful to compare it to the water consumption of their fossil equivalents, for example hydrogen from steam methane reforming (SMR) ("grey hydrogen") and fossil Jet A-1 (aviation kerosene). Water is consumed in both SMR and electrolysis processes as a feedstock (i.e. process water), for the reaction process (steam), and for cooling (where water is lost due to evaporation). One lifecycle assessment by the National Renewable Energy Laboratory (NREL) indicates that SMR hydrogen has a cradle-to-grave water consumption of 19.8 kg per kg of hydrogen, 95% of which (18.8 kg/kg) results from plant operation, i.e. gate-to-grave (Spath and Mann 2000). A more recent LCA with a gate-to-grave boundary found a value of 11.7 kg per kg of SMR hydrogen (Argonne National Laboratory 2015). The cradle-to-grave water consumption of Jet A-1 produced in Germany 2017 to 2019 amounted to 0.53 kg per kg of fuel (Sphera 2019).

For hydrogen from electrolysis, the above-mentioned LCA reports a value of 30 kg per kg of H_2 (Argonne National Laboratory 2015). Figure 2 shows a comparison of gate-to-grave water consumption of SMR and green hydrogen, while Figure 4[6] shows a comparison of cradle-to-grave water consumption of DAC-CO_2-based Fischer-Tropsch PtL-kerosene produced with green hydrogen from wind power, and Jet A-1. It should be noted that this is not an exhaustive overview and that values may vary, mainly depending on the amount of recycled water within the production process as well as the employed technologies, locations, and timeframes.

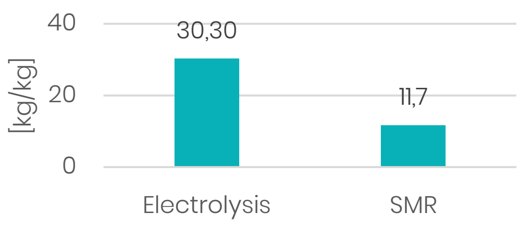

Figure 2: Water consumption, hydrogen, Gate-to-Grave

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[4] Mehmeti et al. (2018) performed a cradle-to-grave LCA of hydrogen produced via 17 different production pathways, including water electrolysis, as well as fossil fuels- or bio-based pathways. The work however does not clearly state the methodology for calculating the presented data, decreasing the comparability and reliability of its results (Shi et al. 2020)

[5] DAC can be employed to provide the feedstock carbon needed in the production of hydrogen-based hydrocarbons.

[6] The value of 1,9 kg/kg for PtL-kerosene represents an average of the studied cases, which are in part reported in figure 5. The underlying assumptions can be accessed upon reasonable request to the authors.

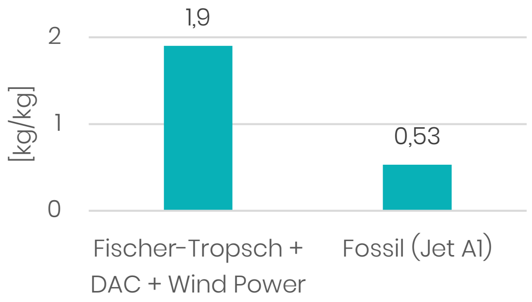

Figure 4: Water consumption, PtL-kerosene vs. Jet A-1, Cradle-to-Grave

Especially for the case of PtL-kerosene, the values can vary widely as illustrated in Figure 5, where within a cradle-to-grave boundary, the water consumption ranges from negative 0.8 kg/kg to 8 kg/kg, i.e. from up to 16 times more than Jet A-1 to being a source of water with an output of 0.8 litres per kg of fuel. Levers for lowering water consumption include using higher shares of electricity from PV and optimizing process efficiency, for example by recovering waste heat.

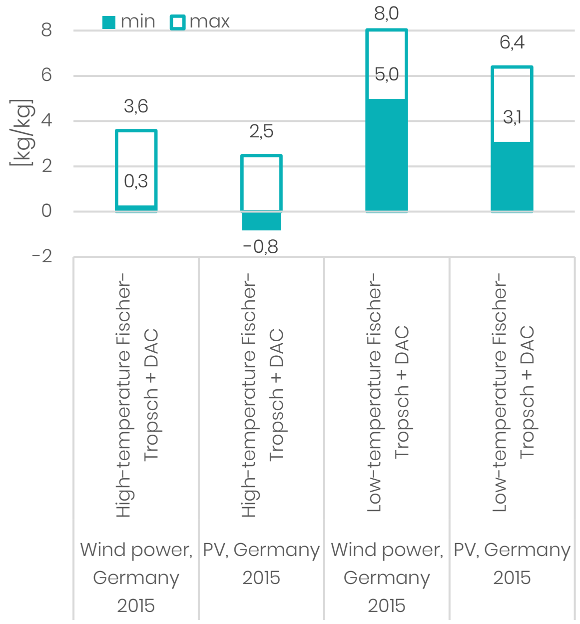

Figure 5: Water consumption, PtL-diesel and PtL-kerosene, Cradle-to-Grave

2 Water supply

Some of the regions often discussed as the most favourable locations for the production of electricity-based hydrogen have high solar radiation but are among the driest regions in the world, e.g. countries in the Middle East and North Africa (MENA). The supply of freshwater is already insufficient in many of these regions (Heinemann and Kasten 2019).

Identifying current and estimating future centres of water scarcity or stress requires considering both stocks and flows, i.e. water availability as well as water withdrawals and water consumption. Indicators most frequently used can broadly be subsumed under two categories: per-capita measurements of water availability (indicating "demographic water scarcity") and use-to-availability ratios ("technical water scarcity") (Xu & Wu, 2017). Use- or consumption-to-availability ratios are generally preferable, because they map actual water use against the total resource. One of the most used indices of this category is the ratio of annual water withdrawals to annual water availability (w.t.a.) (Liu et al. 2017; Vörösmarty et al. 2000)[7]. Other, and even more preferable indicators, are consumption-to-availability ratios, as they subtract the part of the withdrawal water that returns back to water bodies and therefore more accurately depicts the impact on locally available water resources. However, ratios based on consumption are more difficult to implement.

Water availability[8], denoting how much of the resource is accessible for use in the respective region and time frame, is difficult to operationalise as water is not a static resource but exists in dynamic cycles that include phases of rain, runoff, and evaporation (Xu & Wu, 2017). Indices therefore need to define system boundaries, e.g. by only measuring surface water such as runoff and stream flows. Some indicators only count the volume of water that can be consumed without expected adverse ecological impacts as "available". For example, Hoekstra et al. (2012) suggest to subtract 20% of total natural runoff so that "available water" is defined as the maximum amount that can be consumed while maintaining an ecological balance.

For indicators based on a use-to-resource ratio, a threshold of 20% or 40% is frequently used to indicate a medium or high water stress status, respectively, (Moore et al. 2015; Vörösmarty et al. 2005); however, the reliability of this threshold is under question as a rationale is often not provided (Xu and Wu 2017).

United Nations Water (UN-Water), an interagency body in charge of coordinating the UN's efforts with regard

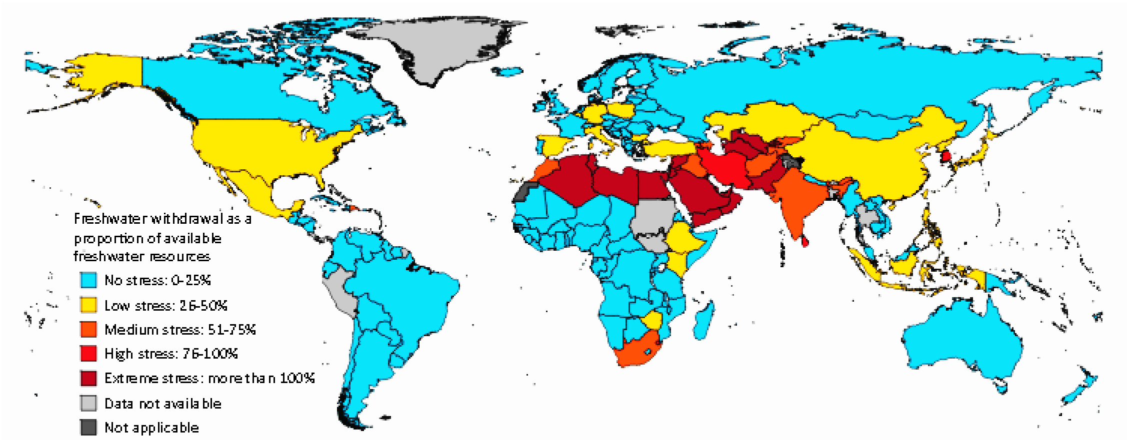

Figure 6: Global country-specific water stress level map (UN-Water 2021)

[7] Flörke and Alcamo 2007) define the annual water withdrawals as the total volume of water abstracted from either surface or groundwater sources for the main water use sectors, hence mirroring the definition of water use outlined in section 1

[8] Only the availability of so-called "blue" water resources, i.e. freshwater that is stored in lakes, streams, groundwater,, glaciers and snow, is considered in this report, as "green"water, precipitation that filtrates into the soil,, is almost exclusively used for agricultural production for human purposes.

to water and sanitation issues, uses a withdrawal-to-availability ratio to map water stress by country (see Figure 6). Based on data on freshwater withdrawals and availability from 2017, UN-Water finds that globally, five out of eleven regions have water stress values between 25% and up to over 100%, denoting levels of low to extreme water stress. UN-Water finds Northern Africa as well as Southern and Central Asia to experience the highest levels of water stress (UN-Water 2021). It further establishes that water stress exacerbated between 2000 and 2017 in all world regions except for Western Asia, Europe and Northern America.

The World Resources Institute's Aqueduct Water Risk Atlas provides high-resolution data on water stress and water depletion, using a withdrawal-to-availability ratio and a consumption-to-availability ratio, respectively. It finds that 17 countries, home to a quarter of the world's population, face "extremely high" water stress and that 44 countries face "high" levels of stress (withdrawal of more than 40% of available supply every year on average) (Hofste et al. 2019). Data from the Aqueduct Water Risk Atlas also indicate that water stress is an inherently local issue, as regions or communities may be experiencing severely water-stressed conditions even if they are located in countries with low overall water stress (e.g. the state of New Mexico in the United States). These data are also used in an atlas depicting the global powerfuels production potential developed by the research institute Fraunhofer IEE. In this spatial analysis, regions with high water stress were excluded (Fraunhofer IEE 2021).

Solution 1: Seawater desalination

Water desalination is a well-established technology practiced in over 150 countries, with over 300 million people relying on desalinated water for their freshwater supply (Panagopoulos and Haralambous 2020). Given the significant water consumption of electrolysis, desalination can play an important role as an upstream technology for green hydrogen production (Fasihi et al. 2016; Hydrogen Europe 2020), as low-grade and saline water is a largely abundant resource in many regions.

In terms of economics, seawater desalination costs approximately 1€/m^3, equivalent to 0.001€ per kg of desalinated water (Food and Agriculture Organization of the United Nations 2006). Therefore, the costs of water consumption for electrolysis as a share of the total costs of producing renewable hydrogen are negligible, even in countries where desalination is necessary for hydrogen production (Agora Energiewende et al. 2018).

However, in Europe, water resulting from desalination currently on average has a 44 times higher CO_2 footprint than tap water (filtrated, disinfected,) (ISCC 2021). This is a result of the high energy intensity of the desalination process, as desalination plants today still rely on the use of fossil energy for operation. To a large extend

The other main environmental impact of desalination is the rejected brine, a hyper-saline discharge stream which may further contain process chemicals and metals (Jones et al. 2019). Brine is typically released to the sea, leading to significant damages to the local ecosystem. Based on a review of six extensive publications on the topic, Panagopoulos and Haralambous (2020) find that the main environmental impacts of desalination are:

- (i) major adverse effects on the quantity and quality of natural resources, including soil, air and water;
- (ii) substantial changes in aquatic ecosystems;
- (iii) human resettlement;
- (iv) public health risk due to the quantity and quality of effluents, emissions or residues especially when near urban or rural areas;
- (v) landscape alteration.

Different brine disposal methods varying in complexity and costs as well as environmental impact are available. As an alternative to conventional methods such as surface water discharge, so-called zero-liquid discharge (ZLD) technologies can help to avoid wastewater disposal in the environment (Panagopoulos et al. 2019) at additional costs that are relatively low compared to the overall renewable hydrogen production costs.
Environmental regulations for brine disposal are in place around the world, and vary significantly from region to region (Friedmann et al. 2020). In this context, selected regulatory recommendations are presented in section 3.

Solution 2: Water from Direct Air Capture

Low-temperature Direct Air Capture based on alkaline solid sorbents extracts approximately 1 kg of water per kg of CO_2 captured from ambient air (Viebahn et al. 2019), corresponding to approximately 3.8 kg of water per kg of PtL-fuel produced. As water is a by-product collected during the extraction of CO_2, very low additional costs result from extracting the respective amounts of water.

However, this water extraction method stems from a relatively nascent technology, and has not been tested at scale to date.

Solution 3: Electrolysis of low-grade and saline water

Hydrogen production via electrolysis generally requires water in drinking quality. Thus, the use of water for electrolysis is in direct competition with the needs of the local population (Heinemann and Kasten 2019). However, research is being conducted on developing electrolysers that are capable of operating with impure water feeds, e.g. low-grade and saline water, directly. Tong et al. (2020) provide an overview of the current state of technologies and key challenges in this domain.

3 Fostering environmental sustainability

Currently, existing regulation neither explicitly specifies criteria for water use and consumption of powerfuels nor defines reporting and monitoring parameters and obligations. However, finding practical and sound criteria is a key towards establishing transparency and sustainability for powerfuels as an energy carrier.

In the EU, the revised Renewable Energy Directive (RED II) does not include explicit criteria for water consumption. While Article 30(4) refers to the principle of water efficiency[9], thresholds or criteria have not yet been defined. It is therefore imperative that water sustainability criteria are added to existing regulation on green hydrogen. To avoid the emergence of diverging standards and facilitate trade of powerfuels between countries, the adoption and implementation of these criteria should be steamlined internationally.

We propose the following criteria:

1. Efficient use of water
   A water efficiency criterion in form of a water consumption threshold is to be established, which will have to be met by operators of powerfuels plants irrespective of the level of local water stress (e.g. max. 50 kg water per kg hydrogen output, cradle-to-grave).

2. Plant-level water impact assessment
   As water scarcity is an inherently local issue, the impact of powerfuels production ought to be measured at regional level based on existing administrative subdivisions, e.g. corresponding to population sizes of approximately 1-3 million. The World Resources Institute's Aqueduct Water Risk Atlas indicates that data on water consumption and availability is available globally at this level.

   Based on these data, the electrolyser must demonstrate ex-ante that it does not increase the risk of declining water levels or negatively affect the existing water supply (see REGATRACE 2020). Hence, when freshwater is used, the electrolyser cannot be installed in areas with declining water availability, i.e. surface and groundwater supplies, or with acute water scarcity. This can be measured by a two-year trend of facing "high" or "extremely high" water stress prior to the installation of the plant (see section 2 for the specification of these terms following Hofste et al. 2019). An ex-ante evaluation of the hydrological condition of the construction site is to be conducted by the operator before the installation is implemented (California Energy Commission and California Natural Resources Agency 2018).

   The evaluation should be audited within the powerfuels certification process. As part of this evaluation, operators may have to provide evidence that the project in question implements measures in order to offset its impact on the local hydrological condition (Shi et al. 2020).

In the case of desalination, further criteria should be implemented:

1. GHG emissions associated with water desalination should be counted towards the overall emissions of the produced hydrogen in

[9] The water efficiency principle is mentioned in the context of voluntary schemes setting standards for the production of renewable fuels: "The Commission may decide that those schemes contain accurate information on measures taken [...] for the avoidance of excessive water consumption in areas where water is scarce"

order to incentivise the use renewable electricity[10];

2. The environmental impacts of the discharged brine should be minimised according to best practices:

   (i) When brine is disposed into the sea in sensitive areas, design criteria of diffusers based on research findings on how to maximize dilution should be applied, e.g. following the concept of minimum return point dilution developed by Ahmad and Baddour (2014);

   (ii) Green antiscalants and green corrosion inhibitors should be employed whenever possible as substitutes to the environmentally toxic alternatives usually in use;

   (iii) To minimise waste streams, desalination brine should be further processed to a larger extend than presently, for example by implementing zero-discharge requirements. Such requirements can contribute to incentivising the development and implementation of technologies which minimize brine discharge, such as ZLD. Ideally, processing brine further can also become economically viable when valuable assets such as metals and chemicals are derived in the process.

[10] Water electrolysis is of interest for the production of renewable hydrogen, which is required to achieve a GHG emission reduction of at least 70% according to the REDII Allocating GHG emissions from electricity for water production to hydrogen therefore incentivises the demand for water desalinated with renewable electricity.

List of Figures

Bibliography

Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018): Die zukünftigen Kosten strombasierter synthetischer Brennstoffe, checked on 7/12/2021.

Ahmad, Nadeem; Baddour, Raouf E. (2014): A review of sources, effects, disposal methods, and regulations of brine into marine environments. In *Ocean & Coastal Management* 87, pp. 1–7. DOI: 10.1016/j.ocecoaman.2013.10.020.

Argonne National Laboratory (2015): Life-Cycle Analysis of Water Consumption for Hydrogen Production, 2015, checked on 5/27/2021.

Barbir, Frano (2005): PEM electrolysis for production of hydrogen from renewable energy sources. In *Solar Energy* 78 (5), pp. 661–669. DOI: 10.1016/j.solener.2004.09.003.

California Energy Commission; California Natural Resources Agency (2018): California's Changing Climate 2018, checked on 7/13/2021.

Fasihi, Mahdi; Bogdanov, Dmitrii; Breyer, Christian (2016): Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants. In *Energy Procedia* (99), pp. 243–268. DOI: 10.1016/j.egypro.2016.10.115.

Flörke, Martina; Alcamo, Joseph (2007): Assessment of global scale water stress indicators, checked on 7/12/2021.

Food and Agriculture Organization of the United Nations (2006): Water desalination for agricultural applications. Proceedings of the FAO Expert Consultation on Water Desalination for Agricultural Applications, checked on 7/12/2021.

Fraunhofer IEE (2021): PtX-Atlas. Available online at https://devkopsys.de/ptx-atlas/.

Friedmann, Julio; Zapantis, Alex; Page, Brad; Consoli, Chris; Fan, Zhiyuan; Havercroft, Ian et al. (2020): Net-Zero and Geospheric Return: Actions Today for 2030 and Beyond. Edited by Columbia University CGEP, checked on 5/12/2021.

Heinemann, Christoph; Kasten, Peter (2019): Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland. Zusammenfassung und Einordnung des Wissenstands zur Herstellung und Nutzung strombasierter Energieträger und Grundstoffe. Öko-Institut e.V. Freiburg, checked on 7/12/2021.

Hoekstra, Arjen Y.; Mekonnen, Mesfin M.; Chapagain, Ashok K.; Mathews, Ruth E.; Richter, Brian D. (2012): Global monthly water scarcity: blue water footprints versus blue water availability. In *PLOS ONE* 7 (2), e32688. DOI: 10.1371/journal.pone.0032688.

Hofste, Rutger Willem; Reig, Paul; Schleifer, Leah (2019): 17 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress. World Resources Institute. Available online at https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress.

Hydrogen Europe (2020): Hydrogen production and water consumption factsheet, checked on 5/21/2021.

ISCC (2021): Impulsvortrag: ISCC - Lösungen für die Zertifizierung von "grünem Wasserstoff".

Jones, Edward; Qadir, Manzoor; van Vliet, Michelle T. H.; Smakhtin, Vladimir; Kang, Seong-Mu (2019): The state of desalination and brine production: A global outlook. In *The Science of the total environment* (657), pp. 1343–1356. DOI: 10.1016/j.scitotenv.2018.12.076.

Koehler, Annette; Thylmann, Daniel (2012): Introduction to Water Assessment in GaBi Software. Version 1.2. PE INTERNATIONAL AG. Leinfelden – Echterdingen, checked on 7/12/2021.

Liu, Junguo; Yang, Hong; Gosling, Simon N.; Kummu, Matti; Flörke, Martina; Pfister, Stephan et al. (2017): Water scarcity assessments in the past, present and future. In *Earth's future* 5 (6), pp. 545–559. DOI: 10.1002/2016EF000518.

Moore, Brandon C.; Coleman, André M.; Wigmosta, Mark S.; Skaggs, Richard L.; Venteris, Erik R. (2015): A High Spatio-temporal Assessment of Consumptive Water Use and Water Scarcity in the Conterminous United States. In *Water Resour Manage* 29 (14), pp. 5185–5200. DOI: 10.1007/s11269-015-1112-x.

Panagopoulos, Argyris; Haralambous, Katherine-Joanne (2020): Environmental impacts of desalination and brine treatment - Challenges and mitigation measures. In *Marine pollution bulletin* 161 (Pt B), p. 111773. DOI: 10.1016/j.marpolbul.2020.111773.

Panagopoulos, Argyris; Haralambous, Katherine-Joanne; Loizidou, Maria (2019): Desalination brine disposal methods and treatment technologies - A review. In *The Science of the total environment* 693, p. 133545. DOI: 10.1016/j.scitotenv.2019.07.351.

REGATRACE (2020): D4.1 Guidelines for the Verification of Cross-Sectoral Concepts. Renewable Gas Trade Centre in Europe (REGATRACE), checked on 7/13/2021.

Shi, Xunpeng; Liao, Xun; Li, Yanfei (2020): Quantification of fresh water consumption and scarcity footprints of hydrogen from water electrolysis: A methodology framework. In *Renewable Energy* 154, pp. 786–796. DOI: 10.1016/j.renene.2020.03.026.

Simoes, Sofia G.; Catarino, Justina; Picado, Ana; Lopes, Tiago F.; Di Berardino, Santino; Amorim, Filipa et al. (2021): Water availability and water usage solutions for electrolysis in hydrogen production. In *Journal of Cleaner Production* 315, p. 128124. DOI: 10.1016/j.jclepro.2021.128124.

Spath, P. L.; Mann, M. K. (2000): Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming, checked on 5/26/2021.

Sphera (2019): GaBi ts. Version 8.

Tong, Wenming; Forster, Mark; Dionigi, Fabio; Dresp, Sören; Sadeghi Erami, Roghayeh; Strasser, Peter et al. (2020): Electrolysis of low-grade and saline surface water. In *Nat Energy* 5 (5), pp. 367–377. DOI: 10.1038/s41560-020-0550-8.

UN-Water (2021): Summary Progress Update 2021 – SDG 6 – water and sanitation for all. Geneva. Available online at https://www.unwater.org/app/uploads/2021/07/SDG-6-Summary-Progress-Update-2021_Version-July-2021.pdf, checked on 7/12/2021.

Viebahn, Peter; Scholz, Alexander; Zelt, Ole (2019): The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis. In *Energies* 12 (18), p. 3443. DOI: 10.3390/en12183443.

Vörösmarty, C. J.; Green, P.; Salisbury, J.; Lammers, R. B. (2000): Global water resources: vulnerability from climate change and population growth. In *Science* 289 (5477), pp. 284–288. DOI: 10.1126/science.289.5477.284.

Vörösmarty, Charles J.; Douglas, Ellen M.; Green, Pamela A.; Revenga, Carmen (2005): Geospatial indicators of emerging water stress: an application to Africa. In *Ambio* 34 (3), pp. 230–236. Available online at https://pubmed.ncbi.nlm.nih.gov/16042282/.

Xu, Hui; Wu, May M. (2017): Water Availability Indices – A Literature Review. Edited by Argonne National Laboratory, checked on 7/12/2021.

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