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1 **The Water Footprint of Hydrogen Production**

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8 **Abstract**

9 Hydrogen (H₂) is the most promising energy carrier for reducing the carbon emissions of
10 the energy sector, but the impact of its production on water resources remains unclear. Here, we
11 quantify the water footprint (WF) of different H₂ production pathways accounting for the WF of
12 the primary energy used in the production process, as well as feedstock and infrastructure water
13 requirements. Results suggest that green H₂ obtained from water electrolysis powered by
14 renewable energy has the lowest WF (65±2 m³/TJ for wind and 204±79 m³/TJ for solar) mostly
15 due to the low WF of renewable energy. The WF of blue H₂ derived from fossil fuels is significantly
16 higher (369±30 m³/TJ for natural gas and 564±82 m³/TJ for coal) due to high WF of fossil fuels
17 as well as the water required for carbon capture and storage (CCS). H₂ produced from nuclear
18 energy and biomass have extremely high WF (741±277 m³/TJ for nuclear and >50000 m³/TJ for
19 biomass). Considering global and country-based energy scenarios, where the main H₂ colors (green
20 and blue) individually account for 15% of energy consumption, we find that the use of green H₂
21 could reduce the water demand of the energy sector while blue H₂ would generally increase it,

22 except in countries already characterized by high water consumption due to reliance on water-
23 intensive energy sources. At the global level, we find that for every 5% of H₂ energy adoption, the
24 energy sector could have water savings between 1 - 4% for green H₂ and increase water
25 consumption between 1 - 5% for blue H₂. These results highlight the potential and criticalities of
26 H₂ within the water-energy nexus.

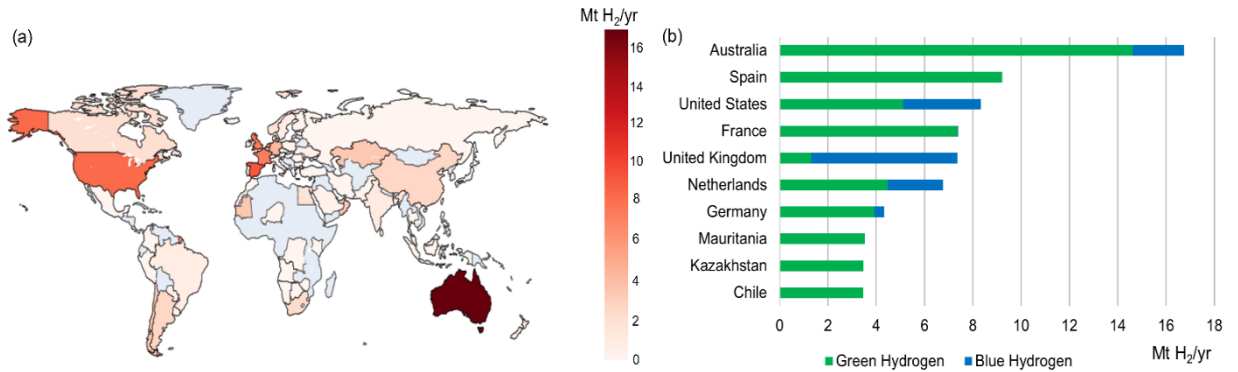
27 Keywords: Water footprint, Hydrogen, Energy Transition

28 **1. Introduction**

29 Hydrogen (H₂) has been receiving a great deal of attention as the low-carbon energy carrier
30 of the future (Hydrogen Council, 2023; IEA, 2022a). The current H₂ demand of 94 Mt in 2021
31 (IEA, 2022a) is mostly for the refining and fertilizer industries, but new H₂ applications are
32 expected to develop in industry, transport sector, and power generation (IEA, 2022a). Announced
33 pledges to produce new H₂ are rising rapidly and extensively around the world, e.g., from 66 Mt
34 H₂/yr in the 2021 hydrogen projects database to 106 Mt H₂/yr in its 2022 update (IEA, 2022b).
35 Production strategies involve multiple approaches, but particularly via either water electrolysis
36 powered by renewable energy or fossil fuel with Carbon Capture and Storage (CCS), referred to
37 as green and blue H₂, respectively. Other production pathways may include water electrolysis
38 powered by nuclear energy (pink H₂) and H₂ from biomass (brown H₂). The H₂ color scheme
39 utilized in this manuscript follows from the summary by Incer-Valverde et al. (2023).

40 The global distribution of announced pledges is shown in Figure 1(a), along with the top
41 prospective H₂-producing countries (Fig. 1b). Countries with significant H₂ production pledges
42 have either access to abundant renewable energy necessary to produce green H₂ or a heavy reliance

43 on fossil fuels, which requires inclusion of low-carbon energy solutions into the energy mix (blue
44 H₂) to meet decarbonization goals.



45
46 **Figure 1.** Global pledges for low-carbon H₂ production from data of the International Energy
47 Agency (IEA, 2022b). (a) Global distribution, (b) Top ten prospective H₂ producing countries.
48 Color bar represents the pathway of H₂ production.

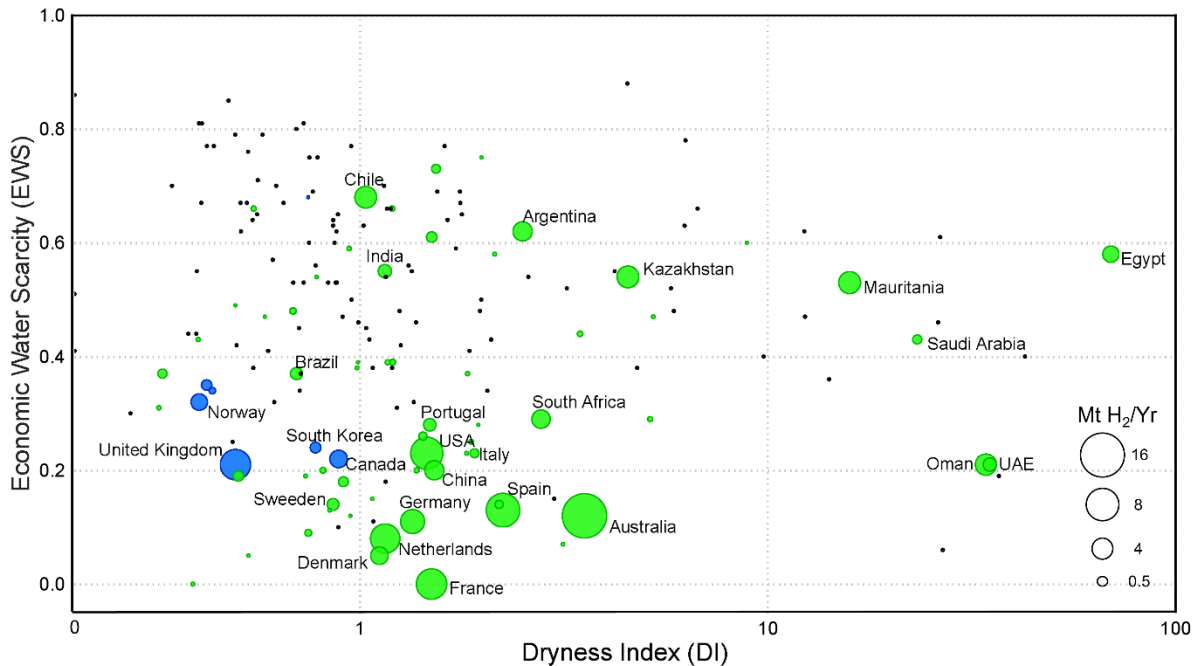
49 The impact of H₂ production on the water-energy nexus remains uncertain, and the
50 intensity of H₂ energy on water resources necessitates thorough quantification for a comprehensive
51 understanding. Consequently, the integration of H₂ into energy transition strategies necessitates an
52 examination of how H₂ impacts the water demand of energy sector at both regional and global
53 scale, bearing in mind the several underlying determinants which can influence these dynamics,
54 including the quantity of H₂ demand, pathway of production, and infrastructural requirements
55 (with or without CCS technologies), amongst others. Previous works (Beswick et al., 2021; Tonelli
56 et al., 2023) quantified the amount of water required globally for a proposed future green H₂
57 demand and observed that this requirement is small compared to the current amount of water
58 utilized in the fossil fuel sector or in agriculture. Specifically, the geographically explicit analysis
59 (Tonelli et al., 2023) reported that the water required for a global green H₂ demand of 400 MtH₂/yr
60 in 2050 does not create water scarcity almost anywhere in the world if water scarcity is not already

61 present. However, on the one hand these previous works (Beswick et al., 2021; Tonelli et al.,
62 2023) focused on green H₂ only, while on the other hand, other works on quantifying the water
63 requirements of H₂ production (e.g., Lampert et al. 2015 and Mehmeti et al., 2018) only provided
64 numerical values for the water requirements without a clear analysis of how the reported values
65 are obtained, and neglected the water requirement of the primary raw material or energy source,
66 leaving unclear the total water requirement of different H₂ production methods and how these can
67 impact regional and global resources. Such an analysis is required, especially considering that a
68 high percentage of the water required for energy is locally sourced and the majority of the proposed
69 green H₂ projects are in countries with abundant renewable energy potential but limited water
70 availability.

71 The water-energy connection of the H₂ economy is already apparent in Figure 2, where we
72 show the country-level H₂ production pledges as a function of physical and economical water
73 scarcities. The physical water scarcity may be quantified by the dryness index (DI), a crucial index
74 in the hydrological sciences (Porporato & Yin, 2022), obtained as a ratio of potential
75 evapotranspiration and precipitation. The dryness index is related to the tendency of a region to
76 be susceptible to water stress or scarcity in the presence of a perturbation in water demand. The
77 Economic Water Scarcity (EWS) is defined as a situation in which technical and institutional
78 capacities or financial resources are insufficient to supply adequate water quantities for human
79 use (Molden, 2013; Rosa et al., 2020; Vallino et al., 2020), and quantified as the complement of
80 the sustainable development goals (SDG) indicator 6.5.1 on the Integrated Water Resources
81 Management (IWRM), i.e., $EWS = 1 - IWRM$. The indicator assesses water governance and
82 management, providing a framework to determine if water resources are managed equitably,
83 efficiently, and sustainably in each country. EWS is close to one when low level of water

84 management is present and to zero when best water management is attained (Vallino et al., 2021).
 85 The majority of the proposed green H₂ projects are in countries with limited water availability
 86 (DI>1), while blue H₂ projects tend to be in water-abundant countries (DI<1). From a
 87 socioeconomic perspective, countries with efficient water management strategies (EWS<0.4)
 88 account for a larger proportion of H₂ production pledges.

89 The water-product connection prompted researchers to introduce the concept of Water
 90 Footprint (WF), which measures the volume of freshwater used to produce a product (here energy,
 91 so that WF is in m³ of water per TJ of energy produced) over the full supply chain (Egan, 2011).



92
 93 **Figure 2.** H₂ production pledges as a function of economic water scarcity (EWS) and dryness
 94 index (DI). The size of each circle is proportional to the H₂ production pledge (Mt H₂/yr). Dryness
 95 index axis in log scale. Black points are countries with no H₂ production pledge, blue points
 96 represent countries whose pledged H₂ production is majorly from the fossil fuels pathway, while
 97 green points represent countries whose pledged H₂ production is majorly from the water

98 electrolysis pathway (IEA, 2022b). Data for EWS was obtained from Harris et al. (2020), and DI
99 from UNEP (2021).

100 The assessment of the WF follows two distinct approaches (Postle et al., 2012; UNEP, 2021;
101 Vanham & Bidoglio, 2013): (1) the volumetric approach which measures the volume of water
102 required for production and (2) the Life Cycle Analysis approach described in (UNEP, 2021)
103 extends beyond production and evaluates the environmental performance of products and services
104 along their life cycle. This paper estimates the WF of H₂ production using the volumetric approach
105 (Hoekstra et al., 2012) and accordingly, the WF of H₂ provides information about the total volume
106 of water required for production, and this quantity can be influenced by several underlying factors,
107 including the WF of the primary energy sources or raw material required for production, water
108 required for feedstock, as well as the infrastructural water requirements (plant cooling and for CCS
109 facilities in case of energy sources relying on fossil fuels). The WF of a product has three
110 components: (1) blue water which measures the volume of surface or groundwater consumed, (2)
111 green water which measures the volume of rainwater consumed, and (3) grey water which is an
112 indicator of freshwater pollution. In the context of H₂ production, the WF is blue water, except for
113 H₂ produced from biomass (Here, WF would be the sum of green and blue water) which can
114 potentially be rainfed.

115 Several prior research studies have implemented the concept of WF in the energy sector,
116 displaying varying extents of application and exploration (Barker, 2007; DoE, 2006; Fthenakis &
117 Kim, 2010; Gleick, 1994; Macknick et al., 2011; Mekonnen & Hoekstra, 2011, 2012; Meldrum et
118 al., 2013; Mielke et al., 2010; Mulder et al., 2010; Tuninetti et al., 2015; Wu et al., 2009).
119 Mekonnen et al. (2015) compared the WF of different energy sources and observed that electricity
120 from renewable sources has the smallest WF when compared to fossil fuels, biomass, and

121 hydropower. Their findings further indicated that operations and fuel supply contribute the most
122 to the WF, while that of plant construction is negligible. More recently, Rosa et al. (2021) found
123 that the WF of CCS technologies can be large, although highly variable (0.74 to 575 m³per tonne
124 CO₂).

125 This study endeavors to (1) investigate the WF of H₂ production via different pathways
126 and compare this WF with respect to other energy sources, (2) investigate the effect of H₂ WF on
127 the WF of energy on both regional and global scales. To achieve the first point, we follow the
128 commonly used approach of estimating the WF of a product by considering all streams of water
129 withdrawal (and consumption) for different H₂ production pathways as described in section 2.1-
130 2.3. Consequently, we present in section 2.4 the process of analyzing H₂ WF impact on the energy
131 sector. Such an analysis provides insights into identifying the potential implications H₂ energy
132 might have on water availability and can help decision makers on environmental and energy
133 transition strategies.

134 **2. Methods**

135 To quantify the WF of H₂, we consider the amount of water consumed and polluted in the
136 different stages of the supply chain, depending on the H₂ production pathway. The method utilized
137 in this study to estimate the WF of H₂ follows from the commonly presented approach of
138 estimating the WF of energy (e.g., Mekonnen et al. 2015, Meldrum et.al 2013). Here, we segregate
139 the water requirement for H₂ production into two distinct categories: WF of the primary energy
140 source or raw material and the water requirement for operation, where the later can be subdivided
141 into feedstock water requirement, plant cooling water requirement and additional water required
142 for CCS facilities for energy sources relying on fossil fuels or have substantial carbon emissions.

143 A general illustration of the steps involved in calculating the WF of H₂ is presented schematically
144 in Figure A1.

145 We consider the three main pathways for H₂ production, namely water electrolysis, fossil
146 fuel, and biomass. We quantify the WF of H₂ both per unit mass (WFM_{H₂} in m³ of water/tonne H₂
147 or kg H₂O/kg H₂) and per unit of energy (WFE_{H₂} in m³/TJ). The conversion is done through H₂
148 higher heating value (HHV=0.142 TJ/tonne H₂). The advantage of having the two quantities is that
149 the WFM provides a very intuitive measurement between water and hydrogen masses, while WFE
150 provides a way to compare the water footprint of H₂ energy with other energy sources. The water
151 requirements for operation via the water electrolysis and fossil fuel pathways considered are from
152 the National Renewable Energy Laboratory (NREL), while that of H₂ from biomass is from Binder
153 et al. (2018) converted and expressed here as m³/tonne .

154 *2.1. Water Electrolysis pathway*

155 This process produces H₂ through the electrochemical conversion of water to H₂ and
156 oxygen (2H₂O → 2H₂ + O₂). To evaluate the WF of H₂ from water electrolysis, we require the WF
157 of the electricity source (WF_{EL}), the amount of electricity, EL (TJ/tonne H₂), as well as the
158 stoichiometric amount of water as feedstock, W (m³/tonne H₂). The WF of the primary energy is
159 estimated as the product of EL and WF_{EL}, while the water requirement for operation is basically
160 W. Hence, WF for this pathway can be calculated as

$$161 \quad \text{WFM}_{\text{H}_2} = \text{EL} * \text{WF}_{\text{EL}} + W. \quad (1)$$

162 We consider electricity from three sources: solar, wind, and nuclear energy. The
163 corresponding values for WF_{EL} (m³/TJ) are from Mekonnen et al. (2015), see Table T1.

164 *2.2. Fossil Fuel pathway*

165 H₂ is produced from fossil fuel either from natural gas, through steam methane reforming
 166 (SMR), or from coal gasification (CG). SMR is currently the most mature production and widely
 167 used process for the generation of H₂ in large central plants (IEA, 2022a). By applying high
 168 pressure steam to methane, carbon monoxide and syngas (containing H₂) is produced (CH₄ +
 169 2H₂O → CO₂ + 4H₂). CG technology produces H₂ by reacting coal with oxygen and steam under
 170 high pressures and temperatures to produce carbon monoxide and H₂ (2C + 2H₂O + O₂ → 2CO₂
 171 + 2H₂) (Mehmeti et al., 2018). To determine the WF of H₂ from fossil fuels, we require the amount
 172 of fuel, F (tonne F / tonne H₂) and the WF per unit mass of fuel, WF_F (m³/ tonne F). In the
 173 production process, water is required as feedstock and to cool the plants, W (m³/ tonne H₂), and if
 174 carbon capture and storage facilities are put in place, additional water is required, W_{CCS} (m³/ tonne
 175 H₂). The WF of the raw material is estimated as the product of F and WF_F , while the water
 176 requirement for operation is the sum of W and W_{CCS} . As a result, WF for this pathway can be
 177 calculated as

$$178 \quad WFM_{H_2} = F * WF_F + W + W_{CCS}. \quad (2)$$

179 2.3. Biomass gasification pathway

180 Biomass and bio-derived fuels can be used to produce H₂ from thermo-chemical and
 181 biological routes (Kırtay, 2011). Biomass gasification is a promising pathway for the conversion
 182 of biomass into energy products taking place at elevated temperatures, between 500 and 1400 °C
 183 without combustion (Iribarren et al., 2014), and it is mostly described as a process with negative
 184 GHG emissions attributed to the amount of CO₂ removed from the atmosphere while growing
 185 biomass (Salkuyeh et al., 2018; Susmozas et al., 2016). To determine the WF of H₂ from biomass
 186 (wood chips), we require the amount of biomass, B (tonne B / tonne H₂), the WF per unit mass of
 187 the biomass, WF_B (m³/tonne B). Additionally, biodiesel fuel, F is used in the scrubber unit to

188 separate the condensable tar from the product gas (Binder et al., 2018). Water is required as steam
189 to cool the plants, W , and if carbon capture and storage facilities are put in place, additional water
190 is required, W_{CCS} . The WF of the raw material is estimated as the sum of the products of F and
191 WF_F , and B and WF_B while the water requirement for operation is the sum of W and W_{CCS} . Hence,
192 WF for this pathway can be calculated as

$$193 \quad WFM_{H_2} = F * WF_F + B * WF_B + W + W_{CCS} \quad (3)$$

194 where WF_F of biodiesel (rapeseed methyl ester) is $790 \text{ m}^3/\text{tonne}$ biodiesel (Spang et al., 2014).
195 Due to lack of specific references that explicitly provide information about the amount of water
196 required due to CCS facilities, the average of W_{CCS} for coal and natural gas is assumed, as the
197 precise value is liable to be irrelevant since the WF of wood chips is about an order of magnitude
198 higher.

199 *2.4. Energy replacement with H₂*

200 The WF of H₂ per unit energy (m^3/TJ) obtained from different pathways are then used to
201 investigate the impact of partial replacement of H₂ on the water footprint of the energy sector on
202 country and global scales, we use primary energy consumption data from Ritchie et al. (2022)
203 which contains the total amount of energy consumed on a country, region and global scale. Primary
204 energy in this context includes energy that the end user needs, in the form of electricity, transport
205 and heating, plus inefficiencies and energy that is lost when raw resources are transformed into a
206 usable form. Globally, net-zero energy scenarios are considering H₂ to potentially account for up
207 to 15% (Gielen et al., 2019; IEA, 2021) of the final energy consumption, where a certain quota
208 must have been lost due to energy conversion inefficiencies. To this end, we assumed a 15%
209 partial energy replacement with H₂ distinctively considering blue and green H₂ on the country

210 scale, while on a global scale, we considered a replacement of 0 - 25% at a 5% increase to illustrate
211 the effects of a gradual global energy transition scheme.

212 **3. Results**

213 *3.1 Comparison with other energy sources*

214 The WF of producing H₂ via different pathways (bars are color coded following Incer-
215 Valverde et al. (2023) with respect to the hydrogen production pathway) is presented in Figure 3
216 in comparison with other energy sources. The numerical results are also reported in Table 1. The
217 WF of firewood, nuclear, oil, coal and lignite, geothermal, natural gas, solar and wind energy are
218 obtained from Mekonnen et al. (2015), converted and represented here as WF per energy unit
219 rather than WF for electricity, as presented in the referenced paper. Provided that variation exists
220 in plant cooling techniques, CCS technologies, as well as method of extraction of raw materials,
221 we also utilized the maximum and minimum values reported in Mekonnen et al. (2015) to evaluate
222 an upper and lower bound for the WF of H₂.

223 The WF of H₂ is lowest when it is produced from the water electrolysis pathway,
224 particularly when electricity is provided by renewable sources, such as wind and solar energy.
225 Green H₂ from solar (204 ± 79 m³/TJ) exhibits a similar WF compared to conventional fossil fuels,
226 with potential for a reduced WF through advancements in electrolyzer and electrification
227 efficiency. Green H₂ from wind (65 ± 2 m³/TJ) has a significantly lower WF. Conversely, when
228 electricity is sourced from nuclear energy (pink H₂), the WF is higher (741 ± 277 m³/TJ), mostly
229 due to the high WF of nuclear energy. Blue H₂ produced from natural gas (369 ± 30 m³/TJ), and
230 coal (564 ± 82 m³/TJ) demonstrates a much higher WF compared to green H₂ obtained from water
231 electrolysis. The highest WF is for brown H₂ derived from biomass (>50000 m³/TJ), primarily
232 attributed to the significant WF associated with wood chips and biodiesel. With regards to the WF

233 of blue H₂, the analysis by D’Odorico et al. (2017) suggests that the WF of fossil fuels (coal, oil
234 and natural gas) are usually underestimated since they do not account for consumption of
235 embodied (ancient) water from the geologic past. With such a consideration, it can be assumed
236 that the WF of H₂ from fossil fuels presented here is tentatively underestimated. A linear scale of
237 the WF of H₂ from different pathways is presented in Figure 3(b) to elucidate the difference
238 between the WF of green and blue H₂.

239 Amongst the components considered to estimate the WF of H₂, the WF of the energy source
240 contributes the most to the total WF (Table 1), except for wind energy, attributable to its low WF
241 of electricity (1.2-12 m³/TJ). The amount of water required during the production process of blue
242 H₂ is larger than the amount that could have been calculated directly from the stoichiometric
243 analysis of the chemical reaction, as additional water is required for cooling and to drive the
244 production process (Lampert et al., 2015). Penev (2022a, 2022b) reports the amount of water
245 required for SMR with and without the consideration of CCS technologies respectively, while
246 Penev (2022c) and Rutkowski & Darlene (2008) reports the amount of water required for CG with
247 and without the consideration of CCS technologies respectively. The sum of water required for
248 feedstock, steam and CCS facilities is similar in both fossil fuel pathways with values of 30.2 m³/
249 tonne H₂, and 29.5 m³/ tonne H₂ for natural gas and coal respectively. However, the disparity in
250 the total WF is attributed to the WF and *F* specific to each fuel source, with values of *F* for natural
251 gas (3.2 tonne CH₄/ tonne H₂), and coal (8.73 tonne C/ tonne H₂). Advances to this method of
252 estimating the WF of H₂ casually stems from better documentation of process water flow, and the
253 advent of new production methods, e.g., Guo et al. (2022) presents a how H₂ can be produced from
254 the direct capture of water vapor from air which eliminates several components of equations 1-3.
255 Osselin et al. (2022) presents a technique through which water is injected in situ in identified

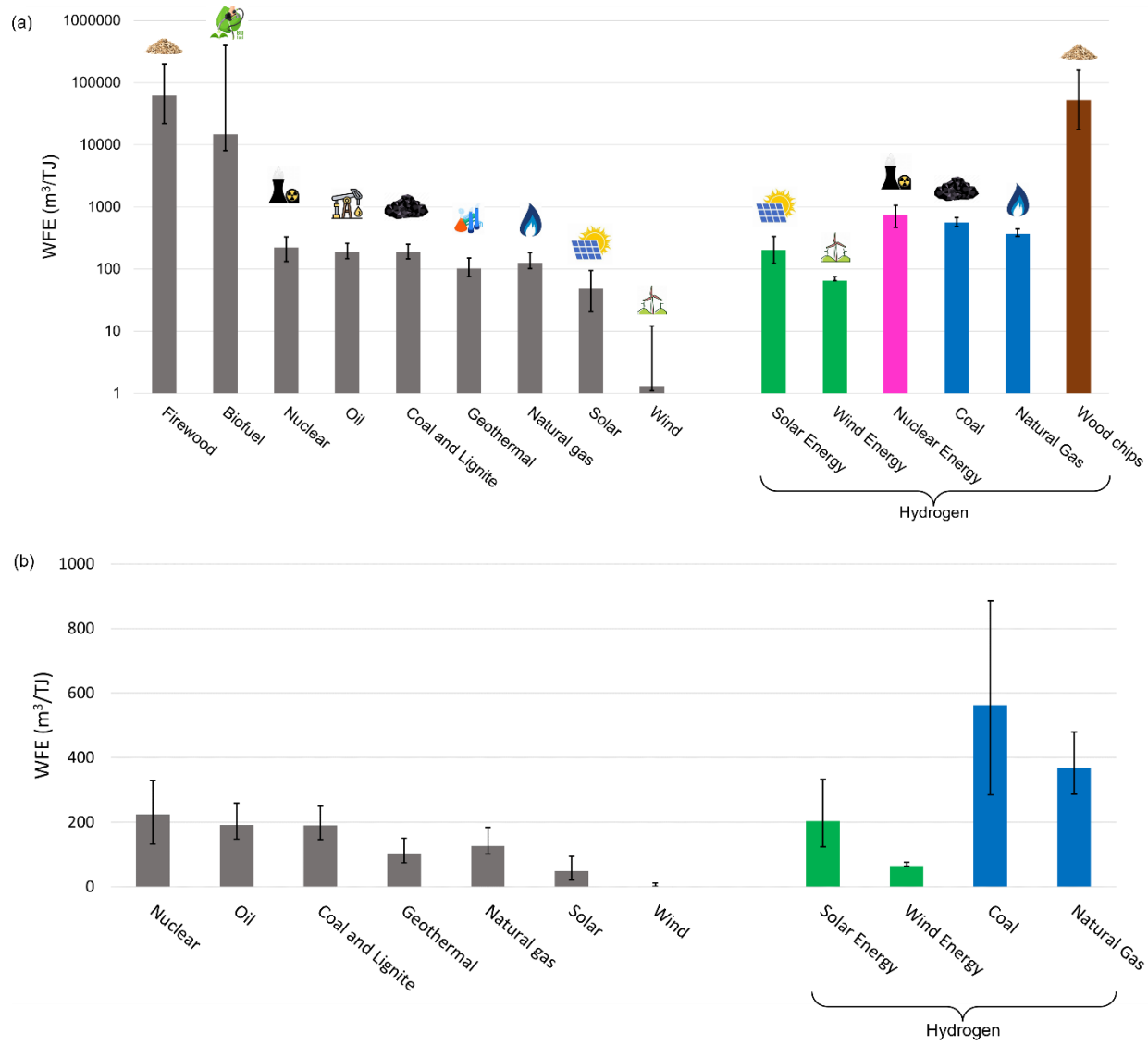
256 reactive formations and H₂ saturated water (termed as orange H₂) is collected from recovery wells
257 surrounding the injection point. Although these methods are yet to be implemented globally on a
258 large scale.

259 **Table 1.** Components to estimate WF of H₂ per unit mass (WFM) and unit energy (WFE). The
 260 conversion is based on the high heating value of H₂ (0.142 TJ/ tonne H₂).

| Pathway | Primary energy source | Energy WF (m³/tonne H₂) | W (m³/tonne H₂) | W_{CCS} (m³/tonne H₂) | WFM_{H₂} (m³/tonne H₂) | WFE_{H₂} (m³/TJ) |
|---------------------------------|--------------------------------|--|--|--|--|---|
| Water | Solar | 20 | 9 | 0 | 29 | 204 |
| Electrolysis^a | | | | | | |
| | Wind | 0.2 | 9 | 0 | 9.2 | 65 |
| | Nuclear | 96 | 9 | 0 | 105 | 741 |
| Fossil fuel | Coal (CG) ^b | 50 | 16 ^e | 13.5 | 80 | 564 |
| | Natural gas (SMR) ^c | 22 | 16 ^f | 14.2 | 52.4 | 369 |
| Biomass | Wood chips ^d | 7450 | 3.4 | 13.8* | 7467 | 52586 |

261 Sources: a) DeSantis et al. (2020), b) Penev (2022c), c)Penev (2022a), d) Binder et al. (2018), e)
 262 Rutkowski & Darlene (2008) , f) Penev (2022b).

263 *W_{CCS} of biomass gasification is assumed to be an average of W_{CCS} for coal and natural gas, due
 264 to lack of specific references that explicitly provide information about the amount of water due to
 265 CCS facilities.



266

267 **Figure 3.** Average water footprint per unit energy (WFE) of H₂ and other energy sources. The
 268 ranges reflect the maximum and minimum values for each energy source. For H₂, range of values
 269 is obtained by utilizing the upper and lower bound the WF of individual energy sources as
 270 presented by Mekonnen et al. (2015). The y-axis is (a) in log scale, while that of (b) in linear scale
 271 to juxtapose the difference between the WF of green H₂ and blue H₂.

272 *3.2 H₂ impact on the water footprint of the energy sector.*

273 *3.2.1. Country-scale scenarios.*

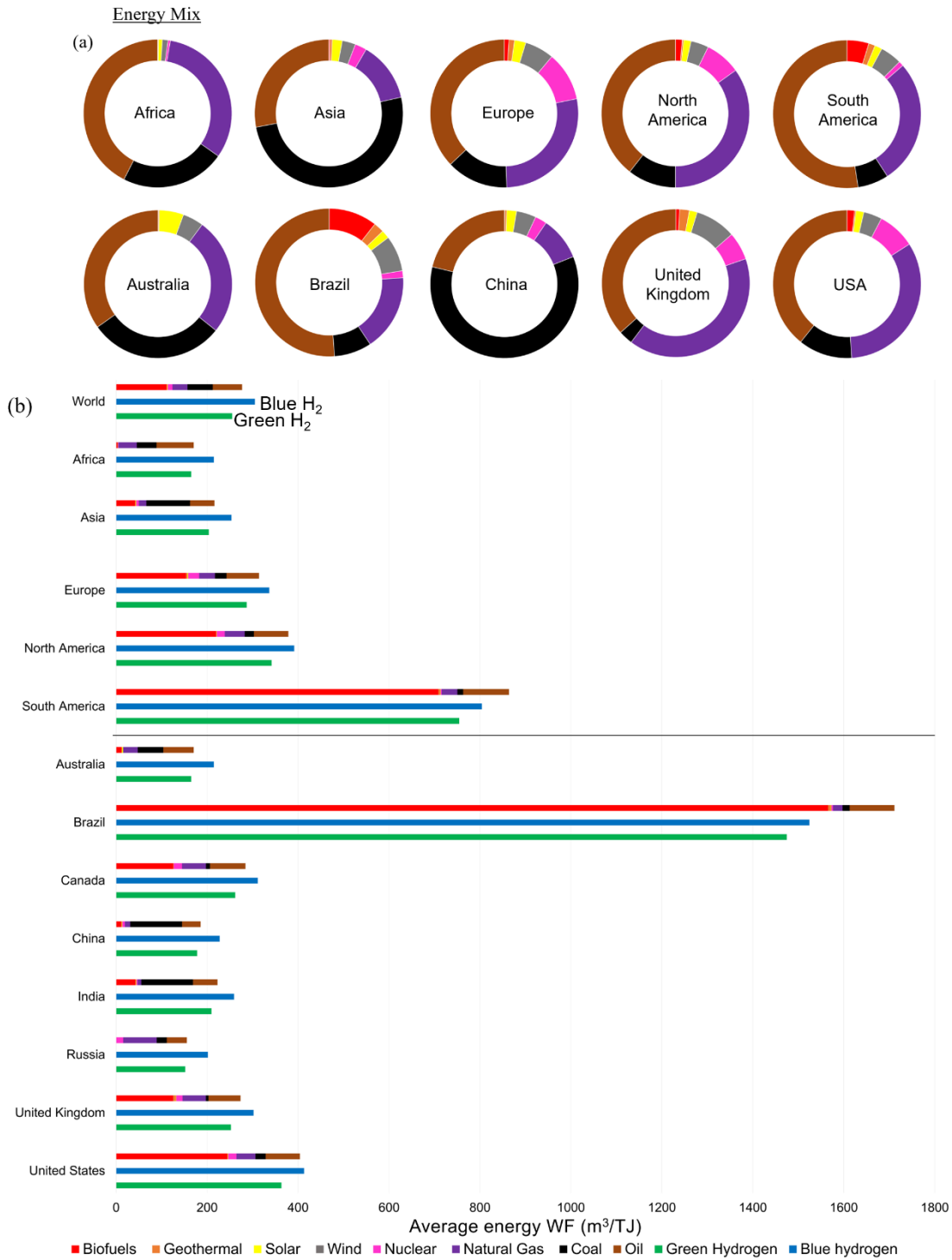
274 In this section, we estimate the water footprint associated with partial energy replacement
275 scenarios distinctively involving the main hydrogen colors namely, green and blue H₂. The water
276 demand of each country energy is estimated as the sum of the products of primary energy
277 consumption data delineated by source (Ritchie et al., 2022) and the corresponding energy WF.
278 The energy mix of selected countries and regions is reported in Figure 4(a), showing the
279 contribution of individual energy sources to the total energy consumed. The average WF of each
280 country energy mix is estimated as the ratio of the total water demand to the total energy consumed.
281 The country WF mix is presented in every first bar in Figure 4(b). We have neglected the
282 contribution of hydropower to the total energy consumed, following previous studies (e.g.,
283 Macknick et al., 2012; Spang et al., 2014), based on the fact that reservoirs are generally multi-
284 purpose, therefore making it challenging to accurately estimate the amount of evapotranspiration
285 water loss (WF of hydropower), solely to hydroelectric power generation. Typically, some studies
286 allocate a certain percentage of the total water evaporated from a reservoir based on the purpose
287 of the reservoir, however, this allocation is considered ambiguous (Macknick et al., 2012; Spang
288 et al., 2014).

289 To estimate H₂ impact on the energy consumed, we consider a scenario whereby 15% of
290 the primary energy consumed is met by H₂ (green and blue separately). The individual green and
291 blue bars in Figure 4(b) represent what would have been the WF of these selected countries and
292 regions if 15% of the primary energy consumed was provided by green or blue H₂. Our result
293 suggests that green H₂ has potential of reducing the WF while blue H₂ causes an increase in WF
294 except for Brazil and the South American region, attributable to their originally high WF.

295 The influence of green H₂ is perceived to be beneficial, most especially in regions with
296 initially high WF, while its influence was minimal in regions with initially lower WF. Regional
297 primary energy consumption and its energy mix play a critical role in reducing the WF when
298 replacing conventional fuel with green H₂. For instance, Africa's low primary energy consumption
299 coupled with a low current WF diminishes the impact of green H₂ as a replacement fuel.
300 Conversely, regions with high primary energy consumption often exhibit elevated WFs,
301 highlighting the significance of green H₂ in such contexts.

302 A suggested replacement strategy would be to reduce the reliance on water-intensive
303 energy sources, given that they exert a significant impact on the WF even when consumed in
304 minute proportions. For instance, despite accounting for less than 2%, 1%, and 1% in the USA,
305 Canada, and the United Kingdom respectively, biofuel has the highest (60%, 44%, and 45% for
306 USA, Canada, and the United Kingdom respectively) contribution to these regions WF.

307 A high WF of the energy sector may have very different impacts depending on the local
308 availability of water resources. In water-limited regions, water demand for energy can pose threats
309 to the sustainability of other water users (agriculture, industry etc.). Our estimates of H₂ WF are
310 under the assumption that all water components of equations 1-3 are locally sourced. Relaxing this
311 assumption would require exploring the trade of raw materials (natural gas, coal, and biomass) and
312 the associated virtual water trade (A. Y. Hoekstra & Hung, 2003) can affect the WF of H₂. Under
313 such conditions, the solely locally sourced components of the WF (equation 2) during production
314 will be limited to water requirements for operation (W and W_{ccs}).



315

316 **Figure 4.** (a) Energy mix of selected countries and regions showing the relative contribution of

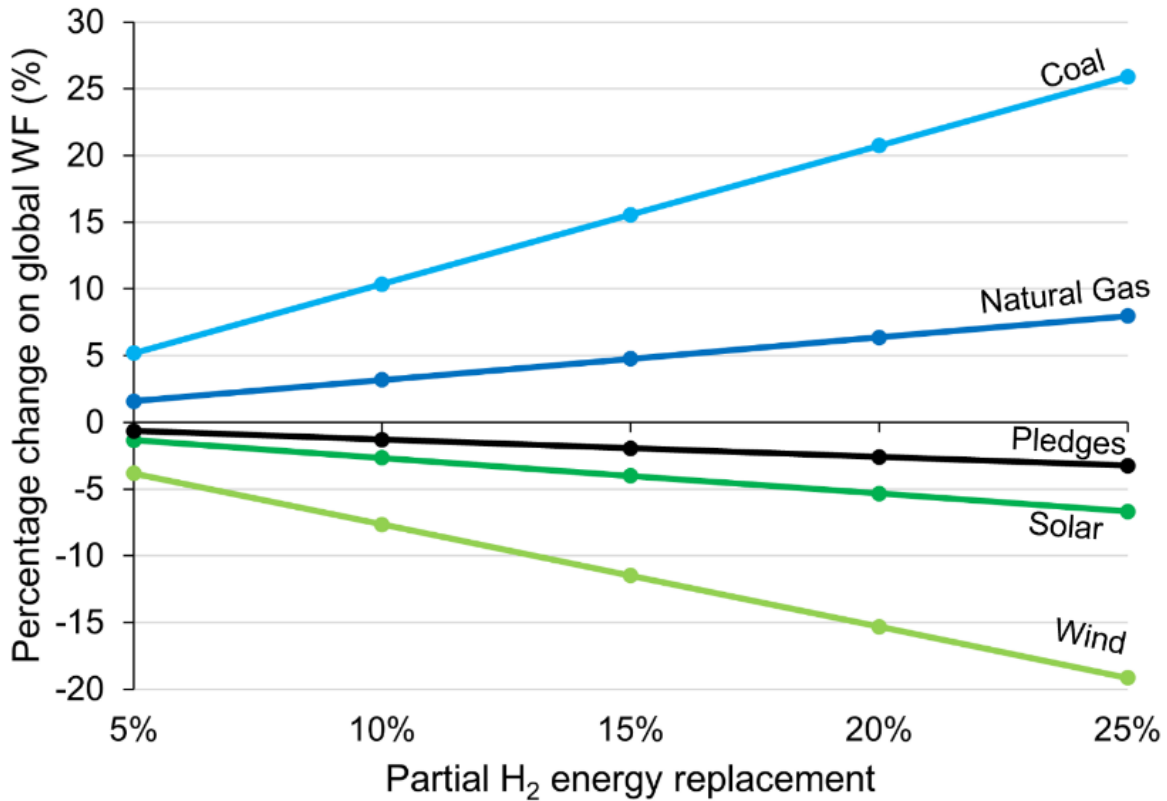
317 individual energy sources in the total energy consumption. Energy data are from Ritchie et al.

318 (2022) for the year 2021. (b) Average water footprint of energy (m^3/TJ). For each country or
319 region, the first bar and labels are presented to indicate individual energy sources, while full green
320 and blue bars represent a scenario of where green and blue H_2 account for 15% of the energy mix,
321 respectively.

322 3.2.2. Global scenarios

323 Energy transition scenarios allocate a specific share for H_2 within the overall energy mix.
324 For example, the International Renewable Energy Agency (IRENA) projects up to 19 EJ (~6% of
325 total final energy consumption – 351 EJ) of energy for electrification provided by H_2 (Gielen et
326 al., 2019). In the Net Zero Emissions (NZE) by 2050 report published by the IEA (IEA, 2021),
327 hydrogen-based fuels are projected to provide up to 33 EJ (~10%) of the total final energy
328 consumption.

329 H_2 energy is believed to enhance energy security through a decreased dependence on fossil
330 fuels, and a diversified energy mix (IEA, 2022b). Here, we investigate the effect of a 5 - 25%
331 partial energy replacement on the global WF associated with primary energy consumption. For the
332 global scenarios, we consider the main H_2 colors, namely green and blue, since other pathways
333 like biomass and nuclear energy have negligible consideration in the announced production
334 pledges (IEA, 2022b). Reported in Figure 5 is the percentage difference in the global WF as a
335 result of H_2 partial energy replacement. For every 5% H_2 partial energy replacement, we observe
336 a 4% reduction in the global WF when water electrolysis and wind energy is the production source,
337 while for solar energy, the percentage reduction was 1.3%. The effect was opposite when the H_2
338 production was from fossil fuel, with a 1.6% increase in WF when the source was natural gas, and
339 5.2% from coal. These results promote renewable energy usage, particularly solar and wind
340 energy, coupled with the electrification of the energy sector.



341

342 **Figure 5.** Effect of partial energy replacement with H₂ energy on the global WF of energy. Labels
 343 show the source from which H₂ is produced.

344 To achieve a reduced global WF of energy upon introduction of H₂ into the energy mix,
 345 Figure 5 suggests that such H₂ must be produced by water electrolysis, with energy sources of
 346 wind, solar, or a combination of both. A small portion of the global H₂ demand can be met by blue
 347 H₂ while still achieving the goal of reduced WF. This is illustrated by the black line in Figure 5
 348 which represents a blend of green (80%) and blue (20%) H₂, aligning with the announced pledges
 349 for H₂ production. The results show a 0.7% reduction in global WF for every 5% H₂ partial energy
 350 replacement. Hence, upon the fulfillment of the announced pledges, a decrease in WF of the energy
 351 sector is anticipated, along with numerous other advantages associated with the integration of H₂
 352 into the energy mix.

353 **4. Discussion**

354 The H₂ economy has been experiencing significant growth in recent years, driven by a
355 commitment to adopt low-carbon energy sources with the overarching goal of achieving net-zero
356 emissions, leading to a question about the water requirements of H₂ production which has been
357 lingering in recent years (Beswick et al., 2021; Lampert et al., 2015; Mehmeti et al., 2018; Tonelli
358 et al., 2023). This fundamental question is one of the bases of discussion when new energy sources
359 are planned to be utilized on large-scale, alongside other questions such as energy sustainability
360 and security, storage, among others. Here, we have presented the water implications of producing
361 H₂ and implementing it into energy transition scenarios and results, such as the capacity of green
362 H₂ to reduce water demand of the energy sector, corroborate existing evidence of H₂ playing a
363 vital role in satisfying future energy demands.

364 The WF of H₂ carries a large variability due to diverse production pathways and the result
365 suggests that green H₂ has a lower WF compared to blue H₂ while H₂ from nuclear energy and
366 biomass have much higher WF. Our finding on green H₂ is remarkably similar to Tonelli et al.'s
367 observation on how green H₂ powered by wind energy has a smaller water requirement compared
368 to green H₂ powered by solar energy. Considering that both pathways have the same stoichiometric
369 water requirements, this striking contrast is as a result of wind energy having a much smaller WF
370 than solar energy (Mekonnen et al., 2015; Meldrum et al., 2013; Spang et al., 2014). The high WF
371 of nuclear energy is also why H₂ possesses a high WF when it is the source of power for water
372 electrolysis. Our findings that blue H₂ from SMR has a lower water requirement than that from
373 CG correlates with Mehmeti et al.'s observation, although the reported numbers are remarkably
374 different.

375 Implementing H₂ into the energy mix of a country can either increase or decrease their
376 water demand for energy depending on the H₂ production pathway, the amount of H₂ demand, and
377 the available resources. The influence on water resources is tentatively different on varying spatial
378 and temporal scales, as on smaller scales, the production of H₂ can lead to local water scarcity,
379 without a substantial effect on country scale water consumption. This calls for location
380 optimization analysis (e.g., for solar and wind energy, Azadeh et al., 2008, 2011; Ruiz et al., 2020;
381 Zoghi et al., 2017) to accurately determine suitable locations for H₂ production plants, taking into
382 account all underlying limitations during the production process.

383 It is typical that countries will consume a combination of green and blue H₂ as the required
384 resources vary in abundance in every region. A proper consideration of local water competition
385 should be a crucial factor in determining H₂ production sites to avoid exacerbating local water
386 competition. For instance, investigating a scenario of water demand for H₂ production to fuel
387 electric vehicles, Lee et al. (2019) found that, while the amount of water consumed in California
388 would be only 1.3 times that consumed in New York state, resulting water scarcity footprint would
389 be 27 times higher due to the low water availability in California. According to our Figure 2,
390 several countries characterized with elevated levels of physical water scarcity (DI>10), including
391 Egypt, UAE, Oman, Saudi Arabia, and Mauritania have committed to H₂ production. This
392 indicates that physical water limitations may be a local-to-regional problem, given the lack of
393 abundant water resources and competition with other water users.

394 In addition to physical water scarcity, some countries with H₂ production pledges (e.g.,
395 Egypt, Kazakhstan, and Mauritania) exhibit economic water scarcity (EWS > 0.5, Figure 2). In
396 order for the proposed H₂ production to not exacerbate a lack of water resources, it will be crucial
397 for these countries to implement efficient water management. Conversely, countries such as

398 France, Netherlands, Germany, Spain, Australia, USA with an EWS < 0.25, are primarily tasked
399 with situating production sites in areas where local water scarcity will not be exacerbated to fulfill
400 their pledged production targets.

401 It is also important to examine green and blue H₂ from a holistic environmental lens. The
402 use of green H₂ clearly reduces the reliance on fossil fuels consumption and promotes the use of
403 renewable energy. By contrast, the use of blue H₂ relies on an increased extraction and use of fossil
404 fuels (due to the energy penalty in the fossil fuel to H₂ conversion). This would have several
405 environmental consequences, including a potential increase in fugitive emissions of methane
406 (Bertagni et al., 2022; Howarth & Jacobson, 2021). Moreover, due to inefficiency in CCS
407 processes (e.g., 60-90% CO₂ capture rate, Brandl et al., 2021 and references therein), blue H₂
408 would still entail some CO₂ emissions. Following research on energy sustainability, we find that
409 the best way to mitigate carbon emissions and reduce water consumption through H₂ production
410 is to promote the use of renewable energy other than considering alternative emissions reduction
411 techniques, such as CCS technologies (D’Odorico et al., 2017; Rosa et al., 2021). Therefore, the
412 supremacy of green H₂ over other production pathways extends beyond just having a smaller WF,
413 but also to economic and environmental sustainability. As an additional remark, for any H₂ color
414 and production pathway, it will be crucial to reduce H₂ fugitive emissions due to H₂ indirect
415 greenhouse gas effect (Paulot et al., 2021; Sand et al., 2023).

416 While it is not immediate that the distinction in the water source for green H₂ (freshwater)
417 and blue H₂ (fresh- or saltwater) is significant factor in their comparative assessment, an analysis
418 by Beswick et al. (2021) demonstrates that desalination of salt water presents a viable alternative,
419 although this added process will cause an increase in energy demand and economic cost of
420 producing green H₂. It is essential to acknowledge that recent research are also considering the

421 production of green H₂ from treated wastewater (Jack et al., 2021; Jiang et al., 2023; Rousseau et
422 al., 2020). Blue H₂ is currently less expensive than green H₂ with prices ranges of 1.4 – 3.2 US \$
423 /kg H₂ and 1.9 – 8.2 US \$ /kg H₂ for blue and green H₂ respectively (IEA, 2019, 2022a; Togni &
424 Fakoury, 2022; UNECE, 2021). Blue H₂ has lower prices as it's the current widely used production
425 technology, but their prices are hypothesized to increase upon the consideration of CO₂ taxes,
426 plummet in the reliance of fossil fuels or due to energy crises, while the actuation of the announced
427 pledges to produce green H₂, growth of renewable energy consumption and improvement of
428 energy convergence efficiency for solar and wind energy will tentatively lead to reduced prices for
429 green H₂.

430 **5. Conclusions**

431 We investigated the potential impacts that hydrogen (H₂) energy may have on water
432 resources following the interests of governments and organizations to incorporate H₂ into the
433 energy mix. For the main production pathways, we considered the WF of energy sources, the water
434 required for feedstock or steam, and WF of CCS technologies. Overall, H₂ has a relatively high
435 WF compared to other energy forms but with a great variability depending on the H₂ production
436 pathway. H₂ production through water electrolysis, particularly when powered by renewable
437 sources such as solar and wind energy, results in the lowest WF. Conversely, H₂ produced from
438 biomass exhibits the largest water footprint, primarily due to the high WF associated with biomass
439 production. There remains the possibility of a reduced WF associated with green H₂ production as
440 advancements in electrolyzer efficiency continue to unfold in the future.

441 Given the influence of the energy mix on the WF of a region, it is essential to consider a
442 transition from water-intensive energy sources to achieve reduced water demand by the energy
443 sector, especially in regions with minimal water resource availability. Our results (Figure 4 and 5)

444 highlight the water-saving capabilities of green H₂ derived from wind energy. This approach not
445 only offers water-saving benefits but also contributes to the overall advantages of utilizing low-
446 carbon energy sources, and this corroborates the announced production pledges (IEA, 2022b), as
447 81% of total H₂ pledges are to be produced from the water electrolysis pathway with renewable
448 energy. The utilization of fossil fuel based H₂ production with CCS would instead exacerbate the
449 anthropogenic pressure on water resources and should hence be considered justifiable only in
450 regions endowed with abundant fossil fuel resources, CCS facilities, and water resources.

451 Improved data availability in the future will allow further exploration of the H₂ impacts on
452 the water-energy nexus and a detailed knowledge of water requirements for hydrogen production
453 will add useful information (e.g., source of water green, blue, grey) to enable improved attribution
454 of H₂ WF, necessitate a LCA analysis, and determine sustainable proportioning of green and blue
455 H₂ into their energy mix.

456 **Appendix**

457 The water footprint for electricity (WF_{EEL}) required for equation 1 is obtained from
458 (Mekonnen et al., 2015), with values reported in Table T1, and for this work, we have only
459 considered electricity from solar, wind and nuclear energy. Simultaneously, to convert the average
460 consumptive WF per unit electricity and heat produced obtained from (Mekonnen et al., 2015),
461 the energy conversion efficiency is required and presented in Table T2 for individual energy
462 source.

463 Figure A1 on the other hand represents a schematic approach to the estimation of the WF
464 of H₂ from the three considered pathways, displaying the water requirements of each process.

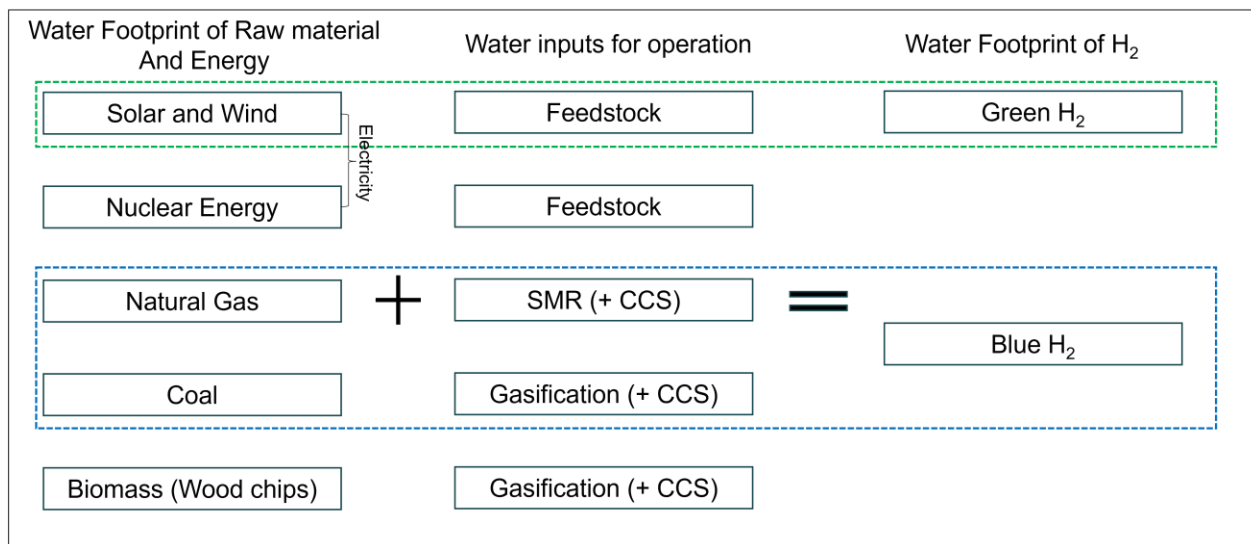
465 **Table T1.** Average consumptive WF per unit of electricity and heat produced (Mekonnen et al.,
 466 2015).

| Energy source | WF (m ³ /TJ _e) |
|------------------|---------------------------------------|
| Firewood | 156400 |
| Nuclear | 678.3 |
| Oil | 496.1 |
| Coal and Lignite | 495.1 |
| Geothermal | 342.1 |
| Natural gas | 247.1 |
| Solar | 140 |
| Wind | 1.3 |

467 **Table T2.** Energy Conversion Efficiency

| Energy Source | Efficiency (%) | References |
|---------------|----------------|-------------------------|
| Coal | 38 | Meldrum et al. (2013) |
| Oil | 39 | Meldrum et al. (2013) |
| Natural gas | 51 | IEA (2000) |
| Nuclear | 33 | Meldrum et al. (2013) |
| Biomass | 20 - 40 | Faaij (2006) |
| Geothermal | 12 - 25 | Zarrouk & Moon (2014) |
| Solar | 20 – 35 | Crabtree & Lewis (2007) |
| Wind | 20 – 40 | EPA (2013) |
| Hydropower | 85 - 90 | Power (2005) |

468



469

470 **Figure A1.** Schematic representation of the WF of H₂ production process.

471 **CRedit authorship contribution statement**

472 All authors have significantly contributed to the success of this research from the
 473 conceptualization phase to the first draft of the manuscript. **Damola Olaitan:** Conceptualization,
 474 Data curation, Formal analysis, Investigation, Visualization, Writing – original draft. **Matteo**
 475 **Bertagni:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Amilcare**
 476 **Porporato:** Conceptualization, Investigation, Writing – review & editing, Supervision, Funding
 477 acquisition.

478 **Declaration of competing interest**

479 All authors state that they have nothing to declare.

480 **Data availability**

481 Datasets for this research are available in Harris et al. (2020), IEA (2022), Ritchie et al. (2022),
 482 and UNEP (2021).

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