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Hydrogen Carbon Footprint in the Context of Clean Hydrogen Standards

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Currently three benchmarks are often discussed as relevant for the emission intensity of clean hydrogen production as can be seen from the horizontal lines and bars in Figure 1:

- ≈10-11 kg CO_2e/kg H_2 as reference for conventional hydrogen production [1]
- ≈3 kg CO_2e/kg H_2 low carbon H_2 such as EU Taxonomy [1] and TÜV Süd [2]
- 1 kg CO_2e/kg H_2 as ambitious threshold from the GH2 Organisation [3]

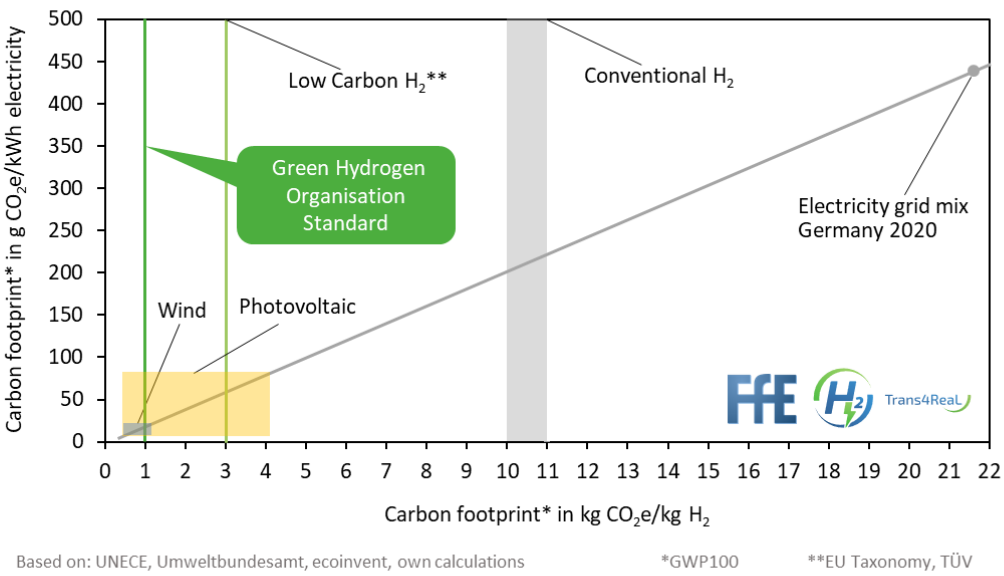

Figure 1: Carbon footprint (incl. upstream emissions) of hydrogen production in comparison to low carbon thresholds

Conventional hydrogen is mainly produced by steam reforming fossil methane. In the future a larger share of hydrogen is expected to be produced by separating water into hydrogen and oxygen with an electrolyzer run by electricity. In this discussion paper we focus on the differences in carbon footprint of hydrogen resulting from different types of electricity used for electrolysis and discuss differences resulting from the amongst calculation of direct emissions and upstream emissions of electricity.

Why is the emission intensity of hydrogen relevant?

Hydrogen enables the decarbonization of a broad range of different energy and non-energy sectors and applications, but the emission reduction potential of hydrogen strongly depends on the production method used. As can be seen from Figure 1 the emission intensity of electricity and consequently hydrogen is not equal to zero due to upstream emissions of the renewable electricity generation, e.g., the production of renewable energy plants. If the whole life cycle with the upstream emissions of renewable electricity is considered the most ambitious benchmarks can only be achieved with wind electricity and solar photovoltaics under suitable conditions. In the case of using German grid mix electricity from the year 2020 with a carbon footprint of 438 g CO_2e/kWh (including upstream emissions) [4] for the electrolysis the carbon footprint of hydrogen is almost twice as high as for conventional hydrogen. Conventional hydrogen is defined as hydrogen produced by reforming fossil methane leading to a carbon footprint of 10-11 kg CO_2e/kg H_2 [1]. In conclusion, hydrogen from electrolysis could contribute to emission reductions - if operated with low carbon electricity.

How is the emission intensity of H_2 calculated?

The carbon footprint of renewable electricity generation at different global locations including upstream emissions is taken from [5] and converted into a hydrogen emission intensity using the following assumptions:

- For the electrolysis technology alkaline electrolysis is chosen.
- Efficiency of electrolyzer: 51.9 kWh electricity per kg H_2 (64.1 %)
- For oxygen as a by-product, it is assumed that it is not used and released into the atmosphere.
- A lifetime of the stack of 60,000 operating hours and a lifetime of the entire plant of 20 year is assumed.
- The resulting emissions for the construction of the electrolyzers (plant construction) and the water purification were created on the basis of the data from the BEniVer project [6, 7]. The water purification is realized by a mix of reverse osmosis seawater treatment, membrane water treatment and ion exchanger water treatment.

What impact has the used electricity on the carbon footprint of H_2?

The vast majority of emissions of the produced hydrogen from renewable electricity result from the upstream emissions of electricity generation, i.e., the emissions caused by the production of the renewable energy plants. The share of the plant construction - i.e. the electrolyzer and surroundings- and the required water purification have very low shares in total emissions. For these calculations, the carbon footprint of electricity was assumed with average carbon footprints from Figure 1: 50 g CO_2e/kWh photovoltaic and 20 g CO_2e/kWh for wind generation in accordance to ranges given in [5]. The carbon footprint of plant construction and water purification is based on values from the BEniVer project [7].

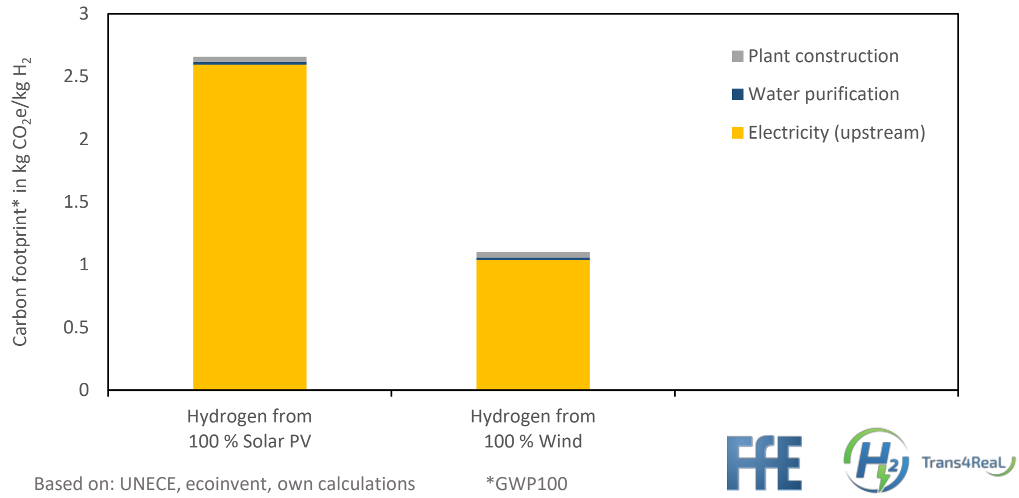

Figure 2: Carbon footprint of H_2 production resulting from plant construction, water purification and electricity generation

What is the emission intensity of hydrogen if only considering direct emissions?

Some regulations do not specifically define whether to include upstream emissions of electricity generation or even exclude them for the calculation of the hydrogen carbon footprint, e.g. the Green Hydrogen Organisation [3]. As shown in [7] most of the life cycle emissions result from the upstream emissions of electricity. If only direct emissions from combustion are considered, i.e. a factor of 0 g CO_2e/kWh is used for renewable energy sources.

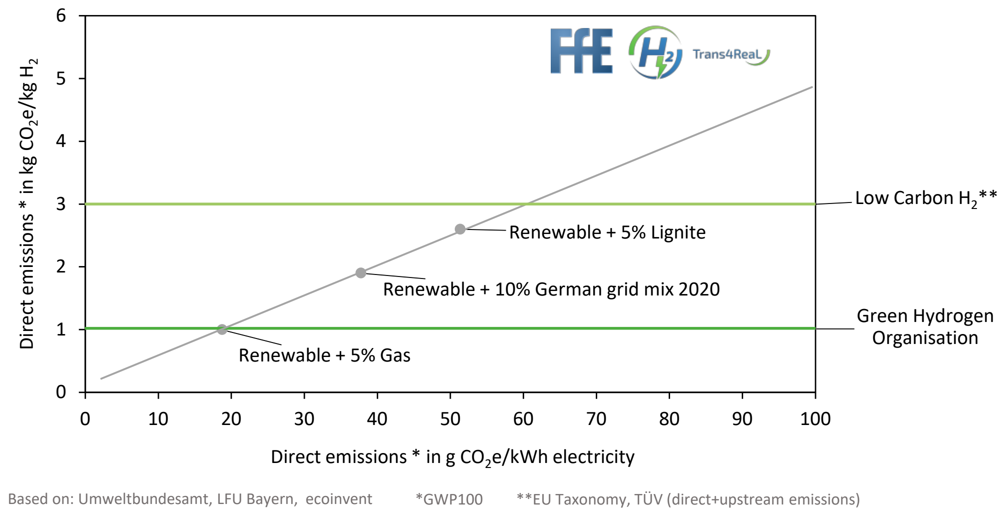

Figure 3: Carbon footprint (excl. upstream emissions of electricity) of hydrogen for different electricity mixes

Considering only direct emissions, all types of renewables reach the thresholds of low carbon hydrogen standards. To reach different emission thresholds even a partial use of electricity from fossil gas respectively coal or partial use of grid electricity is possible as can be seen in Figure 3. This contrasts with Figure 1, where carbon thresholds are not necessarily reached even with 100 % renewables. This difference between Figure 1 and Figure 3 results from the consideration or exclusion of upstream emissions of electricity generation, e.g. the production of a photovoltaic module.

Detailed direct emission factors for different electricity sources can be seem from Table 1.

Table 1: Direct emissions (excl. upstream emissions) of different electricity sources

Electricity source	Direct emissions
German grid mix	0.389 kg CO_2e/kWh_{el} [4]
Natural gas	0.370 kg CO_2e/kWh_{el} [8]
Lignite	1.027 kg CO_2e/kWh_{el} [8]
Renewable	0 kg CO_2e/kWh_{el} [8]

Why is the variation of the carbon footprint of renewable electricity so high?

A major factor on life cycle emissions of a renewable energy plant is the location where the plant is operated. Different locations result in different annual electricity generation per plant installed due to different full load hours [5].

A second aspect especially plays a role for the emissions of electricity from solar photovoltaics (PV): The effect of the cell technology. Currently most PV modules are poly-Si modules. With other technologies e.g. technologies significantly lower emissions intensities are achievable [5].

In Figure 4 the effect of the photovoltaic technology on the emissions intensity of electricity and hence hydrogen based on carbon footprints from [5] is shown. The width of the boxes represents the differences amongst generation locations resulting, e.g. from different full load hours. For poly-Si cells the carbon footprint of electricity is too high to reach the threshold required by the Green Hydrogen Organisation [3]. Less strict low carbon H_2 thresholds are reached at most locations. For thin-film cells even the stricter thresholds of Green Hydrogen Organisation [3] are reached for almost all locations.

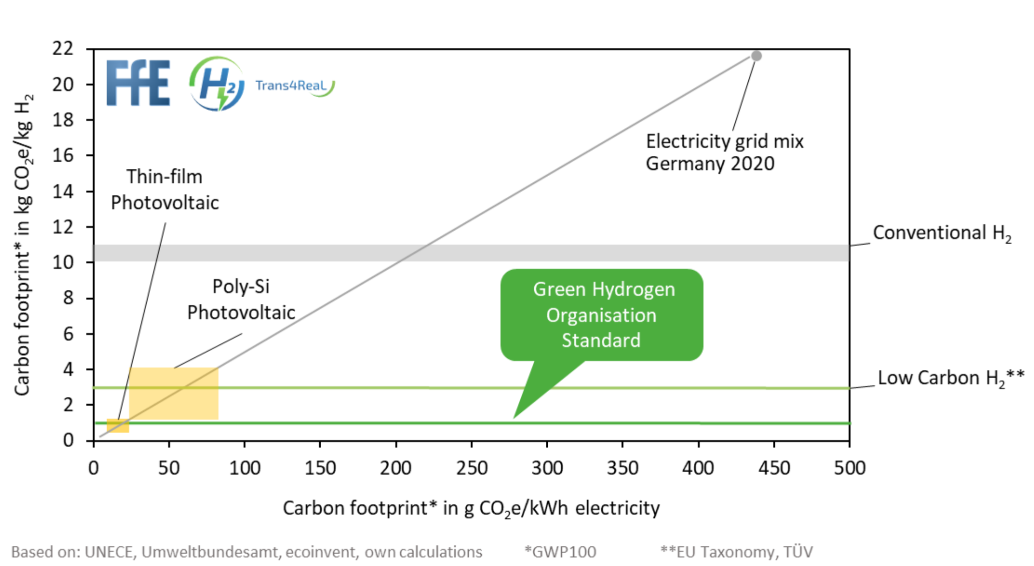

Figure 4: Carbon footprint of different photovoltaic technologies

Outlook

For future hydrogen production intensity can differ for the presented technologies as upstream emissions can potentially be lower in the future, e.g. reduced emissions resulting from a cleaner photovoltaic cell production.

Recently also the RED II Delegated Act Draft from the European Commission was published [9]. In this draft a mixed approach of upstream emissions and direct emissions is suggested. The quantification of hydrogen carbon footprint according to this methodology in comparison to the results of this work are of interest, as it was shown that the consideration of upstream electricity emissions in low carbon hydrogen standards is of high relevance for the evaluation of the carbon footprint of hydrogen produced by electrolysis.

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