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Review and Harmonization of the Life-Cycle Global Warming Impact of PV-Powered Hydrogen Production by Electrolysis

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This work presents a review of life-cycle assessment (LCA) studies of hydrogen electrolysis using power from photovoltaic (PV) systems. The paper discusses the assumptions, strengths and weaknesses of 13 LCA studies and identifies the causes of the environmental impact. Differences in assumptions of system boundaries, system sizes, evaluation methods, and functional units make it challenging to directly compare the Global Warming Potential (GWP) resulting from different studies. To simplify this process, 13 selected LCA studies on PV-powered hydrogen production have been harmonized following a consistent framework described by this paper. The harmonized GWP values vary from 0.7 to 6.6 kg CO_2-eq/kg H_2 which can be considered a wide range. The maximum absolute difference between the original and harmonized GWP results of a study is 1.5 kg CO_2-eq/kg H_2. Yet even the highest GWP of this study is over four times lower than the GWP of grid-powered electrolysis in Germany. Due to the lack of transparency of most LCAs included in this review, full identification of the sources of discrepancies (methods applied, assumed production conditions) is not possible. Overall it can be concluded that the environmental impact of the electrolytic hydrogen production process is mainly caused by the GWP of the electricity supply. For future environmental impact studies on hydrogen production systems, it is highly recommended to 1) divide the whole system into well-defined subsystems using compression as the final stage of the LCA and 2) to provide energy inputs/GWP results for the different subsystems.

Keywords: hydrogen production, global warming potential, photovoltaic electrolysis, LCA, CO2 emissions

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INTRODUCTION

With the increased interest in hydrogen as a sustainable fuel, the life-cycle environmental performance of its production is gaining importance. Hydrogen is generally considered to be a clean fuel because of the absence of emissions during its use. However, so far, the predominant production processes of hydrogen have been steam methane reforming and coal gasification, both of which, due to the use of fossil fuels, result in the emission of a large amount of greenhouse gases, which are by-products of hydrogen production (Bundesministerium für Wirtschaft und Energie (BMWi), 2020; IEA, 2019). In order to contribute to emission reduction targets, hydrogen production has to be powered by renewable electricity sources such as PV systems (Dincer and Acar, 2015). Life-cycle assessment (LCA) can be used to measure and compare the sustainability of

different hydrogen production chains. LCA is generally defined as a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle following DIN 14040 and DIN 14044 (DIN 14040, 2006; DIN 14044, 2006).

From a literature study, it is found that almost all LCA studies on hydrogen production by means of electrolysis report the global warming potential (GWP) in the following unit: kg CO_2-eq/kg H_2. The biggest impact on the GWP is caused by the power supply of hydrogen production (Koroneos et al., 2004; Granovskii et al., 2006; Granovskii et al., 2007; Lombardi et al., 2011; Ozbilen et al., 2011; Simons et al., 2011; Cetinkaya et al., 2012; Pereira and Coelho, 2013; Suleman, 2014; Reiter and Lindorfer, 2015; Suleman et al., 2015; Schmidt Rivera et al., 2018; Lundberg, 2019). The reviews of Bhandari et al. (Bhandari et al., 2014), Valente et al. (Valente et al., 2017) and Mehmeti et al. (Mehmeti et al., 2018) demonstrate how the GWP results change depending on the electricity source used.

To the best of the authors' knowledge, no extensive review of LCA studies of PV-powered hydrogen production is currently existing. Such a review could be useful because values of emissions per kilogram of PV-generated hydrogen found in the literature vary significantly and are often not comparable due to different system boundary assumptions, system sizes, methods, and functional units (FU). Thus, this work aims to fill this gap by identifying these differences and presenting a comparison of harmonized results from various LCAs of PV-powered hydrogen production. In this manner, a more understandable and comparable framework can be developed. To achieve this goal, 13 LCA studies (Koroneos et al., 2004; Granovskii et al., 2006; Granovskii et al., 2007; Lombardi et al., 2011; Ozbilen et al., 2011; Simons et al., 2011; Cetinkaya et al., 2012; Pereira and Coelho, 2013; Suleman, 2014; Reiter and Lindorfer, 2015; Suleman et al., 2015; Schmidt Rivera et al., 2018; Lundberg, 2019) on PV-powered hydrogen production technologies were selected, analyzed and harmonized. As a reference for the harmonization framework, a guidance document published by the European Union and Fraunhofer ISE with the framework of recommendations for LCA on hydrogen production was applied (Masoni and Zamagni, 2011; Lozanovski et al., 2013). The harmonization allows direct comparison between the GWP results of these studies, by recalculating the GWP to the same scope, functional unit and system boundaries.

METHODOLOGY

Life Cycle Assessment Methodology

LCA is a valuable instrument to analyze the environmental performance of any system or product. LCA is commonly described as a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle. LCA studies consist of four main phases, which are covered through ISO standards (DIN 14044; ISO 14040:2006) (DIN 14040, 2006; DIN 14044, 2006): 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation. In the following, each step will be shortly introduced to the reader.

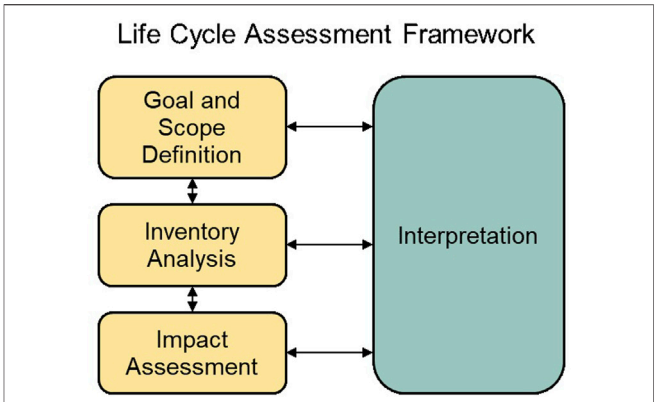

FIGURE 1 | Schematic illustration of the LCA framework (DIN 14040, 2006; DIN 14044, 2006).

The first step of the LCA is used to define the goal and scope of the study. During the second step, a life cycle inventory (LCI) model is analyzed, through which data is collected and organized. The LCI analysis quantifies all elementary flows associated with individual processes, i.e. mass (materials and resources) and energy flows, land use, emissions to air, water, soil, and products of the processes as outputs. The third step is the life cycle impact assessment (LCIA). It is used to understand the relevance of all the inputs and outputs in an environmental framework. The fourth step is the interpretation which covers a systematic technique to identify, check, and evaluate information resulting from the LCIA (see **Figure 1**).

Due to their impact on the global climate, GHG emissions are a major factor of today's energy policy, and their quantification is therefore essential for any comparative energy technology assessment. The LCIA for the reviewed studies is therefore completed for the impact category global warming and are used as an indicator of contribution to climate change. Those GHG emissions and GWP are just a few of the many outputs, which are, however, very important for this application, because of the assumed usage of hydrogen for GHG reductions in the energy and transport transition. Additional LCA impact categories that could be interesting for hydrogen based on its application fields are Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP) (Masoni and Zamagni, 2011; Lozanovski et al., 2013). The 100 years global warming potentials based on the latest IPCC are applied, according to their radiative forcing capacity relative to the reference substance CO_2. The global warming potential (GWP) during the life cycle stages are given as kg CO_2 equivalent. The GWP can be normalized to CO_2 equivalent emissions to describe the overall contribution to global climate change. CO_2 equivalent includes all major emissions CO_2 (GWP = 1), CH_4 (GWP = 25), N_2O (GWP = 298) and chlorofluorocarbons (GWP = 4,750–14,400) and was calculated in a well-known LCA tool named GaBi (Thinkstep, 2019).

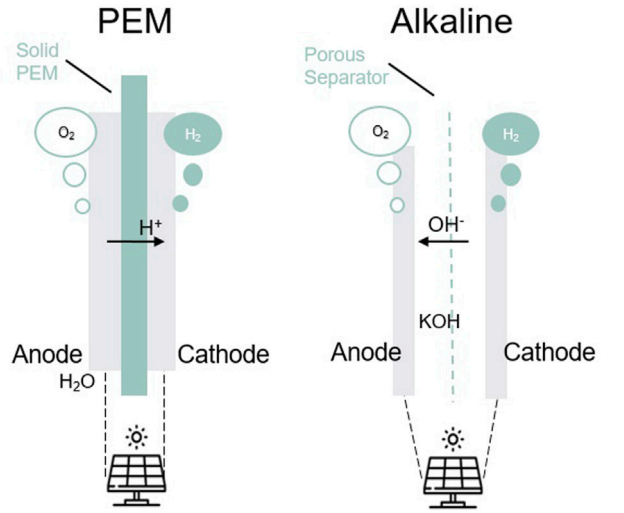

FIGURE 2 | Schematic illustration of the different electrolyzer configurations discussed in this paper (L) Proton Exchange Membrane Electrolyzer Cell (PEM) with Nafion as a membrane. Proton (H+) transport between electrodes (r) Alkaline electrolyzer with potassium hydroxide (KOH) liquid electrolyte. Hydroxyl ions (OH-) transport between the electrodes.

Hydrogen Production via PV Electrolysis

The electrolysis systems analyzed in the reviewed studies are alkaline electrolyzers and proton exchange membrane (PEM) electrolyzers. These electrolyzers produce hydrogen at low temperatures, without any external heating. Thus, their operation can be powered by electricity generated by PV systems only. Alkaline electrolyzers have two electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). The anode (positive electrode) is typically made of nickel and copper and is coated with oxides of metals such as manganese, tungsten, and ruthenium. The cathode (negative electrode) is typically made of nickel, coated with small quantities of platinum as a catalyst. A gas separator, or diaphragm, is used to avoid mixing of the hydrogen and oxygen molecules, although it allows free movement of ions. The lifetime of an alkaline electrolyzer is reported to be up to 30 years, however, the electrodes and the diaphragms have to be replaced after 7–15 years. The purity of hydrogen produced by alkaline electrolyzer reaches 99.9 vol% without auxiliary purification equipment. The alkaline technology was not intended to be flexible, i.e. it has traditionally been operated at constant load and maximum efficiency to meet industrial demand.

On the other hand, PEM electrolyzers do not require any liquid electrolyte. Instead, it is replaced by a gas-tight thin polymer membrane (see **Figure 2**). A synthetic polymer, Nafion, is usually used as the membrane material, which limits the lifetime expectations to 15–20 years. The purity of hydrogen is typically above 99.99 vol%. Since proton transport through the PEM responds quickly to power fluctuations, the PEM electrolyzer has a higher efficiency at a lower current density. Thus, intermittent PV electricity can be efficiently used as an energy source for PEM electrolyzers. The energy required at the theoretical efficiency limit is 39.4 kWh per kilogram of hydrogen. PEM electrolyzers operating at low current density may approach this efficiency limit. Although there are some major differences between the PEM and alkaline technology, the LCA - relevant inputs and outputs are similar for both technologies.

The Selection and Harmonization Process

13 studies, consisting of 10 peer-reviewed papers (Koroneos et al., 2004; Granovskii et al., 2006; Granovskii et al., 2007; Lombardi et al., 2011; Ozbilen et al., 2011; Cetinkaya et al., 2012; Pereira and Coelho, 2013; Reiter and Lindorfer, 2015; Suleman et al., 2015; Schmidt Rivera et al., 2018) and three reports on LCAs (Simons et al., 2011; Suleman, 2014; Lundberg, 2019) on PV-powered hydrogen production technologies, were selected for this review and the subsequent GWP harmonization process. The studies were published between 2004 and 2019. These publications were identified by searching notable electronic databases ScienceOpen, ResearchGate, SpringerLink and Scopus using the keywords "hydrogen", "PV", "life cycle assessment" and reviewing the reference lists of the articles found. The search was restricted to titles and keywords. No restrictions were placed on language and publication date. Since the focus of this work is on PV based hydrogen production, the boundaries of the system are defined corresponding to a cradle-to-gate approach (see **Figure 3**). This scope provides a robust way to interpret various studies that extent to hydrogen compression and exclude hydrogen transport and application. Essential inputs for the operation are electricity and deionized water. To produce 1 kg hydrogen, 55–57.5 kWh of electricity and 9–10 L of water are required [10, 14, 15]. The water must be deionized to suppress undesirable electrochemical reactions.

For the harmonization process, the final conditions of the harmonized functional unit (FU_{har}) in terms of purity, pressure and temperature are defined as the "provision of 1 kg of hydrogen" (purity >99% vol. pressure 20 MPa (p_2), temperature 25°C). This selection is consistent with the FC-HyGuide guidance document and harmonization protocol (Masoni and Zamagni, 2011; Lozanovski et al., 2013). A significant amount of electricity is required to compress the hydrogen. For the compression of 1 kg H_2 from 2 MPa initial hydrogen pressure (p_1) to 20 MPa (p_2) electrical work of 1.18 kWh (W_{el}) is needed (Valente et al., 2017). Using initial hydrogen pressure and electricity demand for compression, the GWP of the compression stage could be calculated based on PV emissions factors used in the studies or the default value of 72 g CO_2/kWh (E) proposed by the protocol (Valente et al., 2017).

$$FU\ (p_1) + W_{el} \times \mathrm{E} = FU_{har}(p_2) \quad (1)$$

Since the stages after hydrogen compression are excluded from the system boundaries, the GWP has to be recalculated up to the final stage. Based on **Figure 4** and **Table 1**, the GWP results of the 13 studies were harmonized and recalculated referring to the FU_{har}. The variation in technological aspects (e.g., feedstock, operating conditions and capacity, the lifetime of the pant etc.) defined by the authors of each case study are not affected by the harmonization, which deals only with methodological choices in LCA.

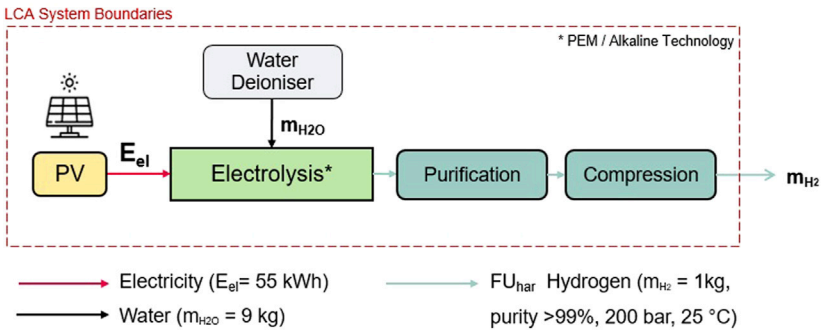

FIGURE 3 | The system boundaries of reviewed LCA studies divided into electrolysis incl. purification and compression subsystems.

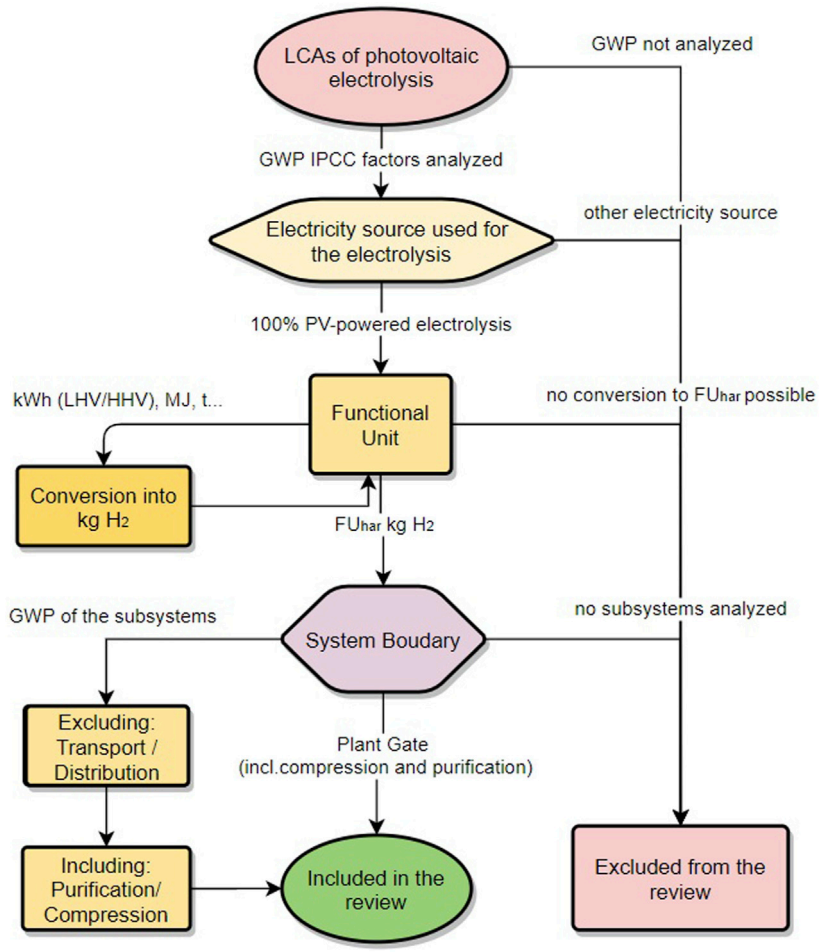

FIGURE 4 | The selection and harmonization process of reviewed LCA studies. IPCC - Intergovernmental Panel on Climate Change, GWP - Global Warming Potential, kWh LHV–Lower Heat Value, HHW - Higher Heat Value.

TABLE 1 | Calculating of harmonized Global Warming Potential (GWP).

Category	Protocol value	Included in the review	Excluded from the review	Comments
Functional Unit	kg H_2	kWh (LHV), MJ, 100 kg	FU without enough data for conversation	Conversation must be possible, (purity >99% vol., 20 Mba, 25°C)
Final Stage	Plant Gate (incl. on-site purification and compression	Initial values of subsystems have to be clarified stage-by-stage	Any study without stage-by-stage clarification	GWP of compression (3 stage cooled compression) and purification based on energy demand, emissions GWP/kWh and initial pressure used can be added, if initial pressure not known default value of 2 MPa is used Valente et al. (2017)
		Liquidation, distribution, use phase GWP can be excluded	Any study without stage-by-stage clarification	If GWP/energy input after the gate is specified, GWP/kWh used in the study can be used to calculate the GWP of the subsystems
Electricity Input	PV	Specific Renewable Mix	Grid Mix, Renewable mix (non-specific)	PV Input can be added according to the Gabi database Thinkstep, (2019) Otherwise default values can be used if the location is not known Valente et al. (2017)
Electrolyzer	PEM/Alkaline	Blackbox	SOEC or not mentioned	H_2 production conditioning (electrochemical plant), feedstock (tap water) can be added according to the GaBi database Thinkstep, (2019)

TABLE 2 | Overview of the reviewed LCA Studies.

Study	Alkaline	PEM	Efficiency (LHV)	Functional unit	Final stage and pressure after compression [MPa]	Location	Life-time	Original GWP [kg CO_2-eq/kg H_2]	Harmonized GWP [kg CO_2-eq/kg H_2]	Difference in [%]
Koroneos et al. (2004)	x		0.77	MJ (LHV)	H_2 liquefaction, 3 PMa	Germany[a]	—	5.71	**4.69**	**–17.9**
Granovskii et al. (2006)		x	0.67	MJ (LHV)	H_2 compression, 20 MPpa	United States, Colorado[b]	30 years	3.67	**3.72**	**+1.4**
Granovskii et al. (2007)		x	—	MJ (LHV)	H_2 compression, 35 MPa	United States, Colorado[b]	30 years	2.15	**2.16**	**+1.4**
Simons et al. (2011)	x		0.58	kg	H_2 compression, 0.45 Mpa	Spain[c]	—	4.30	**4.40**	**+2.3**
Lombardi et al. (2011)	x		—	kg	H_2 production 0.9 MPa	Italy	20 years	6.40	**6.64**	**+3.0**
Cetinkaya et al. (2012)		x	0.78	kg	H_2 distribution, 20 MPa	Canada	30 years	2.50	**2.58**	**+9.0**
Ozbilen et al. (2011)	x		0.62	kg	H_2 production	Canada[e]	20 years	2.41	**2.63**	**+3.2**
Pereira and Coelho (2013)		x	0.63	kWh	H_2 liquefaction	Germany/Portugal	20 years	6.20	**5.80**	**–6.5**
Reiter and Lindorfer, (2015)		x	—	MJ (LHV)	H_2 production, 10 MPa	EU	15 years	3.05	**3.13**	**+2.8**
Suleman et al. (2015)	x		0.46	kg	H_2 production, 0.1 MPa	Canada	—	0.37	**0.65**	**+70.0**
Schmidt Rivera et al. (2018)		x	0,64	MJ (LHV)	H_2 use, 1.38 MPa	EU[f]	20 years	3.05	**3.15**	**+3.2**
Lundberg et al. (2019)		x	0.74	100 kg	H_2 distribution	Sweden[g]	40,000 h	2.31	**3.80**	**+65.5**
Lundberg et al. (2019)	x		0.74	100 kg	H_2 distribution	Sweden[g]	40,000 h	2.60	**4.09**	**+57.3**

Bold values are: GWP after the harmonization and Difference to original GWP in [%]
[a]Insolation of 1,000 kWh/m.^{2}.
[b]BIPV thin film (1,231 kWp average).
[c]1,282 kW h/kWp.
[d]BIPV, eight kWp
[e]80 Wp (efficiency = 12%).
[f]2007 kWh/m^{2}a.
[g]PV emission factor from Sweden was taken from GaBi (66.8 g CO_2 -eq/kWh) (Thinkstep, 2019).

FIGURE 5 | Originally reported (green) and harmonized (purple) Global Warming Potential (GWP) of the functional unit of 1 kg hydrogen produced by PV power. Original GWP recalculated to kg H_2 up to the H_2 compression (when not reported in the original case study; up to the stage before compression). Original Data stem from the studies (Koroneos et al., 2004; Granovskii et al., 2006; Granovskii et al., 2007; Lombardi et al., 2011; Ozbilen et al., 2011; Simons et al., 2011; Cetinkaya et al., 2012; Pereira and Coelho, 2013; Suleman, 2014; Reiter and Lindorfer, 2015; Suleman et al., 2015; Schmidt Rivera et al., 2018; Lundberg, 2019).

RESULTS

Harmonized GWP Life Science Identifiers

The majority of reviewed studies could not be harmonized. A total number of 34 case studies was pre-selected, 13 of which could be harmonized (Cetinkaya et al., 2012; Granovskii et al., 2006; Granovskii et al., 2007; Koroneos et al., 2004; Lombardi et al., 2011; Lundberg, 2019; Ozbilen et al., 2011; Pereira and Coelho, 2013; Reiter and Lindorfer, 2015; Simons et al., 2011; Suleman et al., 2015; Suleman, 2014; Schmidt Rivera et al., 2018). The studies were excluded after screening because of the absence of open access data; for instance, the GWP results were not broken down into sub-systems and the FU parameters were not fully quantified (Dincer and Acar, 2015; Bhandari et al., 2014; Valente et al., 2017; Mehmeti et al., 2018; Utgikar and Thiesen, 2006; Hacatoglu et al., 2012; Kalinci et al., 2012; Boyano et al., 2011; Lotrič et al., 2021; Zhao et al., 2020; Kovač et al., 2021; Sharma et al., 2020; Ozawa et al., 2017). Hence, in these cases, it was not possible to convert the original FU to FU_{har} of 1 kg of hydrogen for the desired system boundaries. After the selection process, 13 LCA´s on electrochemical PV-based hydrogen production, shown in **Table 2**, could be harmonized (Koroneos et al., 2004; Granovskii et al., 2006; Granovskii et al., 2007; Lombardi et al., 2011; Ozbilen et al., 2011; Simons et al., 2011; Cetinkaya et al., 2012; Pereira and Coelho, 2013; Suleman, 2014; Reiter and Lindorfer, 2015; Suleman et al., 2015; Schmidt Rivera et al., 2018; Lundberg, 2019).

Figure 5 presents a comparison between original and harmonized GWP results that show an average difference of 0.27 kg CO_2/FU_{har} and a maximum difference of 1.5 kg CO_2/FU_{har}. The average GWP of all reviewed studies is 3.71 kg CO_2/FU_{har} and the median of 3.69 kg CO_2/FU_{har}. These differences between original and harmonized GWP are mainly caused by the harmonization of the compression stage, which resulted in extra emissions of 0.24 kg CO_2/FU on average. In all studies besides Koroneos et al. (2004) and Ramos Pereira and Coelho (2013) higher emissions were calculated after the harmonization due to the extra electricity demand of compressing hydrogen from the initial pressure used in the studies (0.1–20 MPa) to the goal pressure of the harmonization (20 MPa). In Koroneos et al. (2004) and Ramos Pereira and Coelho (2013) the FU is liquefied hydrogen. The GWP upon compression had to be accurately quantified, to recalculate the original GWP to FU_{har} and the emissions caused by liquefaction were subtracted, causing lower GWP of FU_{har} compared to original results. In the study of Lundberg (2019) also the electricity demand of the electrolyzer was replaced by 100% PV electricity of Sweden based on GaBi data (Thinkstep, 2019), causing higher emissions than the PV mix with hydro plants initially used in the study. The study by Suleman et al. (2015) (Suleman et al., 2015) showed the lowest GWP of 0.7 kg CO_2/FU_{har} and the study by Lombardi et al. (Lombardi et al., 2011) the highest GWP of 6.6 kg CO_2/FU_{har}. This can be explained by different assumptions on the emissions of PV electricity and electrolyzer energy consumption. The study of Suleman et al. (2015) assumes very small emission factors for PV. Even though the efficiency of the electrolyzer is low, the original GWP of FU_{har} is 0.37. Assuming 33.33 $kWh/kg_{hydrogen}$ and reported efficiency of the electrolyzer of 0.46, the GWP value can only be achieved by PV emission factor below 0.005 kg CO_2/kWh. Compared to other studies this value seems to be unrealistically low, however, it can be achieved by very green production of PV. The high GWP results of 6.6 kg CO_2/FU_{har} found in Lombardi (Lombardi et al., 2011) are caused by high emission factors of PV. Those are based on old PV manufacturing

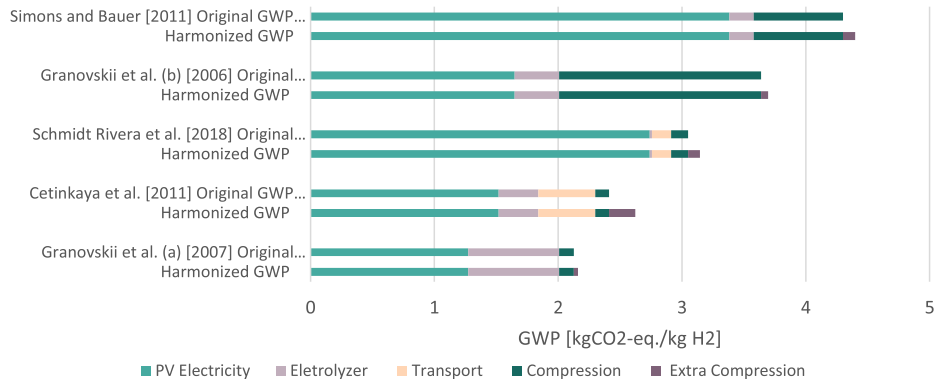

FIGURE 6 | Originally reported and harmonized Global Warming Potential (GWP) of the functional unit of 1 kg hydrogen produced by PV power divided into subsystems. Original Data stem from the studies (Koroneos et al., 2004; Granovskii et al., 2006; Granovskii et al., 2007; Lombardi et al., 2011; Ozbilen et al., 2011; Simons et al., 2011; Cetinkaya et al., 2012; Pereira and Coelho, 2013; Suleman, 2014; Reiter and Lindorfer, 2015; Suleman et al., 2015; Schmidt Rivera et al., 2018; Lundberg, 2019).

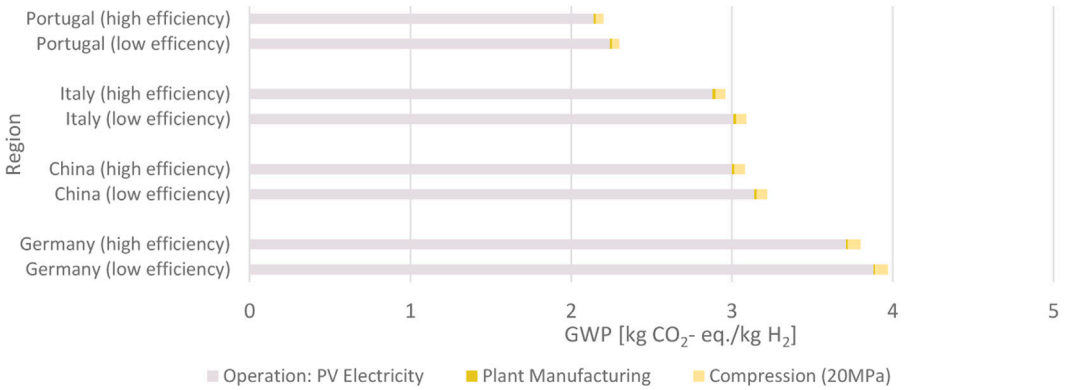

FIGURE 7 | Sensitivity analysis for different insolation levels and electrolyzer consumptions. GWP of PV- powered Hydrogen Production by country with high-efficiency scenario (power consumption 55 kWh/kg H_2) and low efficiency (electricity demand of 57.5 kWh/kg H_2). Purple–GWP caused by PV electricity, yellow - GWP of plant manufacturing and yellow–GWP of compression.

and performance data from 1995 to 1997 combined with assumptions on low PV efficiency and minor solar output. Similarly, in the study by Ramos Pereira and Coelho (Pereira and Coelho, 2013), low irradiation values of Germany (insolation of 1,000 kWh/m^2) combined with low-efficiency modules (11%) cause relatively high emission factors of photovoltaic modules and thus high GWP of the FU_{har}.

GWP of the stages involved in the system's life cycle impact (e.g., purification, compression, storage, distribution, and use) were not always reported and thus could not be exactly allocated. Five studies accurately described the contribution of the subsystems and divided the results into the impact of the PV system, the electrolyzer, compression and transport. **Figure 6** demonstrates the results, allowing direct comparison of the stages. However, since different parameters are used, the interpretation should only be completed based on the background information given in **Table 2**. In all studies, PV electricity is the largest process contributing to overall GWP. However, the PV impacts vary considerably between the studies. The main reasons are different efficiencies and thus electricity consumption of the electrolyzer, PV technology and production, location of use and operation time. The efficiencies of the electrolyzer differ between 58% by (Simons et al., 2011) and 78% reported by (Cetinkaya et al., 2012; Simons et al., 2011) do not report the lifetime assumed. PV technology analyzed is also different (Granovskii et al., 2006, Granovskii et al., 2007 and Cetinkaya et al., 2012): analyze BIPV thin-film technology. Ground-mounted multi-crystalline silicon panels with the efficiency of 14% are considered in (Schmidt Rivera et al., 2018), assuming the insolation level of 5.5 kWh/m^2. day corresponding to the average solar irradiation equatorial areas. Other studies do not state any specific technology (Schmidt Rivera et al., 2018). assumes 20 years of operation and (Granovskii et al., 2006, Granovskii et al., 2007 and Cetinkaya et al., 2012) assume 30 years of operation. Except for (Simons et al., 2011), all studies focus on analyzing PEM electrolyzers.

Unfortunately, not enough information is given to understand why the impacts of the electrolyzers seem to be different. Final pressure reported in the studies varies between 0.45 MPa used in (Simons et al., 2011) and 35 MPa used in (Granovskii et al., 2007. Granovskii et al., 2006) assume a lower isothermal compression efficiency of 0.65, rather higher final pressure of 20 MPa and lower gas-turbine power plant efficiency used for compression. This leads to a higher GWP of the compression stage. After the harmonization, the final pressure is 20 MPa and the GWP of the "extra compression" stage is demonstrated separately.

Sensitivity Analysis

The following parameters can affect the GWP results: electrolyzer manufacturing data (technology choice, capacity), operation conditions (full load hours and lifetime expectancy) and electricity emissions. Electrolyzer system aspects (technology, capacity) hardly influence the GWP results. The GWP of PEM and alkaline technology have very similar results and do not show any major differences in the LCI (Utgikar and Thiesen, 2006; Hacatoglu et al., 2012; Kalinci et al., 2012). Hence, most studies use a "black box" and do not focus on the GWP of the stack and Balance of Plant. Operating conditions have a bigger impact on the GWP. Usually, around 40,000 full load hours are assumed and the amount of hydrogen gas produced during the estimated lifetime is calculated by multiplying the production/hour with the lifetime of the electrolyzers. The efficiency and costs can be indicated by the electricity demand for production (Yang and Ogden, 2007). The impact of the electrolyzer efficiency on the GWP was analyzed by Reiter et al. (Reiter and Lindorfer, 2015). Doubling of the electricity demand of H_2 production leads to an increase in GWP between 87 and nearly 100%. Consequently, the emissions caused by the electricity demand of hydrogen production dominate its GWP, independently of the operation assumptions.

The emissions associated with electricity input for hydrogen depend mainly on PV technology and PV performance (e.g. irradiation based on location and orientation, degradation rate, lifetime expectations). The study of Schmidt Rivera et al. (Schmidt Rivera et al., 2018) focuses on the influence of the efficiency of the PV system from 11 to 17% and insolation level. The results indicate that the GWP is not significantly affected by the efficiency. To understand the impacts on the GWP of hydrogen, we modelled hydrogen production in the LCA in the software Gabi (Thinkstep, 2019) using different PV inputs and locations of hydrogen production. The most complete LCIAs of a 1 MW PEM stack and Balance of Plant was modelled based on the data from Bareiß et al. (Bareiß et al., 2019). Material flows of the electrolyzer stack and Balance of Plant are given in **Appendix A1**, **A2** The data for the Nafion membrane are not available so that the data for perfluorosulfonyl fluoride have been used instead. The reference year of used electrolyzer data is 2019. The photovoltaic power generation mix (CIS, CdTe, mono-crystalline and multi-crystalline) was modelled based on the background data of the ecoinvent database (Wernet et al., 2016). The data sets cover all relevant process steps and technologies along the supply chain. The inventory is partly based on primary industry data; partly on secondary literature data. The most important technologies for power generation are considered according to the national situation. The model is based on the global average market mix of photovoltaic technologies installed: Mono-Silicon 42%, Multi-Silicon 47%, Cadmium-Telluride (CdTe) 7% and Copper-Indium-Gallium-Diselenide 4%. The assumptions on irradiance values and PV performance dominate the GWP of PV. Hence, in the LCA model following countries were analyzed in more detail as operating regions for electrolysis: Germany (DE), Italy (IT), China (CN) and Portugal (PT). All technologies were modelled individually based on country-specific annual irradiance values applied in the GaBi (Thinkstep, 2019) and ecoinvent databases (Wernet et al., 2016).

The manufacturing and operation of the whole system are considered in the model. Key PV characteristics were taken from Report IEA-PVPS Task 12 (Frischknecht et al., 2020). Those are e.g. the PV degradation rate of 0.7%/year and life expectancy of 20 years. Since oxygen produced via water electrolysis is technically not used as a co-product, no multi-functionality occurred. Additionally, since the hydrogen production requirement of 1 kg hydrogen varies between 55 and 57.5 kWh, two different scenarios were modelled for each country: a "high energy demand scenario" with 57.5 kWh and a "low energy demand scenario" with 55 kWh. Adjusting for this demand has a large impact on the GWP results of hydrogen (see **Figure 7**). The operation phase dominates the environmental impacts during the lifetime. GWP of hydrogen from photovoltaics even from the high energy demand scenario still exhibits a lower GWP than any fossil-dominated alternatives production methods like SMR or coal gasification. Experts estimate that in the near future minor efficiency improvements of water electrolysis can be expected (Schmidt et al., 2017). Better efficiencies will lead to a decreased energy demand of hydrogen production and thus reduced GWP per kg of hydrogen. Increasing the efficiency of the electrolyzer results in lower GWP with an approximately linear correlation.

CONCLUSION

The majority of the environmental impacts during the lifespan of the electrolyzer occur from electricity usage in the operation phase. Even for PV powered electrolysis, the electricity used is crucial for the determination of the environmental impacts. The selection process conducted in this study revealed that the majority of the studies show deviations from the evolving impact assessment methodologies within the LCA community. The incomplete reporting of many LCA reviews caused the impossibility of the harmonization of the GWP results. The results after harmonization and sensitivity analysis show that the viability highly depends on the region of deployment and the use-case scenario. All the reviewed studies confirm that the design of the hydrogen plant has less impact and that different electrolyzer technologies (e.g., PEM and Alkaline) have similar outcomes. However, the electricity consumption of the plant and PV emission factors, that are used to cover the demand, have a large impact on the GWP of hydrogen. The remaining difference

between the studies after the harmonization process is shown in **Figure 5**. Even the harmonized GWP results range between 0.7 and 6.6 kg CO_2-eq/FU_{har} depending on the use case. The differences between original and harmonized GWP range up to 1.5 kg CO_2-eq/FU_{har} in individual cases are mainly caused by the harmonization of the pressure. Based on the previous findings, the lowest GWP, which was found in Suleman et al. (Suleman, 2014), can be confirmed for the "green" electricity scenario, where optimistically low consumption of the electrolyzer and low PV emissions are assumed.

In the future, innovative technologies of PV should be analyzed more precisely. If manufactured in an environmentally friendly way, they offer the opportunity to reduce the GWP of hydrogen by lowing the emission factor of consumed electricity. The ecological benefit of prolonged operation time and recycling options should additionally be included in further analyses. Based on a comprehensive database, a full set of harmonized life-cycle sustainability indicators to be analyzed besides GWP.

For further studies of hydrogen production systems, the authors highly recommended 1) breaking down the entire system into well-defined subsystems and using compression as the final stage of the LCA and/or 2) providing energy inputs/GWP results broken down for the different stages. In the case where the system boundaries of the LCA are not limited to the production plant, a FU of 1 kW h (LHV) hydrogen can also be used to assess the environmental sustainability of hydrogen. If the use phase of hydrogen is the focus of the study, a FU 1 kWh (LHV) can simplify the comparison of its environmental impacts with other energy fuels. The results for the transport and distribution of hydrogen should usually be presented separately from production to avoid undesired combinations and to shift the attention on the impact of different transport scenarios with the option to combine production pathways with diverse distribution possibilities.

AUTHOR CONTRIBUTIONS

Conceptualization - AR, UR, KD, KB; methodology - OK, AR; software and validation - OK; formal analysis - KB; writing—original draft preparation, OK; writing—review and editing - AR, KB, KD, and UR; supervision - AR. All authors have read and agreed to the published version of the manuscript.

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APPENDIX

TABLE A1 | A1 Materials for a 1 MW PEM stack, state-of-the-art (Bareiß et al., 2019).

Material	Mass (kg)
Titanium	528
Aluminium	27
Stainless steel	100
Copper	4.5
Nafion	16
Activated carbon	9
Iridium	0.75
Platinum	0.075

TABLE A2 | A2 Main materials and assumed masses for the PEM Balance of Plant (Bareiß et al., 2019).

Material	Mass (t)
Low alloyed steel	4.8
High alloyed steel	1.9
Aluminium	<0.1
Copper	<0.1
Plastic	0.3
Electronic material (power, control)	1.1
Process material (adsorbent, lubricant)	0.2
Concrete	5.6