Global Warming Potential and Societal-Governmental Impacts of the Hydrogen Ecosystem in the Transportation Sector

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HIGHLIGHTS

- Platinum accounts for less than 0.01% of the mass in a fuel cell system.
- A type IV hydrogen tank mass consists of over two-thirds carbon fiber one.
- The societal impact of the tank is higher than that of the fuel cell system.
- The global warming potential of the tank exceeds that of the fuel cell system.
- Assessing societal impacts and governance risks involves inherent uncertainties.

ABSTRACT

The environmental and societal challenges of our contemporary society are leading us to reconsider our approaches to vehicle design. The aim of this article is to provide the reader with the essential knowledge needed to responsibly design a vehicle equipped with a hydrogen fuel cell system.

Two pivotal aspects of hydrogen-electric powertrain eco-design are examined. First, the global warming potential is assessed for both PEMFC systems and Type IV hydrogen tanks, accounting for material extraction, production, and end-of-life considerations. The usage phase was omitted from the study in order to facilitate data adaptation for each type of use. PEMFC exhibits a global warming potential of about 29.2 $kgCO_{2eq}$/kW, while the tank records 12.4 $kgCO_{2eq}$/kWh, with transportation factors considered. Secondly, the societal and governmental impacts are scrutinized, with the carbon-intensive hydrogen tank emerging as having the most significant societal and governmental risks. In fact, on a scale of 1 to 5, with 5 representing the highest level of risk, the PEMFC system has a societal impact and governance risk of 2.98. The Type IV tank has a societal impact and governance risk of 3.31.

Although uncertainties persist regarding the results presented in this study, the values obtained provide an overview of the societal and governmental impacts of the hydrogen ecosystem in the transportation sector. The next step will be to compare, for the same usage, which solution between hydrogen-electric and 100% battery is more respectful of humans and the environment.

KEYWORDS

Fuel cell system; Hydrogen tank; Global warming potential; Societal impacts; Governance

1. Introduction

The energy transition has become an unavoidable global imperative, raising both hopes and significant challenges for contemporary societies. Faced with pressing issues of climate change and greenhouse gas emissions reduction, our transportation methods and energy model must be rethought. However, this transition is constrained by complex contradictions and dilemmas that question our technological, environmental, and societal choices. Despite an increasing call for climate action following the 2015 Paris Agreement, global CO_2 emissions continue to rise, with a 5% increase compared to 2015 in 2022 [1]. To address this issue, low-carbon technologies are emerging with the aim of achieving neutrality by 2050. However, the demand for metals in this model is massive: generating electricity from offshore wind turbines, for instance, requires five times more materials than natural gas-based production [2]. A category known as "materials for the energy transition" has been created for these technologies, including lithium, aluminum, iron, cobalt, nickel, copper, silver, cadmium, and platinum [3]. Many of these materials are also considered as critical materials for energy due to their vulnerability in terms of supply, given their importance for various technologies, limited availability, or geographic concentration. Key critical materials mainly include lithium, platinum, cobalt and graphite [4]. The elements from the periodic table that predominate in the hydrogen ecosystem are categorized into these two groups. Carbon, fluorine, aluminum, silicon, and platinum are regarded as critical materials, with carbon, fluorine, aluminum, and silicon also being part of the materials for the energy transition. Sulfur is also part of the hydrogen ecosystem but does not fall into any of the mentioned categories.

As part of this energy transition, cleaner modes of transportation are being introduced. The electrification of vehicles initially began with the hybridization of internal combustion engine cars and has since evolved to include the integration of hydrogen fuel cells in an all-electric powertrain. Hydrogen fuel cells are increasingly seen as a promising alternative to fossil fuels and greenhouse gas emissions reduction [5]. However, the choice of materials used for fuel cells and hydrogen storage tanks, as well as how they are produced, has a direct impact on equivalent CO_2 emissions [6]. Furthermore, the societal impacts, namely the impact of material extraction on soils and local population of these technologies, must also be considered to ensure a sustainable and equitable transition to a cleaner future.

The article focuses here on the PEM (Proton Exchange Membrane) technology and type 4 tank, which are the most prevalent in the transportation sector [7], [8]. This fuel cell type is integrated with all the balance of plants (BoP) into a fuel cell system. Currently, reference [9] stands as the sole reference comprehensively addressing both global warming potential and societal impacts, despite being limited to the examination of stack impacts. As previously mentioned, the article uniquely contributes by concentrating not only on the stack but also on the entire PEM fuel cell system and the hydrogen storage tank. A meticulous review of references [9]-[18] reveals that, among the listed values of global warming potential for PEM stacks or fuel cell systems, only references [9], [11], [15], [16] align with the specific criteria outlined in the study. Moreover, for the assessment of global warming potential related to hydrogen storage tanks, a specifically chosen selection of five references meeting the defined criteria is identified [16], [18]-[22]. Despite variations in the presented global warming potential values, a unanimous consensus emerges, emphasizing the carbon fiber production phase as the most significant contributor to CO_2 equivalent emissions.

The research objectives of this study are explicitly outlined to guide and provide clarity on the overarching aims. Firstly, the research aims to serve as a comprehensive reference for individuals outside the specialized field of life cycle analysis, particularly those engaged in the development of hydrogen-electric powertrains. By doing so, the objective is to offer insights and knowledge that contribute to the creation of environmentally and socially responsible powertrains. Secondly, the study aims to integrate principles of eco-design and societal objectives into industrial transportation applications. This goal reflects a commitment to advancing sustainable practices and aligning technological advancements with broader environmental and societal aspirations. The study aims to provide clear guidelines for industrials and researchers, ensuring transparency and alignment with the outlined goals.

The paper-based roadmap initially examines the mass composition of the fuel cell system and type 4 tank. After describing the life cycle analysis and global warming potential, equivalent CO_2 emissions are provided. Finally, the societal and governmental impact of materials is discussed to present the overall societal impacts of hydrogen components.

2. Mass composition

Knowledge of the mass composition of the hydrogen fuel cell system and its tank is essential for understanding their global warming potential and societal impacts. Mass composition, i.e. the proportion of different elements and materials contained within these components, directly influences the equivalent CO_2 emissions generated during their production and end-of-life stages. Furthermore, depending on the resources employed in the design of these components, their societal impact and the governmental issues related to materials can vary in significance.

2.1. Fuel cell system

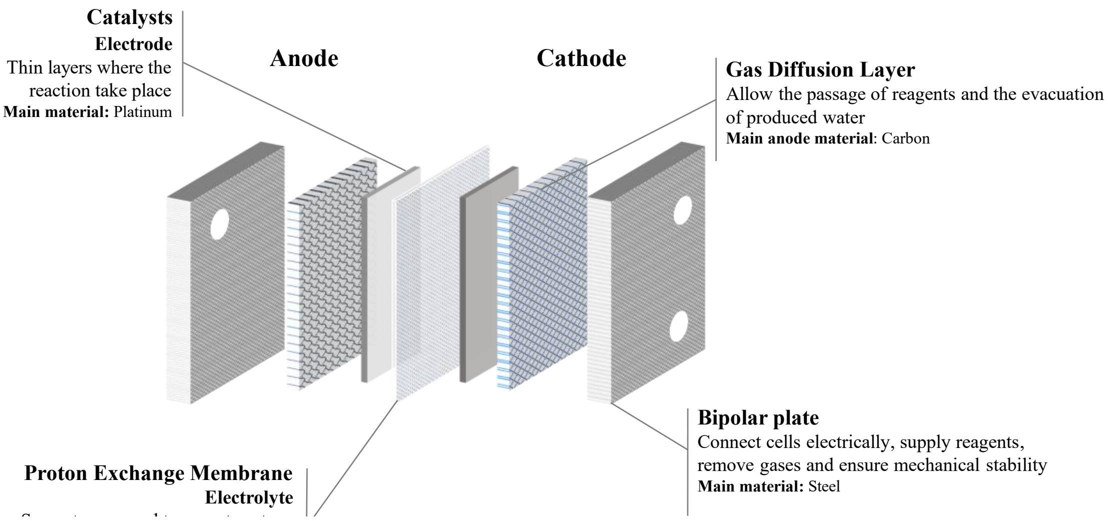

Fig. 1. Composition of a PEM fuel cell

Proton Exchange Membrane Fuel Cell (PEMFC) (see Fig. 1) consists of several cells stacked together. The power of the fuel cell is determined by the number of cell assemblies [23]. Each cell comprises two bipolar plates, two gas diffusion layers (GDL), two catalytic layers, and a proton exchange membrane. Platinum is deposited on the catalytic layers, while carbon is deposited on the electrodes. When the electrolyte is sufficiently hydrated, proton transfer from the anode to the cathode occurs, while preventing electron conduction. This phenomenon is facilitated by perfluorosulfonic acid (PFSA). The diffusion layers surround the electrodes and serve as carbon fiber-based supports that play a crucial role in managing water: they facilitate the transport of gases to the catalytic layers while removing water produced by the electrochemical reaction. Lastly, the bipolar plates, two steel plates, collect electric current and distribute gases (hydrogen, air or pure oxygen depending on fuel cell type). Additionally, the bipolar plates provide mechanical support for the stack.

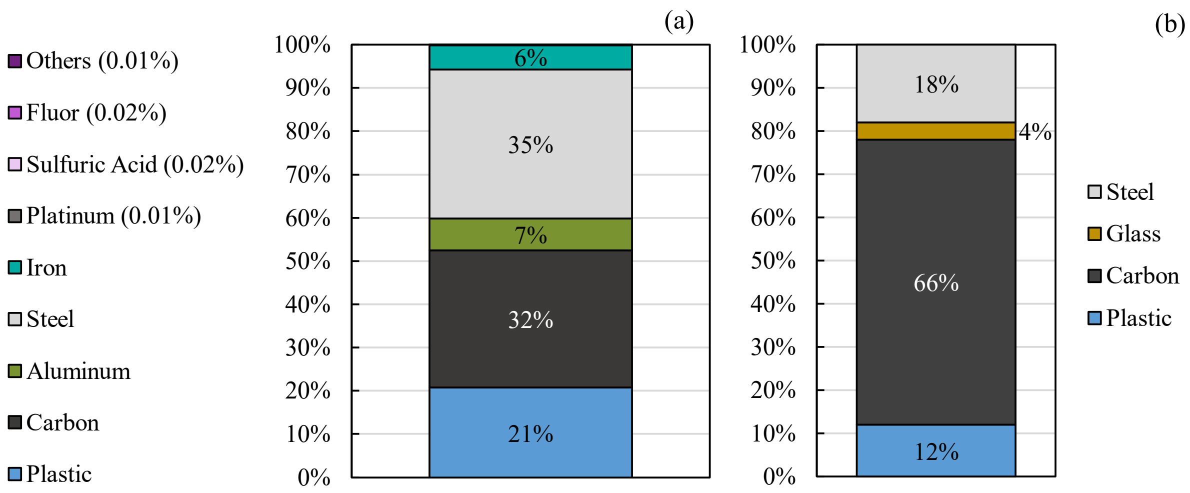

Fig. 2. (a) Mass composition of a PEMFC system and (b) mass composition of a hydrogen tank

A PEMFC cannot operate without a set of components. The key elements of the system include air compressors, the DC/DC converter, pumps, and plate heat exchangers. These components are called the balance of plants and are primarily composed of steel.

The mass composition of a PEMFC system can vary significantly depending on design choices and materials used by manufacturers. Fig. aims to provide a general representation for all existing hydrogen systems in the transportation market. This generalization work allows readers of this article a direct and simple approach for an initial consideration of the global warming potential and societal impacts of a hydrogen system based on PEM technology.

A PEMFC system consists mostly of steel (35%) and carbon (32%) [17]. Steel primarily exists in the balance of plant, while carbon is present throughout all components of a hydrogen fuel cell, primarily serving to improve electrical conductivity and strengthen structures. The predominant steel used in the hydrogen fuel cell system is primarily stainless steel. Consequently, in the depiction of the system's mass distribution (see Fig. 2), stainless steel has been separated from iron. Indeed, during the recycling process, these two elements are treated separately. The detailed specifics of stainless steel are not addressed in this article as they vary considerably from one manufacturer to another.

Despite the current emphasis on reducing platinum content in PEMFC, primarily for economic and environmental reasons [8], [11], [24], this material accounts for only 0.01% of the total mass of the hydrogen fuel cell system.

The mass composition provided in reference [17] does not specify the elements contained within the PFSA membrane. However, fluorite mining significantly degrades water quality and can lead to biodiversity loss. Furthermore, the health of workers is jeopardized due to the use of chemicals [25], [26]. To understand the extent of fluorine's influence on the global warming potential and societal impacts of a hydrogen fuel cell system, to know its mass composition is essential. A PFSA membrane consists of 57.4% tetrafluoroethylene (TFE) and 42.6% sulfuric acid [27]. TFE itself is composed of 57.0% fluorine. At the end, fluorine accounts for 32.7% of the mass of a PFSA membrane and 0.02% of a hydrogen fuel cell system.

2.2. Hydrogen tank

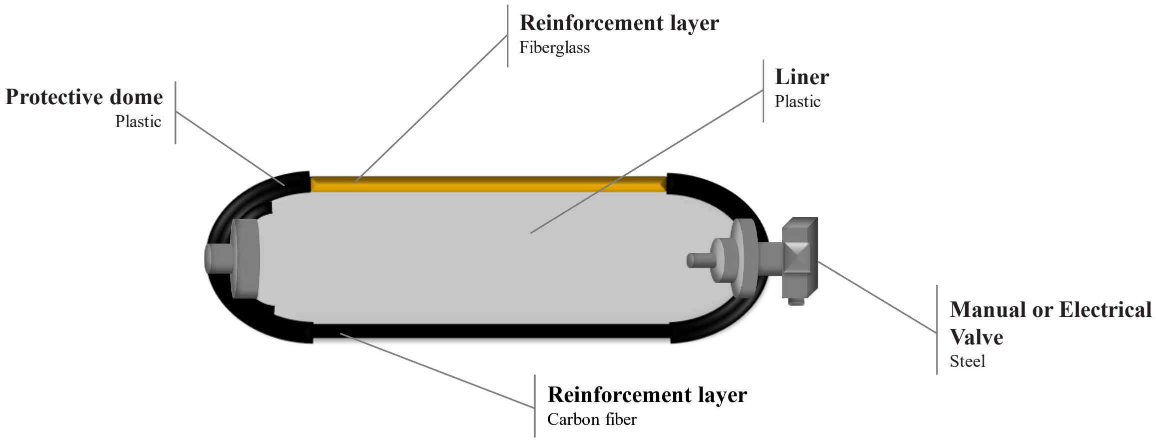

Fig. 3. Composition of a hydrogen tank

A type IV hydrogen tank is primarily composed of fiber-reinforced composite materials (see Fig. 4). The inner layer, the liner, is made from polymer materials such as polyethylene. This material prevents hydrogen leaks. The reinforcement layers are composed of carbon fiber and fiberglass. The protective dome enhances the tank's durability and is primarily made from plastic. Lastly, the tank is equipped with safety elements and valves, consisting largely of steel. A type IV tank is therefore two thirds carbon, followed by steel (18.0% by mass), plastic (12.0%) and glass (4.00%) (see Fig.) [18].

3. Global warming potential

The global warming potential (GWP) measures the potential climate impact of a component or technology by assessing the greenhouse gas emissions it can generate throughout its lifecycle, from production to disposal [28]. The unit used is CO_2 equivalent, representing emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), fluorinated gases (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). In this article, this measurement is normalized to the functional unit of kW for the hydrogen fuel cell system and kWh for the tank.

3.1. Life cycle analysis

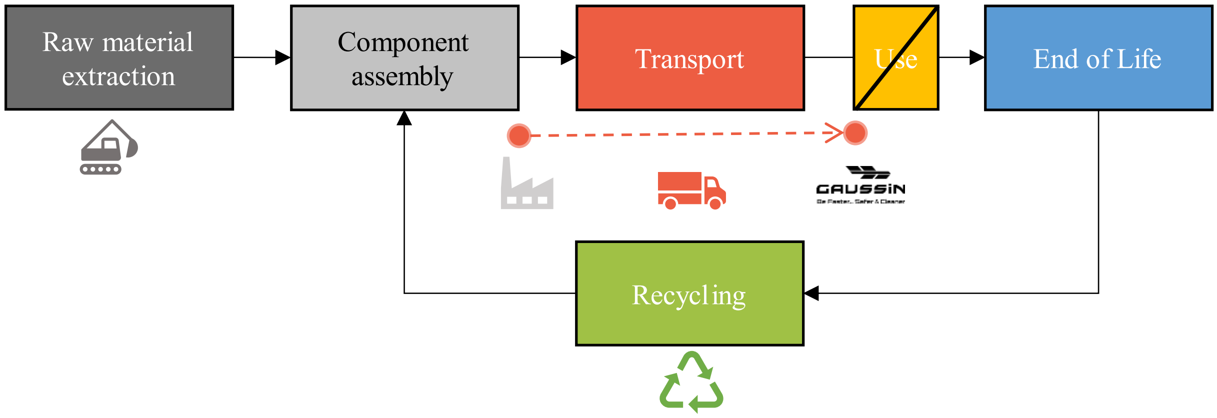

Fig. 4. Considered life-cycle analysis chain.

Life Cycle Analysis (LCA) is a widely used method to assess the global warming potential of technologies throughout their lifecycle, from raw material extraction to end-of-life, including their use phase (see Fig. 4). The global warming potential is then quantified for each stage to evaluate their respective influence on the total global warming potential. In this article, the considered stages include raw material extraction, component manufacturing, transportation from the production site to the vehicle assembly site, end-of-life, and recycling. The use phase is excluded from this analysis so that the final results can be applied independently of usage. Component production includes assembly phases, and end-of-life incorporates dismantling and component destruction stages. Regarding transportation, the distance is calculated from the component assembly site to the vehicle assembly site located in Héricourt, France. This site was chosen as a case study, corresponding to research conducted with the company GAUSSIN, located in this city. However, following the guidelines provided in the reference [28], the calculation of global warming potential can easily be extended to other locations. Finally, the recycling stage is a crucial step in reducing the carbon footprint of components. Although this costly and energy-intensive process is not firmly integrated into the lifecycle of hydrogen fuel cell systems and even less so for tanks, it is essential to consider it whenever possible to assess potential benefits. By reintroducing recycled materials into the value chain, the amount of raw materials required for component construction decreases significantly. In fact, the value of recycling over the entire life cycle is therefore considered to be below zero.

3.2. Global warming potential study

3.2.1. Fuel cell system

To assess the global warming potential of a Proton Exchange Membrane Fuel Cell system, eight key references are reviewed. Reference [17] concentrates on critical materials within a PEMFC system and explores end-of-life strategies, including recycling. While recycling, particularly of platinum, aluminum, carbon, polymer membrane, plastic, iron, and steel, contributes to a 12.2% reduction in the global warming potential during system manufacturing, the study notes that recycling only aluminum lacks visible benefits. The reference [11] indicates a maximum decrease of 34.5% in emissions related to the manufacturing of the system when secondary materials are reused in the manufacturing process and platinum is recycled. If platinum is not recycled, this percentage drops to 1.1%.Reference [16] focuses specifically on material extraction and system production-related global warming potential. Electrode manufacturing stands out with the highest emissions, constituting 57.0% of hydrogen fuel cell design emissions. Membranes have the least impact at

3.60%. Combining references [17] and [16], fuel cell manufacturing contributes 77.5% to the total emissions in a hydrogen system. Reference [11] supplements [17], distinguishing end-of-life emissions and recycling benefits. It reports that the end-of-life of a hydrogen fuel cell system emits 3.90 $kgCO_{2eq}$/kW which is 10% more than the emissions related to the manufacturing of the system, encompassing manual dismantling and end-of-life processes. Several references (see Table 1) delve into the topic of global warming potential, with the earliest found dating back to 2001 [12]. This pioneer study by Ballard focuses on the global warming potential of a PEM stack in a pilot factory. However, its results exclusively present CO_2 emissions, lacking equivalence values and employing energy mix data over 20 years old. References [10], [13], [14] present emissions data, but their focus, unit of measurement, or methodology doesn't align with our study's objectives. References [9], [11], [15]-[17] offer comprehensive and relevant data for our analysis. They present emissions in CO_2 equivalents per kW functional unit, allowing for a detailed breakdown across life cycle stages and system elements (stack and balance of plant).

Table 1. References examined for global warming potential in the manufacturing, end-of-life, and recycling stages of both the PEM fuel cell system and the hydrogen type 4 tank.

Studied reference	Publication date	Components studied	Values
PEM fuel cell system			
[13]	February, 2024	Stack	121 $kgCO_2$ for the raw material extraction of a 17W stack 3.40 $kgCO_2$ for the component assembly 1.00 $kgCO_2$ for the End of Life -91.10 $kgCO_2$ for the recycling
[9]	December, 2023		24.20 $kgCO_{2eq}$/kW for stack manufacturing Including 15.40 $kgCO_{2eq}$/kW
[14]	January, 2023		5.7 x 10^{-3} $kgCO_{2eq}$/km for manufacturing
[29]	May, 2022	PEM fuel cell system	0.60 $kgCO_{2eq}$/kWh for 100 years
[11]	March, 2021		39.0 $kgCO_{2eq}$/kW for stack manufacturing End of Life represents 10% of system manufacturing global warming potential Recycling with reintroduction of secondary materials into the system manufacturing process reduces the global warming potential associated with system manufacturing by -34.5%.
[16]	January, 2021		27.00 $kgCO_{2eq}$/kW for the stack manufacturing 10.80 $kgCO_{2eq}$/kW for the balance of plant manufacturing
[15]	January, 2020		43.30 $kgCO_{2eq}$/kW for the stack manufacturing 6.60 $kgCO_{2eq}$/kW for the balance of plant manufacturing
[17]	September, 2019		87.90 $kgCO_{2eq}$/kW for the stack manufacturing 17.30 $kgCO_{2eq}$/kW for the balance of plant manufacturing
[12]	January, 2001	Stack	Global warming potential between 20 $kgCO_2$/kW and 78 $kgCO_2$/kW
4 type Tank			
[14]	January, 2023	Tank Type 4	9.90 x 10^{-3} $kgCO_{2eq}$/km for manufacturing
[16]	January, 2021		12.10 $kgCO_{2eq}$/kWh for manufacturing
[20]	January, 2021		30.40 $kgCO_{2eq}$/kWh for manufacturing
[18]	September, 2020		12 $kgCO_{2eq}$/kWh for manufacturing
[21]	January, 2019		10.80 $kgCO_{2eq}$/kWh for raw material extraction 0.20 $kgCO_{2eq}$/kWh for component assembly
[19]	April, 2018		6.20 $kgCO_{2eq}$/kWh for manufacturing

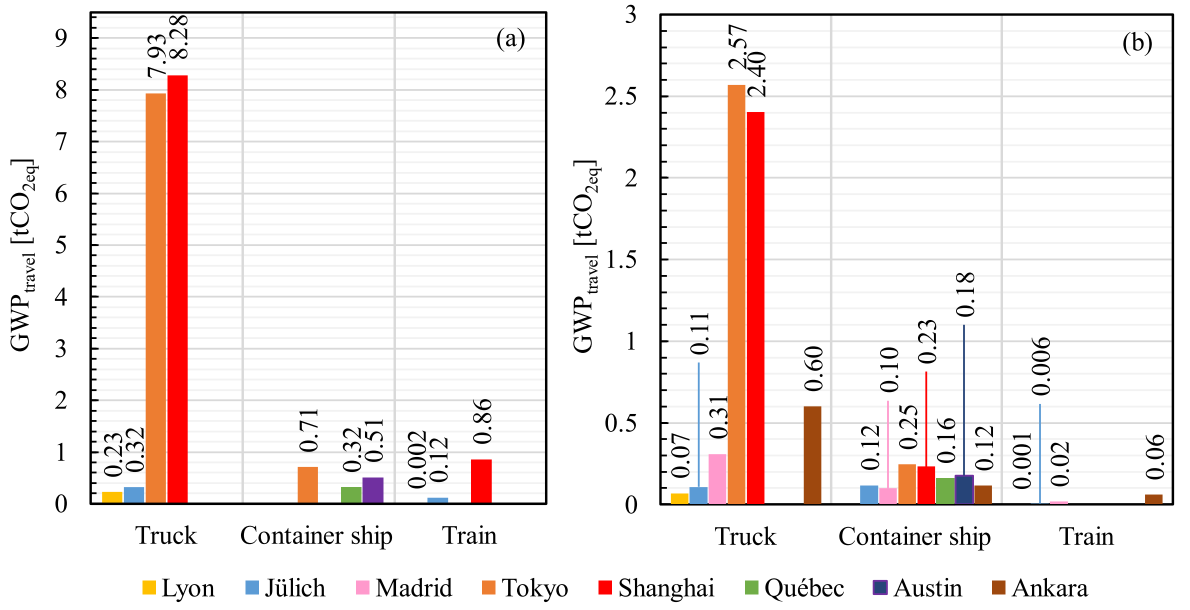

Fig. 6. Transport-related global warming potential of the PEMFC system (a) and tank (b) for different modes of transport and production sites.

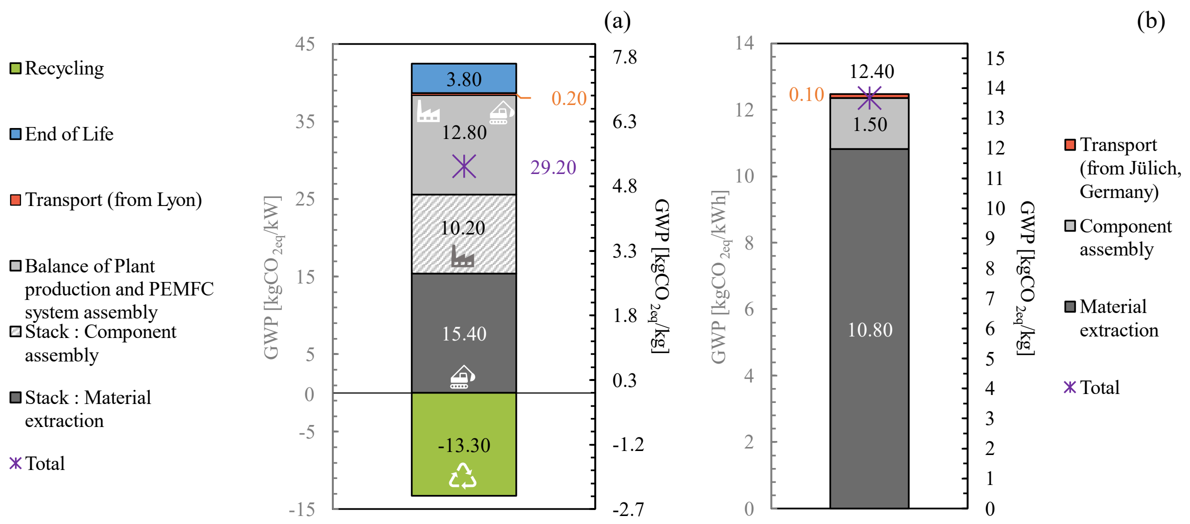

Fig. 5. Global warming potential of a PEMFC system (a) and a type 4 hydrogen tank (b) at different stages of the life cycle

The global warming potential associated with the extraction of stack materials is derived from reference [9]. Concerning the assembly of stack components, including cell assembly as well as the manufacturing of membranes and bipolar plates, the global warming potential is determined as the average of the global warming potentials presented in references [11], [16]. Similarly, the global warming potential to produce the balance of plants and system is calculated as the average of data from these two references. For the end-of-life phase, the global warming potential is determined following the percentage provided in reference [11] representing 10% of the sum of the three previously established global warming potentials. The same principle is applied to recycling-related emissions, reflecting a maximum reduction of 34.5% in the sum of previously calculated emissions.

Regarding transportation, the global warming potential associated with this stage varies from 0.27 $kgCO_{2eq}/kW$ to 8.28 $kgCO_{2eq}/kW$ (see Fig. 5), depending on the system's production location. Emissions are calculated using the method detailed in [28]. Six locations corresponding to the primary sites for producing hydrogen fuel cell systems are studied: Lyon (France), Oslo (Norway), Seoul (South Korea), Shanghai (China), Toronto (Canada), and Austin (United States). Transportation is also considered across several modes: by ship, truck, or train. The figure above summarizes the findings.

Considering a PEMFC system designed in Lyon, France, with transportation from the manufacturing site to the hydrogen vehicle assembly site and recycling rates of 88% for titanium, 76.0% for platinum, and 40.0% for steel, the global warming potential of a PEMFC system is 29.7 $kgCO_{2eq}/kW$ (see Fig. 6).

3.2.2. Hydrogen tank

The global warming potential for an average hydrogen storage tank, as indicated in reference [22], stands at 280 $kgCO_{2eq}/kgH_2$, equivalent to 8.49 $kgCO_{2eq}/kWh$ considering a hydrogen energy density of 33.0 kWh/kg. Remarkably, the tank emerges as the component with the highest global warming potential, primarily composed of 66.0% carbon fiber, rendering its current recycling unfeasible. Nevertheless, the potential for a second life, especially in aerospace applications [30], could mitigate emissions in the design of other components. Additionally, ongoing efforts by Plastic Omnium and a partner to explore cost-effective chemical recycling of carbon fiber composites may offer sustainable alternatives for automotive lightweighting, potentially impacting the life cycle assessments of carbon-intensive components, excluding new hydrogen tank production [18].

On the other hand, life cycle assessments for hydrogen storage tanks are more recent than those for PEMFC systems. Reference [21] is the sole source providing insights into material extraction impacts for the tank. The challenge in estimating the life cycle of tanks lies in the diverse processes involved in carbon fiber manufacturing. Typically, carbon fiber production contributes between 75% and 90% of emissions in tank fabrication [16], [20], [21]. Reference [19] reports the lowest global warming potential for tank production (approximately 6.2 $kgCO_{2eq}/kWh$), while reference [20] records the highest at 30.4 $kgCO_{2eq}/kWh$. References [16], [18], [21], [22] converge around 12 $kgCO_{2eq}/kWh$. Reference [21] is based on the Chinese electric mix and a tank manufactured in China, while reference [20] relies on the German electric mix. References [19], [20] are finally excluded from this discussion due to their extreme values. Despite examining all these references (see Table 1), no information on the end-of-life global warming potential of the tanks was found.

For tank transportation, the same procedure is conducted as for the hydrogen fuel cell system. Eight major tank production locations are considered: Lyon (France), Shanghai (China), Quebec (Canada), Austin (United States), Madrid (Spain), Jülich (Germany), Ankara (Turkey), and Tokyo (Japan). The results are depicted in Fig. 5.

The Fig. 6 illustrates the average global warming potential for the tank production, calculated from the averages of global warming potentials from references [16], [18], [21], [22]. Additionally, the global warming potential related to material extraction is extracted from reference 4, while transport emissions are derived from Fig. 5 (b).

The tank is the component with the highest global warming potential: being composed of 66.0% carbon fiber, its recycling is currently impossible. However, a second life could be considered for carbon fiber, especially in aerospace applications [30]. While this reuse doesn't have a direct impact on the total global warming potential of the type IV tank, it helps reduce emissions in the design of other components. Assuming the tank is manufactured in Jülich, Germany, its maximum total global warming potential is 12.40 $kgCO_{2eq}/kWh$, with approximately 0.90% of emissions attributed to transportation.

Now that the global warming potential is known, the societal impacts of these components are examined.

4. Study of the societal and governmental impacts of materials

Understanding and considering societal impacts when choosing a new technology is crucial. Indeed, material extraction often leads to significant socio-economic issues for communities, with the most vulnerable populations being the most affected. Furthermore, material extraction has long-term negative consequences on soil and land degradation. Societal impacts are subdivided into 3 factors: social vulnerability, land use, and impacts on local populations. Social vulnerability measures access to healthcare and education, as well as poverty and food insecurity in the affected region. Land use illustrates the impact of mines on soil quality and impacts on local populations consider the health hazards for workers and communities. Lastly, governmental concerns are also considered using an economic factor and a global governance indicator.

To focus on the societal impacts of components, knowledge of their mass composition is essential. Once this is determined (see part 2), the societal and governmental impacts of materials are identified.

4.1. Societal impacts of materials

Societal impacts are rated on a scale from 0 to 5, with 5 being the factor with the highest societal impact [31]. A color scale is also assigned, ranging from red for the highest value to green for the lowest value. The societal impacts of carbon are determined in reference [32], while those of aluminum, iron, and platinum are provided in reference [31]. For other materials such as plastic, sulfuric acid, fluorine, and platinum, impacts are determined through the geographic distribution of societal risks provided in the supplementary information of reference [31]. Due to the difficulty in obtaining traceability for the fiberglass used in the construction of hydrogen tanks, these impacts are not studied.

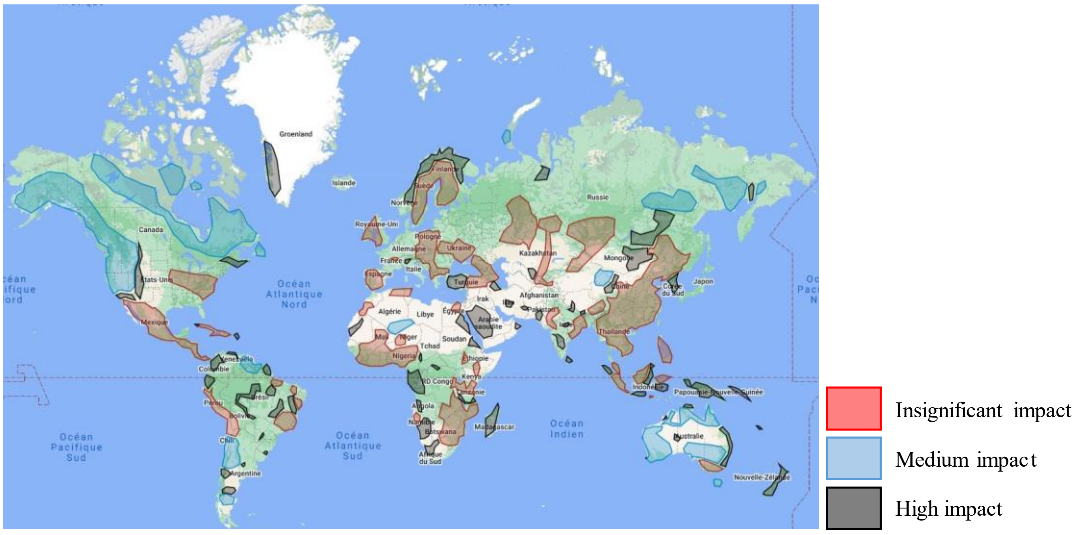

Fig. 7. Impact of mining on local populations

The approach to determine societal impacts begins with the study of maps representing the global distribution of the three factors under investigation. Fig. 7 uses one of the maps presented in the reference [31] to illustrate the global distribution of impacts on communities. The map divides several distinct zones. Black areas indicate regions where mining activities have a limited impact on local populations, blue areas signify a moderate impact, while red areas indicate the most significant impact. In these areas, material production sites are located. Then, a correlation is established between the location of each production site and its corresponding geographical zone. For instance, the platinum mine situated in the Mokopane region of South Africa falls within a red zone, signifying a substantial impact on local populations. This analysis is conducted for every production site of each material. The production sites along with their attributed impact are grouped into 6 regions: Africa, Asia, Europe, North America, South America, and Oceania. The societal factors of each of these regions represent the arithmetic average of the impacts from each production site within the studied region. At this stage, we have the values of each societal factor for each region and material. The next step is to determine the value of each societal factor for each material, regardless of the region.

To define the societal impacts of material, this map is supplemented with data from the Observatory of Economic Complexity [33], which deals with the distribution of material production across all studied regions. By combining the maps and the production data, societal impact for each material and region is determined (see Table 2).

Table 2. Societal impacts of materials used in PEMFC system and hydrogen tank design

Elements	Social vulnerability	Land uses	Impacts on community	Global societal impact
Platinum [a]	4.25	4	3.9	4.05
Fluoride	3.95	3.63	3.78	3.79
Sulfuric acid	2.21	3.47	3.98	3.22
Plastic	1.98	3.15	3.73	2.95
Graphite [b]	1.67	3.33	3.33	2.78
Iron [a] and Steel	2.00	4.00	2.00	2.67
Aluminum [b]	3.00	4.00	1.00	2.67

[a] **[31]**, [b] **[32]**

Societal impact is not determined for steel. Indeed, as steel is composed of over 98% iron in the case of pure steel and over 50% in the case of stainless steel, this material is considered similar to iron in its societal impact. To determine the societal impacts of plastic, the production of propylene and polyethylene was differentiated. Once the societal factors were assigned to these two sub-elements, the societal impacts of plastic were determined by multiplying the impacts of polyethylene and propylene by their production distribution. Generally, the social vulnerability factor is high in Africa and American continent. In Africa, the primary causes are linked to poverty, followed by a lack of access to basic necessities such as clean water, food, and education. On the American one, the high value of this factor is mainly due to wealth disparities and limited access to healthcare. In Europe, the significant impact on communities is attributed to mining conflicts in Spain, Portugal, Eastern Germany, and the Balkans [34]. The highest overall societal impact is found for platinum. Indeed, more than 84% of platinum resources are located in South Africa, an area where social vulnerability, land use, and impact on local communities pose a high risk. The extraction of iron and aluminum, on the other hand, occurs in regions where societal impact is moderate, such as Australia or Canada, which gives these materials the lowest overall impact [31].

4.2. Governance risk assessment for materials

Material governance is a process that primarily assesses the political and economic issues related to the production of these materials. The governance of platinum, graphite, iron, and aluminum is determined in references [32] and [31]. For other materials, a method is implemented based on two indices: the Herfindahl-Hirschman Index (HHI) [35] and the World Governance Indicators (WGI) [36].

4.2.1. Determination of economic risk

The Herfindahl-Hirschman Index determines economic risks associated with material production. Predominantly used in economic fields, it measures concentration levels in markets. To calculate it, the distribution of material production found for the calculation of societal impacts (see supplementary materials) is used. The Herfindahl-Hirschman Index is calculated to account for market tensions at both the territorial and global levels. To determine the territorial-level Herfindahl-Hirschman Index, the distribution of material production in each region is determined. At the global level, the distribution of each region's production relative to global production is studied. Initially, the Herfindahl-Hirschman Index ranges from 0 to 10,000. To ensure that these index results align with societal impacts, the values found are normalized between 0 and 5.

Table 3. Economic risk (a) and governance risk (b) for fluorine, sulfuric acid and plastics production, regionally (a) and (b) and worldwide (a)

<table>
<tr><th rowspan="2">Elements</th><th colspan="2" rowspan="2">Fluoride</th><th colspan="2" rowspan="2">Sulfuric acid</th><th colspan="2">Plastic</th><th colspan="2">Plastic</th></tr>
<tr><th>Polyethylene</th><th>Polypropylene</th><th>Polyethylene</th><th>Polypropylene</th></tr>
<tr><td>Type of risk</td><td>(a)</td><td>(b)</td><td>(a)</td><td>(b)</td><td>(a)</td><td>(a)</td><td>(b)</td><td>(b)</td></tr>
<tr><td>Africa</td><td>2.59</td><td>2.85</td><td>2.68</td><td>3.20</td><td>2.43</td><td>2.36</td><td>3.01</td><td>2.12</td></tr>
<tr><td>Asia</td><td>2.26</td><td>2.39</td><td>4.92</td><td>2.39</td><td>2.01</td><td>2.02</td><td>2.36</td><td>2.49</td></tr>
<tr><td>Europe</td><td>2.02</td><td>1.65</td><td>1.97</td><td>1.63</td><td>3.03</td><td>3.24</td><td>1.70</td><td>3.24</td></tr>
<tr><td>North America</td><td>2.67</td><td>1.83</td><td>2.35</td><td>2.44</td><td>2.39</td><td>2.66</td><td>2.09</td><td>2.81</td></tr>
<tr><td>Oceania</td><td>3.00</td><td>1.00</td><td>2.99</td><td>0.9</td><td>3.00</td><td>2.99</td><td>1.34</td><td>2.46</td></tr>
<tr><td>South America</td><td>2.97</td><td>2.24</td><td>2.87</td><td>2.36</td><td>2.61</td><td>2.12</td><td>2.58</td><td>2.51</td></tr>
<tr><td>Worldwide</td><td>2.15</td><td></td><td>2.07</td><td></td><td>2.20</td><td>2.25</td><td></td><td></td></tr>
<tr><td rowspan="2">Average</td><td rowspan="2">2.52</td><td rowspan="2">2.13</td><td rowspan="2">2.25</td><td rowspan="2">2.25</td><td colspan="2" rowspan="2">2.52</td><td>2.11</td><td>2.74</td></tr>
<tr><td colspan="2">2.43</td></tr>
</table>

When the Herfindahl-Hirschman Index is found to be less than 2 excluded, it indicates a low concentration market, with low economic tension on the material. This occurs when there are very few players in the market. When the index falls between 2 and 4 excluded, there is high concentration, and economic tension on the material is moderate. The number of players is significant enough for the market to be evenly distributed, with a slight risk of a major player emerging. Finally, when the index exceeds 4, there is market risk, and economic tension on the material is high.

For the three materials studied, the Herfindahl-Hirschman Index is moderate, indicating that the market for these materials is fairly evenly distributed (see Table 3).

The Herfindahl-Hirschman Index alone is not sufficient to illustrate material governance. This index focuses solely on economic issues, and the introduction of a second index that considers geopolitical tensions related to materials is necessary.

4.2.2. Determining governance risk

The Global Governance Indicator aggregates a set of data measuring the quality of governance in more than 200 countries and territories [36]. This indicator summarizes opinions on governance quality expressed by a large number of businesses, citizens, and experts. In total, 6 points are addressed. The first, called voice and accountability, deals with the means given to citizens to participate in elections. The second measures political stability, which is the likelihood of political instability or violence related to elections. The third point deals with government effectiveness, which is the quality of public services. The fourth point assesses the quality of regulation or the government's ability to enact laws. The fifth point measures the trust within society and the enforcement of rights, which is referred to as the rule of law. The last point deals with control of corruption.

First, the global governance indicator is defined for each production site. Secondly, this indicator is calculated for each region by computing the arithmetic mean of all the values found. Finally, an overall indicator is defined for each material by weighting the value found for each region by its production percentage.

The global governance risk for plastic is specifically assessed for polyethylene and polypropylene (see Table 3). The result is the average of the global governance risk values obtained for these two sub-materials. In general, when the material is sourced from mining in Europe, governance is moderately weak. The highest governance is found in Africa, primarily due to the political instability in that region. For these three materials under study, governance is moderate.

4.2.3. General governance

Table 4. Global governance (a) and total impacts (b) for materials used in PEMFC system and hydrogen tank design

Elements	Iron and Steel	Plastic	Platinum	Sulfuric acid	Fluoride	Aluminum	Graphite
Societal impact (see Table 2)	2.67	2.95	4.05	3.22	3.79	2.67	2.78
General governance (a)	2.00	2.48	1.50	2.54	2.48	4.00	5.00
Total societal impacts (b)	**2.33**	**2.72**	**2.78**	**2.88**	**3.13**	**3.33**	**3.89**

Combining the Herfindahl-Hirschman Index and the global governance indicators, the general governance is determined for fluorine, sulfuric acid, and plastic (see Table 4). For the other materials, governance is defined in references [32] and [31].

The high-risk governance in graphite is primarily due to China's monopoly on the production of this material. Contrary to platinum, which has such a diverse market that prevents an oligopoly, its governance risk remains the lowest. Indeed, according to reference [31], over 80% of platinum extraction is centralized in South Africa, resulting in a very low governance risk. Although aluminum is abundant in the Earth's crust, its governance carries a high risk with a significant likelihood of conflicts [37].

4.3. Societal and governmental impacts of materials

Averaging governance and societal impacts on the materials found, the total societal impact of the components is deduced (see Table 4). Graphite has the highest factor, primarily due to the significant governance risk. Iron (and therefore steel) has the lowest value due to the minor governance risk, low impact on local populations from material extraction, and low social vulnerability of workers and nearby communities.

With governmental and societal impacts now known, the societal and governmental impact of the components is deduced.

5. Results and discussion

Before presenting the final results, the uncertainty related to the definition of the societal and governmental impacts of the components is addressed. The uncertainty regarding the values of the warming potential is determined using a method of data quality analysis, known as the data quality indicator [38]. The final results involve combining the global warming potential found for the PEMFC system and type IV tank with their societal and governmental impacts.

5.1. Discussion

5.1.1. Uncertainties regarding the definition of the societal and governmental impacts of components

When societal impacts are assigned to the production site, some of them are located in areas where the impacts are not defined. For these sites, the chosen societal factor corresponds to the nearest neighboring area. The ratio between the number of production sites belonging to these undefined areas and the total number of sites defined for the material constitutes an uncertainty ΔF. This uncertainty is calculated for each material and for each of the 3 societal factors studied (social vulnerability, land use, impact on local populations). The overall uncertainty for the materials is the arithmetic mean of the 3 uncertainties found.

Table 5. Uncertainty over societal impacts determined for plastics, sulfuric acid and fluoride

Elements	Social vulnerability	Land uses	Impacts on community	ΔF
Plastic	26.39%	22.46%	28.78%	25.88%
Sulfuric acid	14.43%	24.74%	27.84%	22.34%
Fluoride	26.53%	26.53%	24.49%	25.85%

The Table 5 presents the uncertainties found for the materials studied. The average uncertainty across all materials is 24.70%: roughly one-quarter of production sites are located in areas where societal factors are not defined. The uncertainty regarding the societal impacts of iron, platinum, aluminum, and plastic is not provided in references [32] and [31]; therefore, it is considered to be 0% for these materials. The societal impacts of iron, platinum, aluminum, and plastic are provided in references, and their uncertainty is 0.00%. The uncertainty for steel is the same as that for iron, which is 0.00%.

Regarding governmental impacts, determining the uncertainty Δg for the Herfindahl-Hirschman Index uses the same method as for societal impacts. Moreover, the uncertainty for the global governance indicators is considered to be 10.00%, regardless of the material or region studied. This uncertainty arises from two sources. The first reflects errors in perception by experts, while the second arises from the difference between the measured indicator and its perception based on cultural practices in the country under study [36].

The third uncertainty Δm to be considered before defining the overall uncertainty for the components is related to the mass composition of the components. In the case of the PEMFC system, an "other elements" category is given in the mass distribution. This category constitutes a part of the uncertainty in mass composition, which is reflected in the calculation of societal and governmental impacts. For the tank, this part of the uncertainty related to mass composition arises from the fiberglass, whose traceability is difficult to define. To conclude, the overall uncertainty on societal impacts for the components is calculated as follows:

$$\Delta = \sqrt{\Delta F^2 + \Delta g^2 + \Delta m^2} \quad (1)$$

The uncertainty on societal impacts for the PEMFC system is 5.38%, while for the reservoir it is 3.11%. Concerning the results announced on governance, the uncertainty for the PEMFC system is 2.08%, compared with 1.20% for the reservoir. Uncertainties in mass composition are 0.01% for the PEMFC system and 4% for the reservoir. The total uncertainty on societal impact values is 5.77% for the PEMFC system and 5.20% for the reservoir. Finally, the societal and governmental impact values for the PEMFC system and the hydrogen tank have an uncertainty of around plus or minus 5.50%.

5.1.2. Uncertainties regarding the global warming potential

The uncertainty regarding global warming potential is determined using the method proposed in the reference [38]. The objective is to assign each studied reference a rating based on the assessment of six criteria named U_i. These criteria measure the data reliability (U_1), the completeness of the study (U_2), the temporal (U_3), geographical (U_4) and technological (U_5) correlations with the conducted study, as well as the sample size (U_6). The assessment of the criterion occurs on a scale ranging from 1 to 5, with an uncertainty factor defined for each step of the scale, depending on the evaluated criterion. The temporal correlation of reference 10 is studied as an example. This reference dates to 2019, and the time difference between this reference and the article is less than 6 years but more than 3 years: the corresponding step on the scale is 2, with an uncertainty factor of 1.02.

Among all these studied uncertainty factors, a seventh one is added. It corresponds to the uncertainty related to the studied functional unit and is called the base uncertainty (U_b). For the global warming potential, the value of this uncertainty is 1.05.

The square of the overall uncertainty on the global warming potential is calculated as follows:

$$\sigma^2 = exp\left(\sqrt{\sum_{i=1}^{n=6} ln(U_i)^2 + \ln(U_b)^2}\right) \tag{2}$$

Concerning the studied references for PEM fuel cell system, the uncertainty regarding the global warming potential for reference [16] is 1.14%, 1.10% for references [17] and [11] and 1.06% for reference [9]. The overall uncertainty (sum of all uncertainties) on the presented global warming potential values is therefore 4.40%.

Concerning the studied references for type 4 tank, the uncertainty regarding the global warming potential for reference [21] is 1.24%, for the report [18] 1.06% and for reference [16] the uncertainty still the same as for the PEM fuel cell system, 1.14%. The overall uncertainty on the presented global warming potential values is therefore 3.44%.

5.2. Results

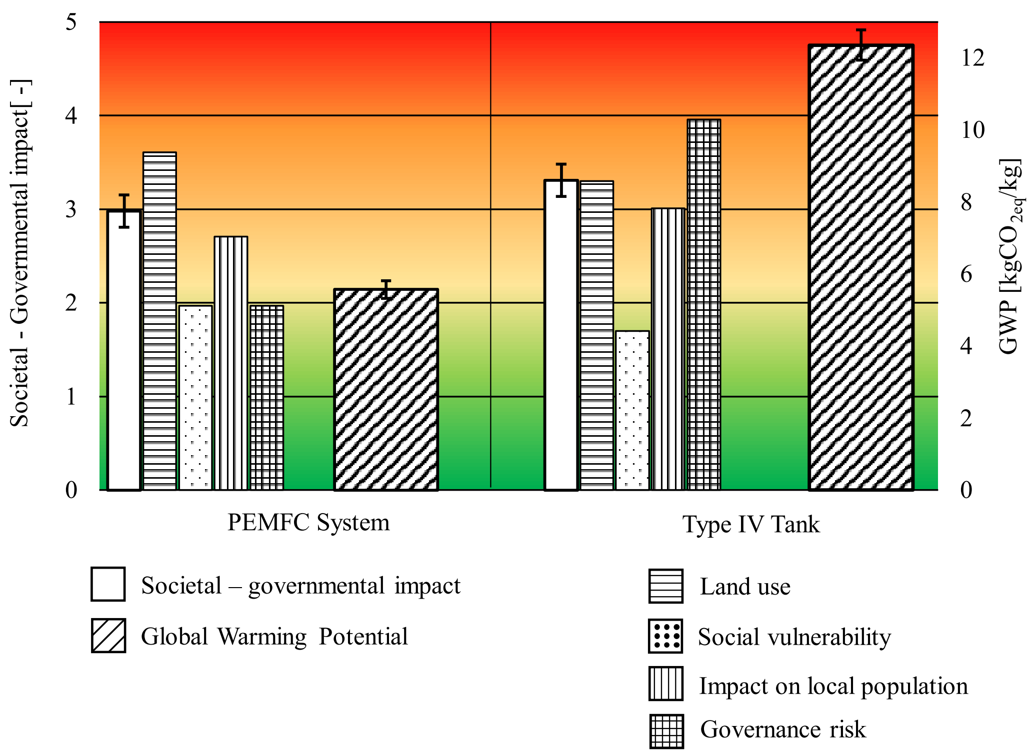

Fig. 8. Comparison of societal - government impacts for a PEMFC system and a type IV hydrogen tank

The study of the societal and governmental impact of the hydrogen system and its tank is deduced by multiplying the mass composition of these components by the impacts found on the materials that compose them. The presented results are given in proportion to the quantity of materials present in the hydrogen PEMFC system and the tank. If this distribution were to be modified, the societal and governmental impacts of the components can easily be redefined by multiplying the new mass composition with the societal and governmental impacts of the materials.

The Fig. 8 displays the values of the societal factors. The PEMFC system shows higher values in terms of social vulnerability and land use compared to the tank, while the impact on local populations and the governance risk are more pronounced for the tank than for the PEMFC system. The overall societal impact, representing the average of the three societal factors, is 3.20 for the PEMFC system and 3.96 for the Type IV hydrogen tank. The societal-governmental impact for these two components is 2.98 for the PEMFC system and 3.31 for the tank.

To best assess all the criteria studied in this article, a comparison between the environmental and societal-governance aspects is necessary. To conduct this comparison, it is not feasible to compare from an energy/power perspective the global warming potential. The functional unit used for this comparison must be mass, in kilograms. According to the manufacturer's data, the average mass density of a PEMFC system is 5.25 kg/kW. For a tank, based on manufacturer data too, the mass density is equivalent to 0.90 kg/kWh. Therefore, the global warming potential is 5.57 $kgCO_{2eq}$/kg for the PEMFC system and 13.74 $kgCO_{2eq}$/kg for the tank.

Due to its high carbon fiber content, the hydrogen tank imposes more societal and environmental constraints on the design of an electric vehicle's powertrain than the PEMFC system itself.

6. Conclusion

Through this article, two new aspects of designing a hydrogen-electric propulsion system have been addressed.

The first concerns the global warming potential of the PEMFC system and the type IV hydrogen tank. From the extraction of the materials needed for their production to their end of life, excluding the usage phase, a PEMFC system has a global warming potential of 29.24 $kgCO_{2eq}$/kW compared to 12.36 $kgCO_{2eq}$/kWh for a tank. The results presented consider the transportation of components from their production site to the vehicle assembly site, both located in Europe.

The second aspect concerns the societal and governmental impacts on the PEMFC system and the hydrogen tank. Due to its high carbon content, the hydrogen tank has the highest societal and governmental impacts.

Utilizing the environmental and societal criteria outlined in this article, along with the corresponding impacts of batteries [39], [40], facilitates the design of a hydrogen-electric propulsion system. The next step will be to compare, for the same application, which propulsion technology, between a 100% battery-based powertrain and a hydrogen-electric powertrain, achieves the best societal and environmental indicators. Do these results vary depending on whether the study is conducted for heavy or light mobility?

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Supplementary information is available for this paper.

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