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Ecological Evaluation Of H_2 Energy Supply In Industry

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Abstract

Limiting climate change through global CO_2 emissions is one of the central challenges of the 21st century. This requires a profound transformation of our energy systems and a far-reaching switch to innovative and emission-free technologies in all sectors, from power generation to the major energy consumption sectors of industry, transport and building heating. Hydrogen will play a significant role in a future energy and economic system.

In this paper, H_2 energy supply scenarios are developed, evaluated and compared as an alternative to a reference scenario that uses conventional technologies to meet electricity, heating and cooling needs. The H_2 energy supply scenarios are evaluated with both purchased and self-produced hydrogen. Both the different colours of the hydrogen and the CO_2 intensity of the electricity mix are considered. To cover the electricity and heat demand, different hydrogen technologies are considered and combined to different H_2 energy supply scenarios. Subsequently, the scenarios are evaluated with regard to their sustainability and compared with the reference scenario. The evaluation shows that blue and green hydrogen have an environmental advantage over natural gas, but availability is limited. Therefore, it is advisable to produce hydrogen oneself. Compared to natural gas, however, this only has an ecological advantage if the emission factor of the electricity mix is reduced through the use of renewable energies.

Keywords

H_2 energy supply; CO_2 emissions; hydrogen technologies; sustainability, ecological evaluation

1. Introduction

Hydrogen (H_2) is considered an important energy carrier for implementing the energy transition to achieve the climate goals by science, industry, and politics [1]. Industry is responsible for a significant proportion of global energy consumption and associated greenhouse gas emissions. It faces the challenge of making its processes more environmentally friendly [2]. In this context, the use of hydrogen as an energy carrier for industrial energy supply is becoming increasingly important. Hydrogen offers a promising alternative to conventional fossil fuels, as its combustion with oxygen produces only water vapour and no carbon dioxide (CO_2) emissions [3]. Moreover, hydrogen can be produced via electrolysis from renewable energy sources, ensuring this technology's long-term sustainability [4,5]. Using hydrogen in industry allows heating, electricity, and cooling in an environmentally friendly way makes an important contribution to reducing CO_2 emissions and achieving climate targets [6]. The environmental assessment of H_2 energy supply scenarios in industry is crucial to make informed decisions on the implementation of this technology.

In this paper, H_2 energy supply scenarios are developed, evaluated, and compared as an alternative to a reference scenario that uses conventional technologies to meet electricity, heating, and cooling needs. The

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methodological approach to energy system planning developed by Emde was used to develop and evaluate the H_2 energy supply scenarios [7]. The H_2 energy supply scenarios are evaluated with both purchased and self-produced hydrogen. Both, the different colours of the hydrogen and the CO_2 intensity of the electricity mix are considered. To meet the electricity and heat demand, different hydrogen-based technologies are considered and combined into different H_2 energy supply scenarios. The scenarios are then evaluated from an environmental perspective. The results are compared with the reference scenario. From this, it can be concluded how hydrogen technologies for industrial energy supply can be an environmentally sound alternative to conventional technologies today and in the future.

2. Fundamentals

The following chapter explains the basics for understanding CO_2 intensity and introduces hydrogen technologies.

2.1 Carbon intensity of hydrogen and electricity

Carbon intensity refers to the amount of CO_2 emissions produced per unit of energy produced or consumed [8,9]. It is a measure of the environmental impact of a particular energy source, activity or sector in terms of its emissions. A lower carbon intensity means that a given energy production or consumption results in fewer CO_2 emissions, which is desirable from an environmental perspective [10].

2.1.1 Colours of hydrogen

In the field of hydrogen production, different colours are used. Grey hydrogen is the dominant technology today. In the standard steam reforming process, hydrogen is produced by using natural gas [8,9]. It is currently the most cost-effective process, but large amounts of CO_2 are released in the process. Direct emissions from grey hydrogen average 398 g CO_2/kWh [8]. Blue hydrogen is produced via steam reforming with subsequent CO_2 capture and storage [8,9]. In this process, 85 % to 95% of the CO_2 emissions can be captured and stored in natural gas reservoirs [1]. Therefore, blue hydrogen can only be partially decarbonised. On average, blue hydrogen produces a greenhouse gas impact of 143 g CO_2/kWh to 218 g CO_2/kWh [8,11]. Green hydrogen aims at the complete decarbonisation of hydrogen production [8,9]. In electrolysers, electricity is used to break down water into its components hydrogen and oxygen. The process releases no CO_2 if the used electricity was produced without emissions. Green hydrogen produced with green electricity can be made available with emissions as less as 26 g CO_2/kWh [8,11]. Currently, around 0,7 % of the world's hydrogen is produced via electrolysis, powered by renewable energies [12]. Figure 1 shows the global hydrogen demand and the available quantities of blue and green hydrogen in TWh today and in the future [13]. It can be seen that the demand for hydrogen significantly exceeds the availability.

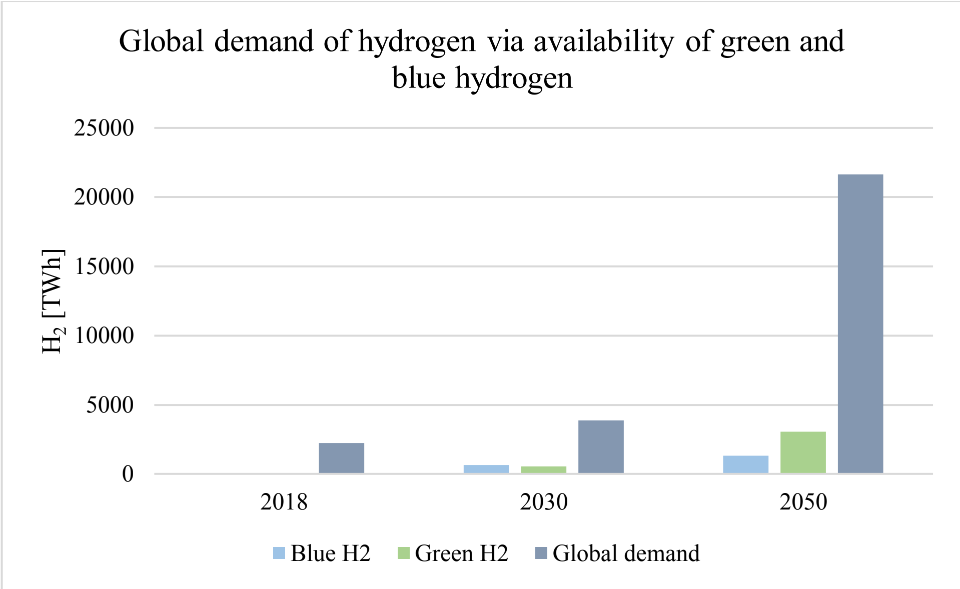

Figure 1: Global demand of hydrogen and availability of green and blue hydrogen [13]

2.1.1 Carbon intensity of electricity

Specific CO_2 emissions from electricity vary depending on the type of electricity generation and the energy mix of a country or region. In general, there are several sources of CO_2 emissions from electricity generation, including for example fossil fuels and renewable energy sources [10]. A worldwide overview of the specific CO_2 emissions of electricity is given in Figure 2. Worldwide, producing one kWh of electricity emits about 436 g CO_2 [10].

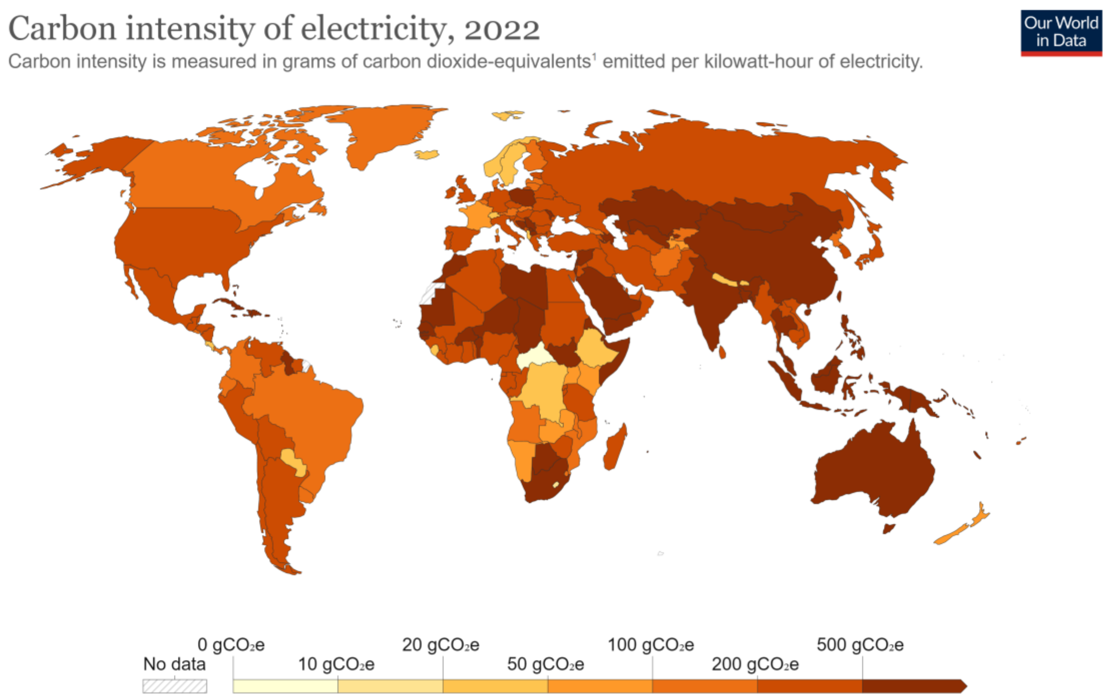

Figure 2: Worldwide overview of the specific CO_2 emissions of electricity [10]

2.2 Hydrogen technologies

Numerous hydrogen technologies were researched and considered for the evaluation. The technologies explained in more detail here prove to be the technically most suitable for the energy supply scenarios investigated to cover the electricity and heat demand.

2.2.1 PEM Electrolysis

Water electrolysis is a process in which water is broken down into its components, hydrogen and oxygen, with the help of electricity [14]. PEM (proton exchange membrane) electrolysis is a special form of water electrolysis in which a proton exchange membrane is used as the electrolyte. The reaction at the electrodes and the electrolyte leads to heat energy generation [6]. This heat must be dissipated to keep the operating temperatures of the electrolysis cells at an optimal level. PEM electrolysers operate in the temperature range from about 20 ◦C to 100 ◦C and the efficiency varies between 67 % and 82 % [15]. PEM electrolysis is used because of its advantages over other types of electrolysis in terms of compactness, scalability, high dynamics and overload capability [6].

2.2.2 PEM Fuel Cell

The fuel cell is an electrochemical energy converter that converts the chemically bound energy of a fuel directly into electrical energy and heat. A PEM fuel cell belongs to the category of low-temperature hydrogen fuel cells. Its central component is the proton exchange membrane, which allows the passage of protons but blocks the passage of electrons. PEM fuel cells operate in the temperature range from about 0 ◦C to 80 ◦C and the electrical efficiency varies around 40 % and the thermal efficiency around 55 % [15]. The PEM fuel cell is used because of its advantages over other types of fuel cell in terms of fast start-up, high power density, and their ability to control operating temperatures [16]. On the other hand, a PEM fuel cell needs a certain amount of time to allow the electrochemical reactions to take place and generate energy.

2.2.3 Hydrogen Burner

The hydrogen burner is a system for generating heat by burning hydrogen to provide process heat. Hydrogen is supplied to a hydrogen burner as fuel and mixed with oxygen [17,18]. A hydrogen burner generates heat immediately as soon as the hydrogen reacts exothermic with the oxygen in the air. The thermal efficiency varies around 90 %. The combustion reaction can take place relatively quickly, providing rapid heat in a temperature range from hundreds to several thousand degrees Celsius [17,18]. Heat energy is used, for example, to heat water and generate steam. Advantages are low pollutant emission values, high efficiency, and flexibility.

3. Hydrogen energy supply scenarios

The reference scenario exemplifies a medium-sized company's electricity, heating in low temperature range and cooling supply in southern Germany over a one-year period. An overview of the reference scenario's processes is given in Figure 3.

To cover its electricity needs, the company obtains electricity from the public grid. Electricity is also used to operate the compression chiller with a power output of 1 000 kW_{th} to cover the company's cooling requirements. A natural gas burner with a power output of 1 200 kW_{th} is used to cover the heat demand. This obtains fuel from the public natural gas supplier. First, the scenario is evaluated with an electricity mix and then with green electricity. In the following, three alternative energy supply scenarios are created, all using hydrogen. The aim is to compare whether, and under which conditions, the use of hydrogen to cover the electricity and heat demand offers ecological advantages compared to the reference scenario.

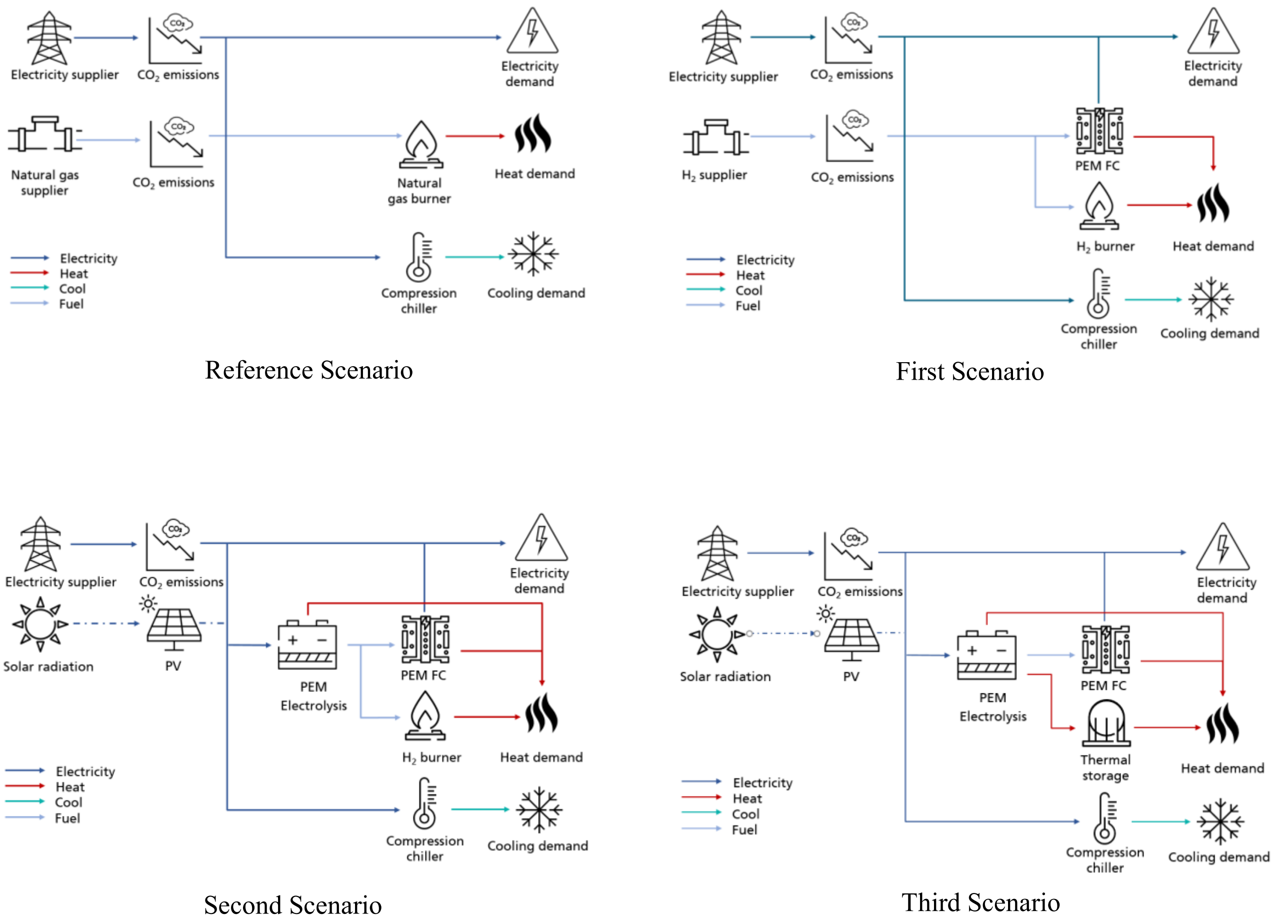

Figure 3: Overview of the processes of the evaluated scenarios

In the first scenario, the company obtains hydrogen from the public hydrogen grid to supply the PEM fuel cell and the hydrogen burner. The PEM fuel cell is designed for 800 kW_{el} and covers both the company's heat and electricity demand. Since the hydrogen burner can generate heat faster than the PEM fuel cell, it is added to the scenario to cover the peak heat demand. This is designed for a capacity of 150 kW_{th}. The hydrogen burner is only used to cover the peak load, as the hydrogen burner does not like to operate at partial load. In addition to the power supply from the PEM fuel cell, the company draws an electricity mix from the public grid to cover the peak loads of the electricity demand. To cover the cooling demand, the compression chiller is operated with a capacity of 1 000 kW_{th}, primarily powered by the electricity produced by the PEM fuel cell and secondarily with electricity mix from the public electricity grid. In this scenario, both grey, blue, and green hydrogen are considered. First, the scenario is evaluated with an electricity mix and then with green electricity. The processes of the second scenario continues to consist of a PEM fuel cell with an output of 400 kW_{el} to cover the base load of the heat and electricity demand and a hydrogen burner with an output of 200 kW_{th} to cover the peak load of the heat demand. Hydrogen is produced via PEM electrolysis. This is also operated with electricity from the public grid and designed for 1 700 kW_{el}. The hydrogen produced is added to the PEM fuel cell and the hydrogen burner. The resulting waste heat from the PEM electrolysis plant is also used to cover the heat demand. The compression chiller covers the cooling demand. It is primarily powered by the electricity produced by the PEM fuel cell and secondarily by electricity from the public grid. First, the scenario is evaluated with electricity mix and then with green electricity. The second scenario is then expanded to include a photovoltaic (PV) system on a roof area of over 7 700 m² with an output of 1 400 kW_p primarily to cover the electricity demand. In addition, the PV system drives the PEM electrolysis system and the compression chiller, which is designed for 1 000 kW_{th}. This expansion is also evaluated first with an electricity mix and then with green electricity. In the third scenario, a thermal storage unit replaces the hydrogen burner with a capacity of 500 kWh. This covers the peak heat demand that can be met neither by the PEM electrolysis nor the PEM fuel cell. In this scenario, the PEM electrolysis is designed for 1 700 kW_{el} and the PEM fuel cell for 500 kW_{el}. First, the scenario is evaluated with an electricity mix and then with green electricity. Subsequently, the third scenario is also expanded to include a PV system with an output of 1 400 kW_p. This expansion is also evaluated first with an electricity mix and then with green electricity.

4. Ecological comparison

For all the scenarios, the CO_2 emission values listed in Table 1 are used.

Table 1: Overview of CO_2 emission values for the evaluation

	Emission value [g CO_2/kWh]	Source
Electricity mix Germany	420	Federal Environment Agency [19]
Green power Germany	16	Federal Environment Agency [19]
Natural gas Germany	247	Federal Environment Agency [20]
Grey H_2 Germany	400	Greenpeace energy [8]
Blue H_2 Germany	140	Greenpeace energy [8]
Green H_2 Germany	26	Greenpeace energy [8]

The first scenario is evaluated for grey, blue and green hydrogen as well as with an electricity mix and with green electricity. The total CO_2 emissions can be divided into electricity-related and fuel-related CO_2 emissions. The results of the evaluation of the first scenario can be seen in Figure 4. The CO_2 emissions of the individual evaluations are related to the CO_2 emissions of the reference case with an electricity mix. In the reference case, electricity-related CO_2 emissions account for about 70 % of total CO_2 emissions. These can be reduced to less than three percent by using green electricity.

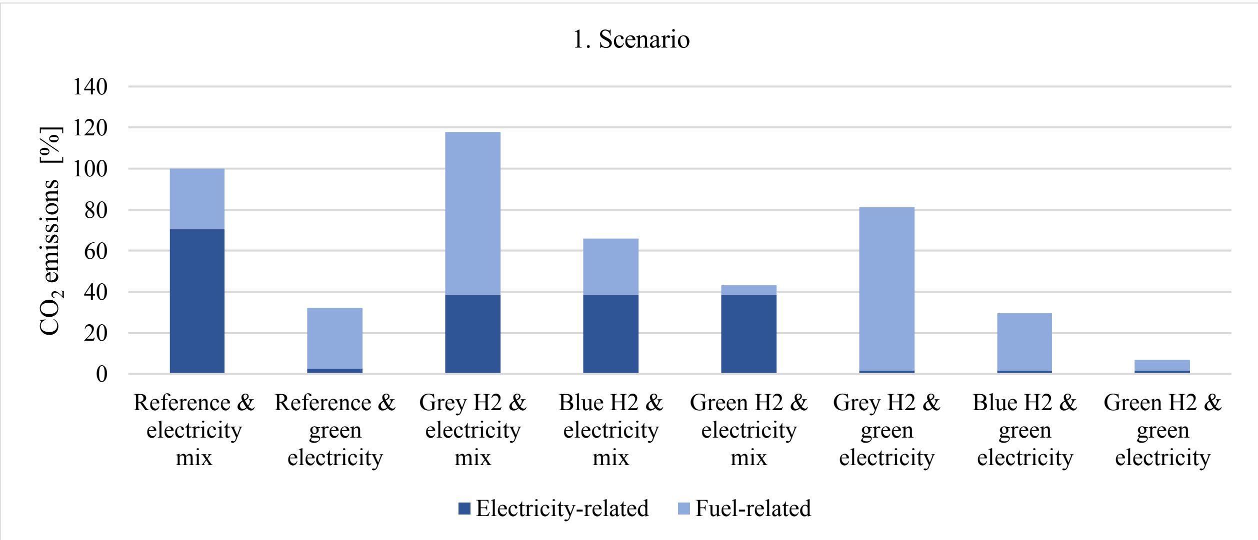

Figure 4: CO_2 emissions in percent of the first scenario compared to the reference scenario

It is striking that the fuel-related CO_2 emissions for the use of grey hydrogen are more than twice as high as for the use of natural gas. However, using PEM fuel cell generates electricity, which is why less electricity is needed from the public grid. Therefore, the electricity-related CO_2 emissions decrease. When using an electricity mix, they fall by about half; when using green electricity, they fall to less than two percent in relation to the reference case. The fuel-related CO_2 emissions for using blue hydrogen are slightly below those of the reference case. However, since using PEM fuel cell saves electricity-related CO_2 emissions, this case offers ecological advantages compared to the reference scenario. The fuel-related CO_2 emissions from the use of green hydrogen fall to about five percent relative to the reference case. In combination with the reduction of electricity-related CO_2 emissions, the use of green hydrogen saves almost 60 % of the emissions compared to the reference scenario.

The second scenario is assumed with and without the feed-in of the PV system as well as with electricity mix and with green electricity. The results of the scenarios are shown in Figure 5.

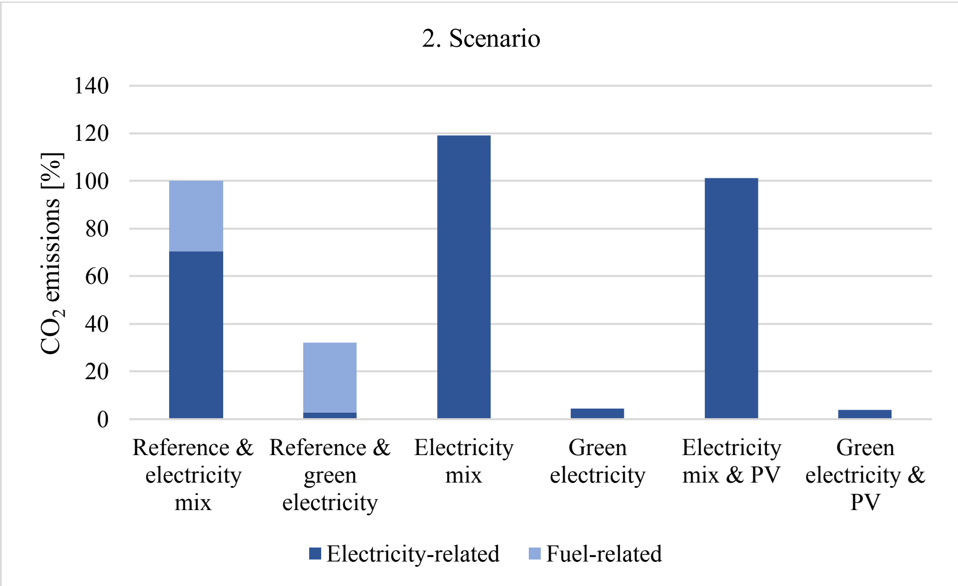

Figure 5: CO_2 emissions in percent of the first scenario compared to the reference scenario

The CO_2 emissions of the individual evaluations are again related to the CO_2 emissions of the reference case with an electricity mix. In the second scenario, the use of PEM electrolysis for the self-production of hydrogen eliminates fuel-related CO_2 emissions. However, the PEM electrolysis requires more electricity than is produced by the PEM fuel cell, which is why the electricity consumption from the grid increases. When using an electricity mix, the total CO_2 emissions increase by almost 20 %. The emission factor of the electricity mix must drop by 16 % to 350 g CO_2/kWh for the emissions to correspond to the reference. By using green electricity, about 95 % of the CO_2 emissions can be saved compared to the reference scenario. The use of a PV system for the self-generation of electricity shows ecologic advantages. When using the electricity mix and PV, emissions are 1 % higher than in the reference scenario, but fall by over 17 % compared to the electricity mix alone. With the use of green electricity and PV, the CO_2 emissions are reduced by more than 97 % compared to the reference scenario.

The third scenario is assumed with and without feed-in from the PV system as well as with electricity mix and with green electricity. The results of the scenarios are shown in Figure 6.

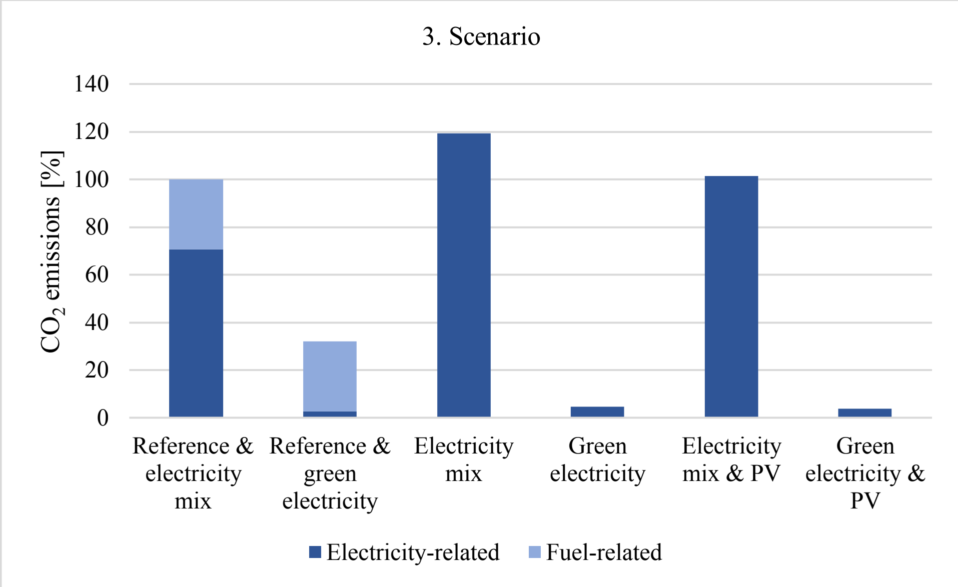

Figure 6: CO_2 emissions in percent of the first scenario compared to the reference scenario

The CO_2 emissions of the individual evaluations are again related to the CO_2 emissions of the reference case with an electricity mix. The third scenario behaves similarly to the second scenario. By using PEM electrolysis for the self-production of hydrogen, the fuel-related CO_2 emissions are eliminated. PEM electrolysis again requires more electricity than is produced by the PEM fuel cell, which is why electricity consumption from the grid increases. When using the electricity mix, the total CO_2 emissions increase by almost 20 %. The emission factor of the electricity mix must drop by 16 % to 350 g CO_2/kWh for the emissions to correspond to the reference. By using green electricity, more than 95 % of the CO_2 emissions can be saved compared to the reference scenario. Once again, using a PV system for the self-generation of electricity shows ecological advantages. With the electricity mix and PV, emissions are 1% higher than in the reference scenario but more than 17% lower than with the electricity mix alone. The use of green electricity and PV reduces CO_2 emissions by more than 97% compared to the reference scenario.

5. Evaluation and Conclusion

Scenario 1 shows that using blue and green hydrogen has environmental advantages compared to the reference case. Companies should thus aim to increase the use of blue and green hydrogen. However, as shown in Figure 1, the availability of blue and green hydrogen today and in the future is low compared to the demand. Therefore, self-production of hydrogen by electrolysis is recommended to cover the hydrogen demand. Companies can consider investing in electrolysis plants to produce their own hydrogen. This allows greater independence from external hydrogen suppliers and contributes to the reduction of CO_2 emissions, especially if electrolysis is coupled with renewable energies such as PV plants. On average, both the use of grey hydrogen and the use of the electricity mix for the self-production of hydrogen through PEM electrolysis do not show any ecological advantages compared to the reference scenario. For hydrogen self-production to make environmental sense compared to the reference scenario, the emission factor of the public grid must be very low. The emission factor of the electricity mix must be 350 g CO_2/kWh or less in the evaluated scenarios for hydrogen self-production through electrolysis to have an ecological advantage over the reference scenario. This value lies below the world average. The CO_2 intensity of the electricity mix must drop to 185 g CO_2/kWh for hydrogen produced by electrolysis to have the same emission factor as the heat supply using natural gas. The CO_2 intensity of the electricity mix must decrease to 75 g CO_2/kWh so that hydrogen produced by electrolysis has the same emission factor as blue hydrogen. Companies should take measures to reduce the CO_2 emission factor of the electricity used for electrolysis to produce hydrogen. This can be done by using renewable energies such as PV systems or purchasing green electricity. This reduces the CO_2 intensity of the hydrogen produced and achieves environmental benefits compared to the reference scenario. Since industrial companies cannot influence this emission factor of the public grid, local measures should be taken into account to reduce the CO_2 emission factor of the electricity used for electrolysis to produce hydrogen. Depending on the location, different measures may be required to reduce the CO_2 intensity of the hydrogen produced. Therefore, it is important to analyse the specific conditions on site and to develop appropriate emission reduction strategies. Since this paper focuses on the environmental benefits of hydrogen integrated energy supply, further work should subsequently address the environmental and technical feasibility of the H_2 energy supply scenarios

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Biography

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