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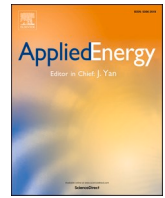
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Meta-analysis of climate impact reduction potential of hydrogen usage in 9 Power-to-X pathways

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HIGHLIGHTS

- Emission reductions were evaluated in the different pathways using hydrogen.
- Power-to-X solutions using carbon dioxide resulted in the least reductions.
- Co-electrolysis is an interesting option but is unmaturing technology.
- Green hydrogen is not the only hydrogen source capable of emission reduction.
- LCA studies using primary data are desirable.

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ABSTRACT

Owing to the ongoing energy crisis, increasing shares of renewables, and climate mitigation targets, a green hydrogen economy through water electrolysis has gained interest. Hydrogen can be directly utilised or converted via different Power-to-X pathways to produce fossil-free substitutable products; therefore, their life-cycle emissions were studied to determine whether these solutions could provide sustainable alternatives. Thus, understanding which Power-to-X solution can provide the greatest greenhouse gas emission reduction is crucial. This study provides nine meta-analyses of different pathways to compare climate emissions reductions based on the literature. The minimum, maximum, and average values were estimated for each investigated Power-to-X pathway. The direct use of hydrogen or its service to produce steel, biogas upgrading, protein, or ammonia resulted in over 10 kg_{CO2} kg_{H2}⁻¹ reductions on average while using low-carbon energy sources. Co-electrolysis can potentially provide higher emission savings owing to lower electricity consumption compared with low-temperature electrolysers. In addition, the possibility of integrating electrochemical synthesis with hydrogen production has great potential, but the usability depends on the advancement of the technology in the future. Selections of carbon dioxide sources, substitutable products, and other assumptions of the investigated studies significantly impact the reduction potential. Low-emission-factor electric grid mixes containing fossil sources can result in emission savings in many Power-to-X systems. However, using grid mixes that result in emission savings is system-dependent, and the largest emission savings are achieved through renewables or nuclear energy.

1. Introduction

Because of climate change mitigation actions and the low cost of wind and solar power, the use of fluctuating energy sources has rapidly increased worldwide. This ongoing energy transition enables the

possible development of a green hydrogen (H₂) economy, which can further help decarbonise society [1–3]. A green H₂ economy refers to H₂ produced via water electrolysis using renewable energy (RE) sources. H₂ can also be used as a building block for other purposes, such as for hydrocarbons or ammonia production [4]. Currently, large-scale green H₂

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production cannot compete economically with H₂ produced from fossil sources [5]. However, the economic feasibility is predicted to increase rapidly. BloombergNEF [6] predicts that green H₂ production can cost approximately 0.9 € kg⁻¹, rendering it cheaper than H₂ production from natural gas by 2050. Cost reduction is possible because of the reduced costs of water electrolyzers, electricity prices, and the increasing capacity of RE sources [6,7]. Feasible green H₂ provides extensive possibilities for decarbonising different industries [2,8]. For instance, H₂ can be used for transportation, heating, as a power source for buildings, in the energy industry, and in other existing industry sectors, which could provide approximately 24% of the total energy demand in 2050 in the EU [9].

Technologies capable of converting power to H₂ and possibly further refining it for other uses, such as fuels for transportation, is termed Power-to-X (PtX) technologies. PtX can play a significant role in the future H₂ industry because it is thought to provide a low-carbon alternative for current systems [10–13]. In this study, PtX is considered a technology that uses water electrolysis to produce H₂ in different value chains, although various definitions have also been proposed. For example, some studies have included heat pumps and thermal storage as part of the PtX technologies that do not use H₂ as an intermediate product [14,15]. Furthermore, in several cases, PtX solutions uses only RE for power processes. For instance, the term “renewable PtX technologies” describes PtX solutions using only RE [10]. Excluding low-carbon energy sources other than RE, such as nuclear energy, can diminish the implementation or full potential of these technologies. For some applications, a need for continuous production of PtX end products from an economic perspective exists, because the operational hours of the facilities significantly affect the cost of the end product owing to high investment costs [16,17], or the storage capacities for electricity or H₂ can significantly increase the capital costs while exclusively using fluctuating energy sources [18]. Therefore, in the present study, PtX technologies were not only categorised as those using RE.

In recent years, several piloting-phase PtX projects have been conducted in Europe [19]. In Finland, there have been Power-to-Fuel (PtFuel), Power-to-Gas (PtGas), Power-to-Solid hydrocarbon (PtS) [20,21], and Power-to-Food (PtFood) [22,23] pilot projects. Thus, there is a clear interest in these technologies. However, bottlenecks exist in implementing PtX solutions, such as the amount and price of available RE sources or available capital for investments. For example, assuming that all steel would be acquired from the Power-to-Steel (PtSteel) route, to generate approximately 19 billion tons per year [24] steel production via direct H₂ reduction would require 3.48 MWh per liquid steel [25]. Thus, the required amount of RE would be multiple times higher than the predicted total global capacity in 2026 [26]. Meaning that the substitution of all fossil-source-derived products with low-carbon PtX products in the near future is not feasible, especially if only RE is used. Therefore, it is imperative to determine where H₂ should be used primarily.

One key factor determining H₂ usage is the possible emission reduction potential that PtX solutions can provide, owing to the tightening of emission reduction targets. In addition, the price of carbon is estimated to upsurge investment decisions to meet emission reduction targets, such as those set by the EU [27]. When considering the environmental impact reduction potential of different PtX-derived end-products, recognising the impacts of the relevant substitution products and their lifetimes is crucial. However, the evaluation of impact reduction potential becomes increasingly complex when impacts other than climate-related emissions are included in the assessment. Then again, the evaluation of several impact categories can be relevant because different industry sectors can have diverse environmental issues. For instance, PtFood applications can produce high-quality protein, which has shown major reduction potential in land and water use and eutrophication related emissions compared with other major plant-based proteins, with over 90% reduction. Still, the climate impact reduction was less than 10% than that of soybeans. When comparing

protein from PtFood with animal-based proteins, climate reduction can be manifolds higher [22,28]. Although PtX solutions can potentially provide emission reduction in multiple impact categories, the focus has typically been on climate impacts because several PtX solutions are closely related with the energy sector. Power-to-Methane (PtMethane) can replace natural gas; PtFuels can replace diesel, gasoline, or kerosene; Power-to-Syngas (PtSyngas) can replace syngas derived from natural gas; Power-to-Ammonia (PtA) can replace ammonia derived from natural gas; Power-to-Methanol (PtMethanol) can replace methanol derived from natural gas; and the used H₂ in PtSteel can replace coal as a reduction agent.

A few review papers have focused on the life-cycle assessment (LCA) of PtX production pathways and their sustainability. Koj et al. [11] reviewed the methodological issues in LCA studies on PtX, and the effect of different technological choices on climate impacts. In addition, they exhibited that the climate change impact was the most investigated environmental impact category, which further favours the decision to focus on it in this study. Ince et al. [12] assessed the impacts of end products derived from some PtX pathways and concluded that emission reductions could be achieved via RE. Focusing on methodological choices, Garcia-Garcia et al. [29] investigated the climate impacts of different LCA studies on carbon capture and utilisation (CCU), which is also related to the PtX pathways. They revealed that providing substitutable products for fossil-based products with lower climate emissions is possible, but they did not attempt to determine which method resulted in the greatest emission reductions. However, as previously mentioned, the emission reduction potential depends not only on what is substituted but also on the emission reduction quantity. To the best of our knowledge, no studies have focused on determining the most feasible PtX pathway from the perspective of H₂ use.

Therefore, this study, focused on identifying feasible PtX solutions based on possible impact reduction on climate via conducting a meta-analysis of different PtX pathways. Similar studies have been conducted to investigate the environmental benefits of value chains other than PtX solutions [30–32]. The feasibility was evaluated based on the emission reduction per unit of H₂. As the amount of usable RE is limited to providing substitutes for every fossil-based product and a constant energy supply can ease the economic aspects of PtX pathways, other electricity generation sources to power H₂ production and their impact were investigated. These results can help decision-makers, researchers, and people in the energy sector in planning and focusing on the optimal usage of H₂ from a climatic perspective.

2. Method

The climate change mitigation potential of utilising hydrogen in different PtX pathways was identified using existing literature, from which the climate impact of PtX products was compared with the impacts of reference product values in those studies (Supplementary material). The reference values represent the current products, in which the products from the PtX pathway are thought to be substitutes. When the amount of consumed H₂ per product and the climate impact of the product derived from the PtX pathway and the reference product are considered, it is possible to calculate the emission reduction potential for each PtX-derived product and draw comparisons. A short description of the technology used is presented in the Results and Discussion section to compare the value chains and technological solutions. The criteria for peer-reviewed studies, calculation of the emission reduction potential, and data collection are presented in the following subsections.

2.1. Meta-analysis on climate impacts of different PtX pathways and reference products

The thematic literature review focused on gathering relevant information collected by the authors regarding the climate impacts of the investigated PtX pathways (Fig. 1). In the case of PtFuels, the focus is on

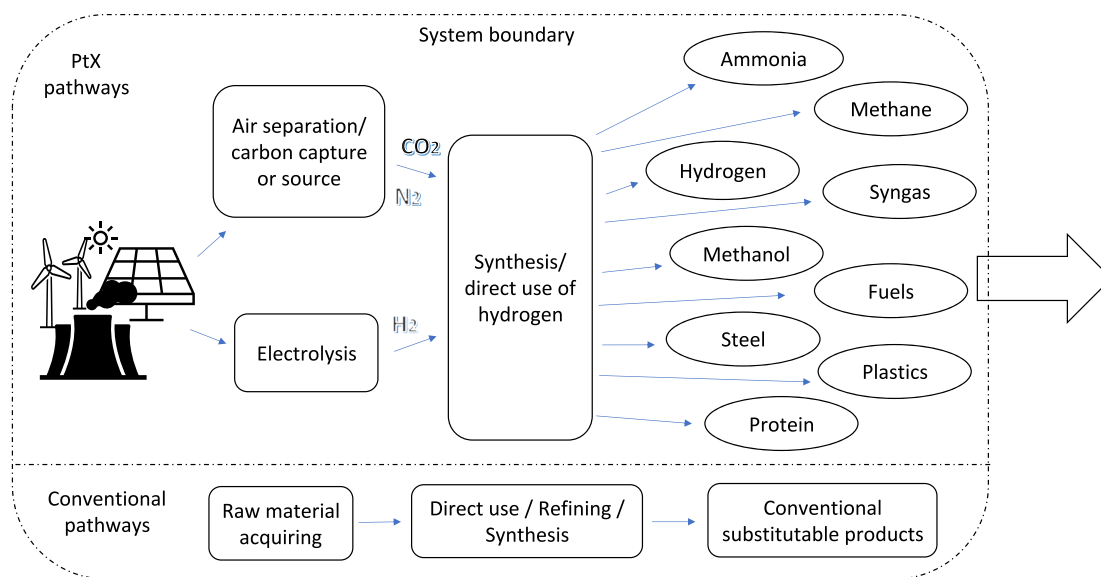


Fig. 1. Investigated Power-to-X (PtX) pathways.

the products used in conventional internal combustion engine vehicles. These data are presented in the Supplementary Material.

The data search focused on literature published from 2015 to recent year. PtHydrogen has excessive amount of found literature. In that case, the authors focus on finding literature covering relevant information to conduct the analysis. Relevant information consists of information to estimate the impact of different energy sources and technologies to lifetime emissions. For example, search terms “Hydrogen” AND “LCA” resulted over 9000 found papers by using Elsevier’s search engine only. The search contained multiple different variations, such as “environmental impact”, “carbon footprint”, “GWP”, “e-methanol”, “Power-to-Methanol”, “water electrolyser” to be able to find suitable literature. Terminology varies in studies evaluating climate emissions from PtX pathways, which makes the search using only certain words challenging. For those pathways having less found literature, the found studies not fitting the criteria described in this section’s subsections but contains relevant information about emissions compared to reference product, are presented for the readers in the Supplementary material. Overall, 75 different found literature sources from which 19 did not fit the criteria are presented. It should be noted that a found literature can contain multiple different PtX pathways.

Several end products can be used as reference values for comparison, and the impact of different reference products vary considerably [33]; thus, including all different reference values is not suitable while calculating the average impact reduction. In these cases, the average values were calculated separately for each reference product to avoid errors. For example, producing fossil-fuel-based ammonia from coal gasification or natural gas is possible, resulting in different amounts of generated emissions. This method also identifies the possible emission reduction potential in the local value chains. In addition, one study can contain several differently modelled value chains, which are each used in calculations.

2.2. Emission reduction potential calculations and criteria

To compare the PtX pathways, the climate impacts of the established studies were converted to the impacts per consumed kg H₂. Additionally, the studies that used the GWP100 indicator were included. If the reference did not state the characterisation factor used, it was assumed as GWP100, because it is one of the most commonly used indicators. In addition, minor differences could be present if the investigated studies use different characterisations, such as CML, TRACI, or EDIP; however,

in these cases, the error margin was assumed to be negligible [38].

2.2.1. Hydrogen as a functional unit

As numerous possibilities exist for designing different PtX technologies [28,34] and numerical end-products or intermediates can be substituted with the products of PtX technologies [12], the sustainability comparison of different PtX pathways is a challenge. For instance, comparing products with different functions, such as steel, food, and methane, is not rational based on mass, energy content, or economics because they act in different markets and have different functions.

H₂ utilisation is a common factor, and H₂ production contributes significantly to the total footprint and electricity consumption of the investigated PtX pathways, even when only RE are used [33,35,36]. When reviewing the amount of H₂ consumed by each PtX pathway (see the Results and Discussion section, Tables 2,3), the H₂ requirements of the PtSteel and PtFood routes were small compared with the other production routes. Still, H₂ production consumes high amounts of electricity in PtSteel and PtFood value chains [28,37]. Thus, H₂ production can be considered a key unit process in different PtX pathways, making it a well-suited functional unit.

2.2.2. System boundary

For consistency, only those studies where the impact of the cradle-to-gate or gate-to-gate phases could be determined were considered (Fig. 1). Cradle-to-gate refers to an assessment including processes considering, for example, energy and material flows from resource extraction, cradle phase, to the factory gate, gate phase. Whereas a gate-to-gate assessment does not necessarily include all processes from cradle phase. Moreover, only those gate-to-gate studies were used from which comparing all similar phases of the investigated value chain between the PtX pathway and reference product was possible. If gate-to-gate is used for the impact reduction calculations, the impact reduction calculation is performed separately for each case study to avoid affecting the average impact reduction calculations because they do not include the same number of life-cycle stages. If a study included emission reductions from substitution with the reference product, these substituted emissions were excluded from the impact reduction calculations. When it was not possible to reduce the substituted emissions from the studies using substitution, those studies were not included in calculations. Studies using different allocation methods were used for the calculations. The calculations are divided into two categories based on the energy sources used in H₂ production: average electric grid mixes and a

category that includes only RE or nuclear power. Nuclear power is included in the same category as RE because it can be considered a low-CO₂ source.

2.2.3. The bound carbon dioxide in the product

Several studies consider that CO₂ embedded in the products acts as a carbon sink when used to produce hydrocarbons via PtX pathways [39]. In addition, a few other studies allocate the bound carbon as CO₂-equivalents for the product if the carbon is taken from fossil sources using carbon capture technology [40]. The variety of methodological choices for calculating CO₂ emissions while using the CCU can drastically impact a product's overall climate impact. Müller et al. [41] disclosed that the results could vary significantly depending on the method used, such as system expansion or different substitution methods. The idea was to investigate how climate change impacts vary for different PtX production pathways; thus, the manner in which CO₂ is considered must be consistent. Bound carbon is assumed to have no impact when investigating the PtX pathways, implying that it is considered as waste. To compare the studies, the amount of bound carbon was then either added or removed from the total footprint, depending on the choices in the investigated studies, which allows for comparisons on how technological choices impact a product's footprint while neglecting how the CO₂ embedded in the product is evaluated. When comparing the products from PtX with those derived from fossil sources, the bound CO₂ in the reference product was considered in the calculations because it can be evaluated as extra CO₂ added to the carbon cycle (Fig. 2).

2.2.4. Emission reduction potential calculation

The impact values of the investigated products are presented in a variety of units. For example, in numerous studies, the LCA data or impact values were given per MJ, m³ or kg (Supplementary Material). For comparison, values were converted to the same unit, kg_{CO2-eq}/kg_{H2}¹, for investigated product. For some PtFuel production routes, the comparison is based on the energy content of the products because some substitutable products can have different energy contents. In these cases, the lower heating values of the investigated fuels were used per kg_{H2}. For instance, methanol can replace gasoline as a fuel in combustion vehicles [42], but also Fischer-Tropsch (FT) route can provide a replacement for fossil gasoline (Supplementary Material). When all unit conversions were performed, the emission reduction potential was calculated using the following equation:

$$GWP_{red,i} = \frac{1}{m_{H2,i}} * (GWP_{PtX,i} - GWP_{Con,i})$$

Where:

GWP_{red} is the reduction potential [kg_{CO2-eq}/kg_{H2}]

m_{H2} is the amount of consumed hydrogen [kg_{H2}/kg_{Product}]

GWP_{PtX} is the footprint of the investigated product [kg_{CO2-eq}/kg_{Product}]

GWP_{Con} is the footprint of the reference product [kg_{CO2-eq}/kg_{Product}]

i is the investigated PtX pathway

Minimum (MIN) and maximum (MAX) values were calculated based

on the values used in a literature. If a reference value was not found in the study, the impact reduction potential was calculated based on the average value of the reference product found in the investigated literature. The average value of the reference product was used to calculate the average reduction potential value (MEAN) (see the Average emissions of reference products section). The reduction potential was calculated for each value of H₂ consumption and emissions of the PtX product found in the investigated studies, from which the MEAN was calculated. If studies did not clearly depict information regarding H₂ consumption per product, then the average H₂ consumption found in the literature for that production pathway was used.

3. Results and discussion

First, the average emissions of reference products used for MEAN calculation and common notifications from the results are presented. Subsequently, the results of each PtX pathway are discussed separately, followed by a discussion related to credibility, limitations, and future research necessities.

3.1. Average emissions of reference products

Many investigated studies used a reference product to which they compared PtX products. From Table 1, you can find the average emission factors used for MEAN reduction calculations for each pathway. The values used for calculating the average emission factors can be found from supplementary material. The average emission factor of protein is not presented, as there are multiple different protein sources available (see the Power-to-Food Pathways section).

Table 1 Average emission factors used for MEAN calculation based on investigated studies.

Reference product	Average emission	Reference product	Average emission
H ₂ from SMR	11.95 [kg _{CO2-eq} /kg _{H2}]	Methanol from natural gas	2.01 [kg _{CO2-eq} /kg _{CH3OH}]
H ₂ from coal gasification	25.27 [kg _{CO2-eq} /kg _{H2}]	Methanol from coal	3.19 [kg _{CO2-eq} /kg _{CH3OH}]
Natural gas	3.59 [kg _{CO2-eq} /kg _{CH4}]	Jetfuel	3.50 [kg _{CO2-eq} /kg _{Fuel}]
		Gasoline	3.99 [kg _{CO2-eq} /kg _{Fuel}]
Syngas from natural gas	1.47 [kg _{CO2-eq} /kg _{Syngas}]	Diesel	3.94 [kg _{CO2-eq} /kg _{Fuel}]
	2.37 [kg _{CO2-eq} /kg _{Syngas}]	DME	2.72 [kg _{CO2-eq} /kg _{Fuel}]
Syngas from coal	1.94 [kg _{CO2-eq} /kg _{Steel}]	Polypropylene from petrochemical factory	5.20 [kg _{CO2-eq} /kg _{Plastic}]
Steel from BF-BOF route	1.94 [kg _{CO2-eq} /kg _{Steel}]		
Protein	- [kg _{CO2-eq} /kg _{Protein}]		

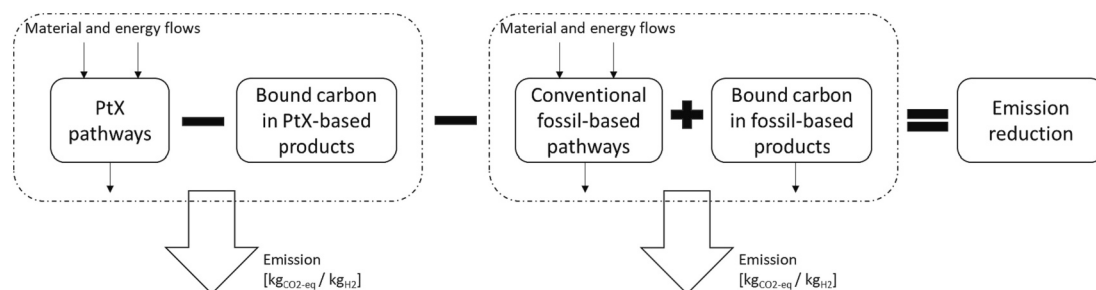


Fig. 2. Simplistic scheme on how bound carbon is evaluated, when comparing PtX products to conventional products.

3.2. Emissions of PtX pathways supplied by electric gridmixes and fossil fuels

Almost all PtX pathways have a reduction potential, even if electric grid mixes are used (Table 2). PtAmmonia, PtPlastics, and PtSyngas were the pathways that did not achieve a reduction potential when grid mixes were used to evaluate MAX values. In these cases, the studies investigated only a few different regions, such as China and Germany (Supplementary Material), which have relatively high emission intensities of their grid mixes compared with other regions [43], or the other parts than H₂ production in a value chain was not designed to be free from fossil sources. Considering this observation, many PtX production pathways achieve emission reduction using low-carbon electric grid mixes. PtSteel achieved emission reduction even when calculating MEAN values, but the reduction did not occur in high-emission-intensity electric grid mixes. The results for PtSteel can be explained by the high emission intensity of the reference product and electric grid mixes used in the investigated studies.

3.3. Emissions of PtX pathways supplied by renewables and nuclear energy

Regarding the emission reduction potential, when using renewable or nuclear energy, a reduction can be achieved in almost all cases (Table 3). Only the PtMethanol, PtSyngas, and PtPlastics had production routes that resulted in no reduction potential. For PtMethanol, two studies showed no reduction potential. Fernández-González et al. [44] used non-optimised technology (low-technology-readiness-level technologies) for some routes. The second study performed an LCA based on primary data from a laboratory-scale experiment [45], which did not necessarily represent state-of-the-art technology. These studies impacted the PtFuel route, in which methanol was thought to be a

substitute for gasoline. Regarding PtPlastics, one study reported higher emissions than the reference product, which can be explained by the direct air carbon capture devices using fossil fuels [46]. This result highlights the importance of decarbonising the energy sources used for unit processes other than H₂ production. For the PtSyngas route, Choe et al. [47] investigated how the different RE sources impact the product. The PtSyngas route produces higher emissions than in the reference product when using hydropower or biomass-based power, whereas emission reduction can be achieved using solar or wind energy.

Over 20 kgCO_{2-eq} kg_{H₂}⁻¹ reduction potentials (MAX) is found from PtSteel, PtMethanol, PtDiesel, PtFood and PtHydrogen production routes (Table 3). However, the largest MEAN values over a 10 kgCO_{2-eq} kg_{H₂}⁻¹ reduction potential were found for PtSteel, PtAmmonia, PtHydrogen, and PtMethane (biogas upgrading), depending on the reference product used. The high value of biogas upgrading compared with that of PtMethane can be explained by the investigated system boundary, as biogas upgrading also contains methane from the biogas facility. The difference between MEAN and MINMAX for different PtX technologies can be explained by the single investigated studies, resulting in an average of considerably higher or lower emission reductions than the other studies. For instance, Isaacs et al. [48] employed co-electrolysis, which consumes less H₂ than the commonly studied Fischer-Tropsch (FT) reverse water-gas shift reaction (RWGS) production route, resulting in lower GWP values in the PtDiesel route.

3.4. Power-to-Hydrogen pathway

Alkaline electrolysis (AEL) is the most commercialised electrolysis technology with the highest technological readiness level and lowest price [49]. AEL has the highest durability and lifetime compared with other alternatives because the stack components are mature enough, and there are no noble metals on its structure. Nevertheless, AEL is less

Table 2
Impact reduction potentials of different PtX pathways per 1 kg of H₂, when using electric gridmixes or fossil fuels to power H₂ production.

	H ₂ -required	Unit	Reference products	MIN, MAX [kgCO _{2-eq} kg _{H₂} ⁻¹]	MEAN [kgCO _{2-eq} kg _{H₂} ⁻¹]	No of LCA studies
PtHydrogen	1	kg _{H₂}	H ₂ from SMR; coal gasification	No reduction potential –15.25	No reduction potential	9
PtSteel	0.059–0.060	kg _{H₂} /kg _{Steel}	BF-BOF production route	No reduction potential –33.46	6.3	3
Partial hydrogen injection	–	–	–	–	–	–
PtAmmonia	0.18–0.19	kg _{H₂} /kg _{NH₃}	Ammonia from natural gas	No reduction potential	No reduction potential	2
PtMethane	0.46–0.50	kg _{H₂} /kg _{CH₄}	Natural gas	No reduction potential –1.53	No reduction potential	6
Biogas upgrading	0.17–0.19	kg _{H₂} /kg _{CH₄}	Natural gas	No reduction potential –5.82	No reduction potential	3
PtSyngas	0.13	kg _{H₂} /kg _{Syngas}	Syngas from natural gas or coal	No reduction potential	No reduction potential	1
PtMethanol	0.20–0.24	kg _{H₂} / kg _{CH₃OH}	Methanol from natural gas or coal	No reduction potential – 9.2	No reduction potential	5
PtFuel						
PtDiesel	0.30–0.49	kg _{H₂} /kg _{Diesel}	Diesel	No reduction potential –4.17	No reduction potential	3
PtGasoline	0.48–0.64	kg _{H₂} / kg _{Gasoline}	Gasoline	No reduction potential –5.72	No reduction potential	1
PtDME	0.26	kg _{H₂} /kg _{DME}	Diesel (based on MJ)	No reduction potential –5.06	No reduction potential	1
PtJetfuel	–	–	–	–	–	–
PtMethanol	0.22	kg _{H₂} / kg _{CH₃OH}	Gasoline (based on MJ)	No reduction potential – 8.32	No reduction potential	5
PtPlastics	0.50–0.58	kg _{H₂} /kg _{Plastics}	Polypropylene from petrochemical factory	No reduction potential	No reduction potential	1
PtFood	0.12–0.15	kg _{H₂} /kg _{Protein}	Plant proteins; Other microbial proteins; animal proteins	No reduction potential – 301.66	–*	2
					Total	41

* Several different protein sources are present; thus calculating the mean value is unreasonable. The reduction potential is separately discussed.

Table 3
Impact reduction potentials of different PtX pathways per 1 kg of H₂ when using RE or nuclear to power H₂ production.

	H ₂ required	Unit	Reference products	MIN, MAX [kg _{CO2-eq} kg _{H2} ⁻¹]	MEAN [kg _{CO2-eq} kg _{H2} ⁻¹]	No of LCA studies
PtHydrogen	1	kg _{H2}	H ₂ From SMR; coal gasification	5.68–24.96	9.61; 22.96	11
PtSteel	0.051–0.059	kg _{H2} /kg _{Steel}	BF-BOF production route	21.4–38.96	31.97	2
Partial hydrogen injection	0.025	kg _{H2} /kg _{Steel}	BF-BOF production route	10.28–12.8	11.54	1
PtAmmonia	0.18–0.19	kg _{H2} /kg _{NH3}	Ammonia from natural gas	4.09–15.14	11.33	7
PtMethane	0.46–0.50	kg _{H2} /kg _{CH4}	Natural gas	1.28–6.8	3.91	9
Biogas upgrading	0.17–0.19	kg _{H2} /kg _{CH4}	Natural gas	9.52–15.35	12.43	2
PtSyngas	0.126	kg _{H2} /kg _{Syngas}	Syngas from natural gas or coal	No reduction potential –16.2	0.91; 8.11	2
PtMethanol	0.19–0.34	kg _{H2} /kg _{CH3OH}	Methanol from natural gas or coal	No reduction potential –22.88	3.33; 8.92	11
PtFuel						
PtDiesel	0.30–0.64	kg _{H2} /kg _{Diesel}	Diesel	1.76–30.93	9.75	6
PtGasoline	0.48–0.64	kg _{Gasoline} /kg _{H2}	Gasoline	2.06–6.71	5.69	2
PtDME	0.23	kg _{H2} /kg _{DME}	Diesel (based on MJ)	5.03–8.49	6.37	2
PtJetfuel	0.20–0.64	kg _{Kerosine} /kg _{H2}	Kerosine	4.55–16.62	8.41	2
PtMethanol	0.22	kg _{H2} /kg _{CH3OH}	Diesel or Gasoline (based on MJ)	No reduction potential –8.30	3.15	11
PtPlastics	0.50–0.58	kg _{H2} /kg _{Plastics}	Polypropylene from petrochemical factory	No reduction potential –7.02	2.46	2
PtFood	0.12–0.15	kg _{H2} /kg _{Protein}	Plant proteins; Other microbial proteins; Animal proteins	No reduction potential –347.52	–*	2
					Total	72

* Several different protein sources are present; thus calculating the mean value is unreasonable. The reduction potential is separately discussed.

flexible to fluctuating renewable power because of its lower load range, lower ramp up/down, and higher start-up/shutdown time compared with proton exchange membrane electrolysis (PEM). However, PEM has not been fully commercialised for large-scale applications because of their short lifetime, the use of expensive noble metals in their structures, and their high cost [50]. Solid oxide electrolysis (SOEC) has a higher electrical efficiency than that of AEL and PEM. However, the operating temperature of this technology requires high temperatures (700–800 °C), reducing its total energy efficiency. This limitation also leads to low flexibility if the operating temperature cannot be maintained at a high level. Moreover, this technology is the least developed among the investigated electrolyzers [51].

Conventional H₂ production, for example, steam reforming, is CO₂ intensive (Supplementary Material); thus, some electricity grid mixes can reduce emissions. However, the carbon intensity of the electricity used considerably affects its potential. For instance, Delpierre et al. [52] presented that AEL and PEM could result in a higher carbon footprint than that of steam methane reforming (SMR) if the relatively highly CO₂-intensive Dutch grid supplies electricity for electrolysis technologies. Moreover, they concluded that by scaling up the electrolysis technologies and utilising renewable electricity, the carbon footprint of water electrolysis for both PEM and AEL decrease considerably with similar impacts for both PEM and AEL because the system configuration constitutes only 10% of the environmental impacts of electrolysis technologies. On comparing the carbon footprint of AEL and PEM, we established that their impacts are similar. The possible differences in stack efficiency, lifetime, materials used, and material flows explain the slight difference and could result in favouring one or the other depending on the mentioned characteristics [52,53]. SOEC technology could result in a higher emission reduction than that of PEM or AEL if the required thermal energy is provided by waste or RE sources. Gerloff et al. [53] showed that SOEC could result in up to 25% lower GWP values than AEL. Similarly, Karaca et al. [54] revealed that high-temperature electrolyzers can reduce approximately 30% emissions compared with typical water electrolyzers. Although SOEC appears as the best option from the investigated H₂ production technologies from a climate perspective, other aspects, such as flexibility and technological maturity, still favour AEL and PEM technologies.

3.5. Power-to-Steel pathway

Several pathways exist for the use of hydrogen in iron or steelmaking processes; however, cradle-to-gate LCA studies on PtSteel pathways are limited (Supplementary Material). However, some studies focus on estimating CO₂ reduction based on energy and iron ore reduction agent sources used in furnaces. Thus, the reduction potential is majorly calculated based on gate-to-gate studies on how different energy or reduction agent sources and furnace types impact emissions derived from steelmaking.

To reduce the GHG emissions of steelmaking, replacing a portion of the coke in the blast furnace process with hydrogen injections is possible. This route has been proposed in the COURSE50 project, which aims to achieve approximately 30% GHG emission reduction in steelmaking. Approximately 10% of the reduction is sourced from injecting the hydrogen into the blast furnace and 20% from the sequestration of CO₂ from blast furnace gases [55,56]. Yilmaz et al. [57] simulated that the optimal hydrogen injection rate is 27.5 kg_{H2} t_{hotmetal}⁻¹ with coke replacement ratio of approximately 0.3 kg_{Coke} kg_{H2}⁻¹, corresponding to 21.4% CO₂ emission reduction from conventional blast furnaces. The hydrogen for injecting can be produced by separate water electrolysis, or as proposed by Kim et al. [58] that water electrolysis can be integrated as a part of a blast furnace with the maximum hydrogen injection of 25 kg_{H2} t_{hotmetal}⁻¹ with the coke replacement ratio of 0.255–0.344 kg_{Coke} kg_{H2}⁻¹. The proposed integration uses SOEC, which is still an immature water electrolysis technology compared with AEL or PEM. However, as most steelmaking pathways use blast furnaces, hydrogen injection can be a viable option for reducing emissions in the short term if SOEC is found to be a feasible technology.

The idea of direct hydrogen reduction is to replace CO₂ derived from coke or natural gas as a reducing agent with H₂ to produce reduced iron directly. Hydrogen can be produced by external water electrolysis. The reduced iron is then converted to steel in an electric air furnace. Among the investigated PtX pathways, the PtSteel pathway exhibited the lowest H₂ consumption from the investigated PtX pathways (Tables 2,3). If approximately equal shares of scrap metal and iron ore pellets are used, the hydrogen should be reduced to 25 kg H₂ t_{steel}⁻¹. The low hydrogen requirement of the process is one of the key factors that render it favourable when considering relevant hydrogen utilisation pathways in

an environmental context. However, water electrolysis consumes most of the energy, approximately 70%, to produce steel using H₂ [25,59]. When considering environmental feasibility, hydrogen direct reduction process has been shown to emit 2.8% CO_{2-eq} from that of blast furnaces emissions [25,60]. Based on Table 3, the direct hydrogen reduction process has the greatest impact reduction potential and can have approximately triple the reduction potential compared with the hydrogen injection pathway or other PtX pathways, such as ammonia production. The impact reduction potential can be achieved using average EU grid mixes, but most CO₂ intensive grid mixes can result in higher emissions than conventional steelmaking [59].

3.6. Power-to-Ammonia pathway

Among the investigated pathways, the PtAmmonia pathway did not require CO₂ during synthesis. However, this process requires N₂, which can be obtained from the air using an air separation unit. There are two methods of producing ammonia via electrolysis. It is possible to integrate electrolysis with the Haber–Bosch process or use electrochemical ammonia synthesis, such as molten salt-based electrolytes, composite electrolytes, or proton-conducting solid electrolytes, by which the latter pathways are not yet commercially available. However, novel technologies are promising as the energy consumption for electrochemical routes can be significantly lower, even at 4000 kWh t_{NH₃}⁻¹, compared with the combination of Haber–Bosch and water electrolysis [61,62,63,64,65]. Currently, the combination of water electrolysis and Haber–Bosch processes to replace fossil fuel sources and produce H₂ is more relevant than electrochemical routes because of their technological maturity [66].

Based on Table 3, PtAmmonia can result in major emission savings of over 10 kg_{CO_{2-eq}} kg_{H₂}⁻¹, being in the pathways with the largest reduction potential. From a technological perspective, LCA studies on the Haber–Bosch pathway combined with water electrolysis are well covered, and the MIN MAX results do not differ much compared with, for example, PtMethanol or PtDiesel routes. The immature electrochemical pathways had a limited number of LCA studies (Supplementary Material), and further investigations are required to reach a consensus. The investigated electrochemical pathway [67] did not significantly affect the MEAN value, less than 0.5%. However, the results were obtained from an experimental system without scaling the production, which typically results in high footprints in pathways using electrochemical routes owing to technological immaturity [44,45].

3.7. Pathways using carbon dioxide

According to Tables 2 and 3, using CO₂ to produce different hydrocarbons reduces the climate benefits gained compared with those without the need for CO₂. This result can be explained by the energy and materials consumed during the capture, separation, and purification processes to obtain the required CO₂ [40,46,68]. The effect of separating CO₂ depends on the sources, technology, and energy used to power the separation process. The average MEAN of all other PtX pathways was almost three-fold that of the average MEAN values of all PtX pathways utilising CO₂. However, the results showed that it is possible to produce low-emission alternatives to fossil-fuel-based products.

3.7.1. Power-to-Methane pathway

In the PtMethane process, H₂ and CO₂ can be synthesised to produce CH₄ through Sabatier, biological methanation, or electrochemical processes (Supplementary Material). The electrochemical route uses SOEC, which can directly convert steam and CO₂ to methane under the appropriate conditions [69,70]. The Sabatier process is the most widely investigated PtMethane pathway (Supplementary Material). When excluding the investigated biogas upgrading systems, the PtMethane pathway has a relatively low emission reduction potential compared with the other investigated PtX pathways, which can be explained by the

relatively low emission factor based on embedded CO₂ of natural gas compared with others.

Insufficient information was available to compare the GWP differences of the different synthesis routes. No studies have used electrochemical routes for these calculations. In the case of biological methanation, the system boundaries were different in numerous investigated studies; thus, a direct comparison was not possible in these cases. Naturally, the benefits of integrating biogas production facilities and biogas upgrading resulted in much higher emission reductions than those of a separate PtMethane facility, as methane from the biogas facilities was also formed. The MEAN value of the integrated systems was approximately three times higher than that of separate facilities (Tables 2,3). However, only a limited number of biogas facilities could substitute for the consumed natural gas. Considering the differences between Sabatier and biological methanation, De Roeck et al. [71] compared these two routes. The catalytic (Sabatier) route was found to have a slightly smaller GWP than the biological production route, but the difference was negligible, less than 1%.

In addition to the electricity source used for the electrolyzers, CO₂ is also a substantial element in the environmental performance of CH₄ production. Naturally, the same applies to other PtX routes, including CO₂ utilisation. For instance, Reiter and Lindorfer [40] showed that when CO₂ is supplied from biogas, the GWP can decrease by 23 kg CO_{2-eq} MJ_{bioCH₄}⁻¹ compared with scenarios in which it is obtained from fossil resources. This result can be explained by the fact that the carbon capture device typically uses energy from the point source when CO₂ is captured from fossil sources, such as coal plants. This can lead to CO₂ sources having over five times more GWP than the impact of H₂ production using wind energy; however, emission reduction can still occur. However, emission reduction is only possible if the captured CO₂ has no effect. Similar findings have been reported in other studies [36,72]. When reviewing biological upgrading pathways, some savings could be achieved by applying the hydrogenotrophic process, as no extra energy is consumed to separate CO₂ from biogas [73]. However, issues remain to be solved, such as inefficient conversion rates, which still needs to be demonstrated on a larger scale [74].

3.7.2. Power-to-Syngas pathway

Syngas production by PtSyngas routes includes the direct reduction of CO₂ to CO and H₂ by the RWGS [68] and direct one-step co-electrolysis, combining high-temperature electrolysis and high-temperature gas-phase conversion of CO₂ (Foit et al. 2017). The main disadvantage of direct reduction is that, apart from the reduction process, a separate process for hydrogen production is required. However, a limitation of the RWGS is that it also produces water, leading to a decrease in hydrogen yield, and the combination of low-temperature electrolysis and high-temperature gas-phase conversion is challenging. Combining direct one-step co-electrolysis with high-temperature electrolysis and high-temperature gas-phase conversion is a promising option but requires further technological development.

From the investigated literature, a GWP reduction comparison of different routes was not feasible, as both studies used SOEC (Supplementary Material). According to Table 3, PtSyngas can achieve environmental benefits compared with conventional syngas production from natural gas when the utilised electricity mix is based on RE production. According to Choe et al. [47], the emissions of PtSyngas can be six times lower when electricity is produced by wind power; however, if hydro pumped power storage is used, the emissions from PtSyngas can be even higher than those of conventional syngas production. Furthermore, Schreiber et al. [75] found that utilising a German grid mix for PtSyngas led to higher emissions than conventional SMR (Table 2).

3.7.3. Power-to-Methanol pathway

Direct hydrogenation of CO₂ (also called thermocatalysis) and co-electrolysis [76,77] are possible routes for producing methanol via H₂ and CO₂. The thermocatalytic route is more advanced than co-

electrolysis. Typically, thermocatalytic routes require separate reactors, which operate at approximately 170–270 °C and 20–80 bar, depending on the system configuration [77]. Nevertheless, electrochemical and co-electrolysis routes are promising because they can directly convert CO₂ to methanol using an H₂ production unit. Co-electrolysis is economically feasible at low production rates [45]. Electrochemical routes currently face major challenges that are difficult to solve as feasible options for large-scale production [77].

Five of the investigated studies involved electrochemical routes (Supplementary Material). Adnan and Kibria [39], Fernández-González et al. [44], and Guzmán et al. [45] compared the environmental impacts of these routes and showed that the thermocatalytic route has a slightly lower impact than co-electrolysis. However, the co-electrolysis route results in much higher emissions at a lower level of technological readiness. Nabil et al. [78] used an electric grid mix, and Rumayor et al. [79] used solar energy to power co-electrolysis, which resulted in a similar range of emissions as the thermocatalytic routes. Because the routes with low technological readiness for co-electrolysis resulted in high emissions, these routes greatly affected the overall MEAN values. By neglecting the results of those studies investigating co-electrolysis, the MEAN values changed from 3.33; 8.92 to 4.01; 9.86 kg_{CO₂-eq}kg_{H₂}⁻¹.

3.7.4. Power-to-fuel pathways

Power-to-liquid fuels produce liquid hydrocarbons from electricity, water and CO₂. Liquid hydrocarbons are then further upgraded or converted into specific products, such as diesel, gasoline, dimethyl ether (DME), and kerosene. Two main pathways for producing liquid hydrocarbons are FT synthesis and the methanol route [80,81]. Methanol can also be used directly as a substitute for gasoline [42]. During the FT synthesis, syngas is converted into synthetic crude oil, a mixture of hydrocarbons and other oxygenated products. The products of this process are then refined into diesel, gasoline, and kerosene via hydrocracking, isomerisation, and distillation. Another option is to use a SOEC (co-electrolysis). In this case, CO and hydrogen can be produced in a single step; therefore, the RWGS step is not required. The methanol route produces liquid hydrocarbons using an intermediate product, methanol, instead of syngas. Methanol is converted and upgraded into liquid fuels via direct DME synthesis, olefin synthesis, oligomerisation, and hydro-treatment. The FT route has been investigated more extensively for commercialisation than the DME route [81,82].

The investigated PtGasoline, PtDiesel, and PtKerosene pathways were based on FT-synthesis synthesis using either low-temperature electrolyzers (AEL or PEM) or high-temperature electrolyzers (SOEC) (Supplementary Material). Because it is possible to produce gasoline, diesel, and kerosene from the FT process simultaneously, the impacts were allocated between the produced products via the energy content, MJ, in many investigated studies [80,83]. This explains the similar ranges of reduction potentials observed in the investigated pathways (Table 3). The slight differences in the reduction potential can be explained by the technological choices and assumptions made in the investigated studies. For instance, by removing the highest reduction potential achieved via co-electrolysis in a study conducted by Isaacs et al. [48], the MEAN value of the PtDiesel route was 6.44 kg_{CO₂-eq}kg_{H₂}⁻¹. Similarly, by removing the highest reduction potential reported by Schmidt et al. [82], the MEAN value of PtJetfuel was 6.69 kg_{CO₂-eq}kg_{H₂}⁻¹. No credible conclusions can be made when comparing the low- and high-temperature electrolysis routes, as the assumptions regarding how co-electrolysis is modelled and whether a low or predicted high technological readiness level is used considerably impact the results. From a single study point of view, Isaacs et al. [48] investigated the difference between co-electrolysis and PEM with RWGS in the FT process, and exhibited that the co-electrolysis route could result in significantly, almost twice, lower emissions than the more typical route using PEM with RWGS. The abundance of the RWGS process when using co-electrolysis and the smaller need for H₂ generation rendered this route promising, and it can potentially result in lower CO₂ emissions.

However, co-electrolysis is still a less mature technology than FT with the RWGS, which currently makes co-electrolysis a less appealing alternative.

The PtDME route resulted in values similar to those of the PtGasoline, PtDiesel, and PtKerosene pathways; thus, no significant differences were observed among these four PtX pathways. One exception was the direct use of methanol, which resulted in the lowest reduction potential. One possible explanation for this difference is the LHV of the investigated products. Diesel, Kerosene, and Gasoline have over double times higher LHV, and DME has approximately 40% higher LHV values than that of methanol.

3.7.5. Power-to-Plastics pathways

There are multiple plastic types and grades; therefore, plastic production routes can vary. However, the two plastics with the highest global production are polypropylene and polyethylene [84]. Both can be produced using methanol [13]. The production of methanol from hydrogen and CO₂ was described in chapter 3.6. There are two main routes for producing plastics from methanol, both of which are based on advanced technology. The first is the methanol to olefins route (MTO), which simultaneously produces propane and ethane from methanol. The second produces propane from methanol (MTP). Both processes require electricity and steam and produce additional co-products, such as gasoline and butene. China produces plastics from fossil fuels using these processes [13,85]. Propane and ethane can be converted into polypropylene and polyethylene, respectively, via polymerisation. In addition, some speciality polymers, such as polyoxymethylene (POM) can be produced from methanol. When POM is produced, methanol is partially oxidised to formaldehyde, which is then polymerised [46].

According to Kuusela et al. [13], power-to-polypropylene routes (both MTO and MTP) lead to significant GHG emission reductions if renewable electricity is used as an electrolyser and fossil plastics are substituted. However, if a grid mix of electricity is used, GHG emissions can be higher than those routes from fossil plastics, for example, Hoppe et al. [46] and Keller et al. [86] concluded that both polypropylene and polyethylene production from power-to-methanol leads to higher GHG emission reductions compared with fossil plastics. All of these studies led to similar conclusions regarding GHG emissions related to power-to-polypropylene and polyethylene production. However, slight differences were observed owing to the selections related to the system boundaries, initial data, and assumptions. The low MEAN value compared with other PtX pathways (Table 3) can be explained by the fact that both investigated studies used fossil sources in parts of the value chain other than H₂ production.

3.7.6. Power-to-Food pathway

Microbial proteins can be produced using PtX technology. In such cases, a hydrogen-oxidising bacterium (HOB) capable of utilising hydrogen and oxygen derived from water electrolysis and CO₂ is used to build biomass. These HOB species can produce large quantities of protein biomass to replace proteins used for feed or food [87,88].

Although interest in PtFood pathways has increased [87], only a limited number of LCA studies exist (Supplementary Material) from which consensus about typical emission reduction potentials cannot be formed. However, HOB-based biomass can achieve lower climate impact than plant-based proteins [22,28]. On comparing emissions, for soybeans the reduction in climate impact is negligible compared with other PtX pathways. Compared with meat-based proteins, the reduction potential can be the most significant among the investigated pathways, even at 350 kg_{CO₂-eq}kg_{H₂}⁻¹. Thus, in the case of PtFood applications, the systemic impact reduction is more dependent on substitutable products than on other PtX products. PtFood can achieve considerable environmental benefits on environmental impacts other than climate impacts [22,28], which can be a greater benefit than climate impact for the agricultural sector [89].

3.8. Implications, credibility and future research

Different PtX pathways require varying amounts of H₂ for production; thus, using H₂ as a functional unit may not always be optimal when comparing PtX pathways from an emission reduction perspective. However, H₂ production accounts for a major share of the total environmental impact of different PtX pathways, consumes a considerable amount of energy, and contributes significantly to the investment costs of the investigated PtX processes [25,33,90,91]. In addition, there may be bottlenecks other than purely economic or available RE sources that hinder the utilisation of H₂. Generally, H₂ is a molecule that is difficult to store and distribute and is dangerous owing to the explosion risk [92,93]; thus, focusing on H₂ usage is a valid perspective.

From the investigated pathways, the highest emission reduction per hydrogen used was achieved through the PtFood application. However, in this case, the substitutable product is difficult to define and can result in the lowest MEAN value achieved. Among the PtX routes with a clear substitutable product, PtSteel had the largest MEAN value. The PtHydrogen, PtMethanol, and PtAmmonia routes can also provide significant emission reductions, especially if a substitutable product is produced using coal. Thus, to obtain the largest possible emission reduction, highly harmful products (coal-derived products) should be substituted first.

For PtHydrogen, PtMethane, PtMethanol, and PtAmmonia, numerous studies were used in the calculations compared with those for other pathways. For other PtX pathways, further research is required to improve the credibility of their emission reduction potentials. However, based on the studies identified, the assumptions used and technological pathways in the LCA models influenced the results more than the number of studies. For instance, the highest reduction potential values in the PtDiesel route using co-electrolysis in one study were almost twice as high as the highest reduction potentials achieved in all other studies using the same energy source. A similar but opposite effect was found when using low technological readiness level co-electrolysis in the PtMethanol route. When the results of the co-electrolysis routes were neglected from the calculations, they did not deviate considerably from the investigated pathways when similar CO₂ and energy sources were used. Overall, further investigation is required on the possibilities and challenges related to co-electrolysis and the use of SOEC in every PtX pathway. Another impactful assumption was related to how the CO₂ source influenced the GWP and whether the entire value chain was modelled as fossil-free. For instance, different point sources of CO₂, DAC devices, and even assumptions on how CO₂ is modelled can have a major influence when H₂ is produced through RE. In addition, differences were present related to whether or how the impact of H₂ storage was included in the investigated studies. However, in this study, further analysis of H₂ storage was not conducted, as it can be regarded as a common factor for every pathway, and the impact was typically found to be negligible on the overall results. Koj et al. [11] made a similar conclusion from assumptions made considering CO₂ sources in their review paper considering LCA usage for PtX systems. However, because the key unit process is H₂ production, the assumption on how much H₂ is consumed in the value chain has a drastic impact on the GWP. For instance, studies have used theoretical stoichiometric H₂ consumption or high yields without major leakages from secondary data in some value chains instead of primary data [28,71,94]. These assumptions are understandable, as in many cases, PtX solutions are still under R&D or on a pilot scale; however, this assumption can lead to extremely low footprints. However, as technologies develop and scale increases, the solutions tend to become increasingly efficient. Thus, whether the assumptions are valid cannot be currently determined. Regardless, the value chains that result in the smallest footprints should be viewed with caution. Overall, when possible, more footprint evaluations using primary data from industrial-size solutions are needed in the future. In addition to choices made in found literature sources, there is a possibility that some relevant literature sources were not found because of inconsistency of terms used

describing different PtX pathways, products, and impact to climate. For instance, some literature studied the climate impact by using low technological readiness level applications, which can impact to MEAN values, if such a literature was not included in the calculations.

Several regions plan to use only green H₂ when initiating a hydrogen economy. For instance, the EU has set regulations that renewable H₂ should be produced using RE alone when producing synthetic fuels [95]. However, the results imply that it is possible to achieve emission reductions even when using electric grid mixes containing fossil-based energy sources or nuclear power to produce H₂ (Tables 2 and 3). The carbon intensity in these grid mixes must be sufficiently low to provide emission savings. To understand the sufficient level of carbon intensity of electric grid mixes, case evaluations are needed. The reason is that different background processes and technological choices can impact to the lifetime emissions of the specific pathways, which then impacts to the sufficient carbon intensity levels. However, there are some studies available in which the sufficient carbon intensities of electricity sources are evaluated for the specific P2X value chains [96,97]. Notably, global emissions should be reduced quickly, thereby prompting the question of whether legislation should allow the production of H₂ from grid mixes if emission reduction can be achieved. The current solution could also be a transition-phase solution before the regional grid mixes are possibly changed to be near or entirely renewable. Notably, some RE sources, such as electricity from biomass, could result in higher emissions than the reference product, thus the source of RE matter. However, hydrogen related legislation is novel, and it is still developing. For instance, the EU commission is currently debating on whether hydrogen should have a separate category, "low-carbon hydrogen", other than green for those that can achieve 70% emission reductions compared with fossil natural gas [98]. Therefore, regions that can provide a grid mix with sufficiently low CO₂ intensity to obtain reduction potential in different PtX pathways could gain a competitive edge over those that cannot. The possibility of using grid mixes could also accelerate the implementation of PtX technologies, as PtX value chains can save storage volumes or continuously function while producing low-carbon products when no fluctuating RE is available. Continuous production and amount of storage capacities can have conclusive impacts on economic feasibility of some PtX value chain [16,18]. Therefore, investigations on the regions and levels of emission factors in grid mixes should be performed to identify feasible locations to achieve emission reduction for different PtX pathways. Hence, combining the economic boundaries of different PtX solutions with emission reduction potentials should be included in future studies to determine the PtX pathways that can achieve the highest reduction from an economic perspective.

4. Conclusion

This study investigated the climate impact reduction potential of different PtX pathways. The outcome of this research supports previous research showing that the largest emission reductions can be achieved using RE or nuclear energy to power H₂ production. Nevertheless, gaining emission savings via low-carbon electric grid mixes is still possible in some systems; thus, the total ban on grid mixes containing a sufficiently low amount of fossil energy might be unreasonable. In particular, a fast transition towards a hydrogen economy and climate change mitigation actions is desired. From an H₂ production technology perspective, routes using co-electrolysis resulted in the lowest carbon footprints in several cases, but the technological readiness level for large-scale production is currently low. However, the electricity sources used for H₂ production is more important than the use of co-electrolysis. Excluding the PtFood pathway because of difficulties in defining the substitutable products, the PtSteel pathway resulted in the largest emission savings, followed by those of PtHydrogen, biogas upgrading, and PtAmmonia. Overall, this study's results indicate that the use of hydrogen can be initiated primarily to gain the greatest environmental benefits from transitioning to a hydrogen economy.

CRedit authorship contribution statement

Jani Sillman: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Jouni Havukainen:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Rami Alfasfos:** Writing – original draft, Investigation. **Nashmin Elyasi:** Writing – original draft, Investigation. **Miro Lilja:** Writing – original draft, Investigation. **Vesa Ruuskanen:** Writing – review & editing, Validation. **Emma Laasonen:** Writing – review & editing, Validation. **Lauri Leppäkoski:** Writing – review & editing, Writing – original draft, Investigation. **Ville Uusitalo:** Writing – review & editing, Writing – original draft, Validation. **Risto Soukka:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Used references for the calculation can be found from supplementary material

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Appendix A. Supplementary data

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