Journal of Cleaner Production 299 (2021) 126866

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis

Mathieu Delpierre [a], Jaco Quist [b], Jan Mertens [c, d], Anne Prieur-Vernat [c, d], Stefano Cucurachi [a, *]

[a] Leiden University, CML Institute of Environmental Sciences, Einsteinweg 2, 2333, CC Leiden, the Netherlands
[b] TU Delft, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628, BX Delft, the Netherlands
[c] ENGIE Research, 1 Pl. Samuel de Champlain, 92930, Paris-la Défense, Paris, France
[d] France & Department of Electromechanical, System and Metal Engineering, Ghent University, Technologiepark Zwijnaarde 131, Zwijnaarde, Belgium

A R T I C L E I N F O

Article history:
Received 18 July 2020
Received in revised form
18 March 2021
Accepted 24 March 2021
Available online 28 March 2021

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Ex-ante LCA
Exploratory scenarios
Technology analysis
Hydrogen
Electrolyser
Morphological analysis
Low carbon

A B S T R A C T

Two electrolysis technologies fed with renewable energy sources are promising for the production of CO_2-free hydrogen and enabling the transition to a hydrogen society: Alkaline Electrolyte (AE) and Polymer Electrolyte Membrane (PEM). However, limited information exists on the potential environmental impacts of these promising sustainable innovations when operating on a large-scale. To fill this gap, the performance of AE and PEM systems is compared, using ex-ante Life Cycle Assessment (LCA), technology analysis and exploratory scenarios for which a refined methodology has been developed to study the effects of implementing large-scale sustainable hydrogen production systems. Ex-ante LCA allows modelling the environmental impacts of hydrogen production, exploratory scenario analysis allows modelling possible upscaling effects at potential future states of hydrogen production and use in vehicles in the Netherlands in 2050. A bridging tool for mapping the technological field has been created enabling the combination of quantitative LCAs with qualitative scenarios. This tool also enables diversity for exploring multiple sets of visions. The main results from the paper show, with an exception for the "ozone depletion" impact category, (1) that large-scale AE and PEM systems have similar environmental impacts with variations lower than 7% in all impact categories, (2) that the contribution of the electrolyser is limited to 10% of all impact categories results, and (3) that the origin of the electricity is the largest contributor to the environmental impact contributing to more than 90% in all impact categories, even when renewable energy sources are used. It is concluded that the methodology was applied successfully and provides a solid basis for an ex-ante assessment framework that can be applied to emerging technological systems.

1. Introduction

The Paris Agreement aims to limit global warming well below 2 °C, requiring a massive decarbonisation of all energy-intensive sectors (UNFCCC, 2015). Hydrogen fuels are considered a viable alternative to reduce traditional fossil fuel use (Ball and Wietschel, 2009; Acar and Dincer, 2014). However, around 96% of hydrogen production in the world is currently based on fossil fuels (Shiva Kumar and Himabindu, 2019). Approximately 50% of the worldwide production of hydrogen is still produced via steam methane reforming (SMR) (Nikolaidis and Poullikkas, 2017). SMR is the cheapest technology for producing hydrogen, but does not solve the issue of CO_2 emissions (Gielen and Simbolotti, 2005; Singh et al., 2015). On average, the production of 1 ton of hydrogen through SMR produces 10 tons of CO_2 (Hydrogenics, 2018). Consequently, a major shift of hydrogen production towards more sustainable pathways is necessary.

Water electrolysis combined with renewable energy sources

* Corresponding author.
E-mail address: s.cucurachi@cml.leidenuniv.nl (S. Cucurachi).

https://doi.org/10.1016/j.jclepro.2021.126866
0959-6526/

offer most potential to producing hydrogen with reduced emissions (Acar and Dincer, 2014). Two types of electrolysers[1] are promising: the alkaline electrolyte (AE) and the polymer electrolyte membrane (PEM) electrolysers. However, electrolysis powered by renewable energy is currently only implemented at small scale and requires large development efforts, which could potentially lead to unexpected and undesired environmental impacts (Nikolaidis and Poullikkas, 2017). Despite the potential, to the best of our knowledge, no detailed environmental comparison is currently available for these technologies at pilot scale and at commercial scale. Moreover, there is only limited information on environmental impacts from renewable-based hydrogen with large-scale electrolysers, although this knowledge would provide relevant insights for the hydrogen economy development.

This knowledge gap is taken up in this paper, in which we propose a combination of *ex-ante* life cycle assessment (LCA) (Cucurachi et al., 2018) and exploratory scenario analysis (Ritchey, 2011.). Such an approach can support decisions in earlier stages of the development process of a technology system and facilitate promising sustainable innovations early on. However, due to the prospective nature of the approach, only limited data are available, and significant degrees of uncertainties are present. Recent contributions reviewed the theory and methods of ex-ante LCA and how scenarios could be used but without extended examples (Thonemann et al., 2020; van der Giesen et al., 2020). Scenarios can thus help to envision future states that orientate the evolution of an emerging technology. By applying different assumptions and analysing dimensions, a framework for future development of the technology can be established and an ex-ante LCA implemented. In this paper, an ex-ante LCA is combined with scenarios that describe futures where the studied technology would operate at a large scale. Scenarios can depict likely futures, possible futures or desirable futures (Quist, 2013), also referred to as predictive or Business-As-Usual (BAU) scenarios, exploratory scenarios, and normative scenarios, respectively (Höjer et al., 2008; Quist, 2013). Given the uncertainties surrounding the development of emerging technologies and large-scale implementation, predictive scenarios are less useful in ex-ante LCA. By contrast, both explorative and normative scenarios are very useful to consider uncertainties and complexities around emerging technologies and their large-scale implementation. Scenarios have already been used in various LCA studies, such as Ravikumar et al. (2015) who used scenarios to compare the environmental performances of solar panels' recycling. Tsoy et al. (2019) also used exploratory what-if scenarios to take into account upscaling effects for a novel anti-reflective coating. Each scenario represents a possible future state and allows to deal with data uncertainties, complexities and limitations to available knowledge.

The aim of the paper is to assess both AE and PEM technologies at current stage of development, and to further assess their potential impacts at a large-scale implementation using LCA prospectively. Additionally, AE and PEM were compared to the incumbent SMR process. The general morphological analysis (GMA, Ritchey, 2011), an approach for exploratory scenario analysis was used to construct scenarios with an assessment and a focus on specific factors. The implementation study of AE and PEM considers the Netherlands as a case study. As this country aims to be free from natural gas by 2050, hydrogen is widely considered as a crucial energy carrier for the future and scenarios were constructed upon this vision (van Wijk et al., 2017). We take into account the development of the two technologies over time and various scenarios in the Netherlands shedding more light on the environmental gains of a future hydrogen economy. Eventually, the paper seeks to highlight recommendations based on the extended ex-ante LCA/scenario combination as well as some recommendations from the ex-ante LCA results.

The remainder of the paper is organised as follows. An overview of hydrogen production technologies is provided in section 2, together with the description of our approach for ex-ante LCA, technology analyses and scenarios methodologies. Section 3 shows the different results for the pilot-scale and ex-ante LCA with the various scenarios development. Finally, some elements of discussions are provided in Section 4.

2. Methodology

2.1. Background: towards sustainable hydrogen production in the Netherlands

The Netherlands aims to produce 30 Kton of hydrogen for mobility by 2050 (van Wijk, 2017). Wind energy is considered to be the most likely and preferable renewable source to produce hydrogen on a large-scale in the Netherlands, based on its power generation potential (Ghandehariun and Kumar, 2016; Patterson et al., 2014). More specifically, van Wijk (2017) predicts that wind turbines will provide 4000 MW for the Northern Netherlands Hydrogen Economy. Furthermore, the average wind power density in the NL is estimated at 400 W/m^2 (DTU, 2018), whereas the global solar irradiance is estimated at 120 W/m^2 (ESMAP and Solargis, 2016). So, in the Netherlands wind energy has a stronger potential as a renewable energy source compared to solar energy.

An electrolyser splits water (H_2O) into oxygen (O_2) and hydrogen (H_2 using electricity). The main differences between technological setups for electrolysers are due to the operating conditions (temperature, pressure, etc.) and the type of electrolyte used.

An AE contains a liquid electrolyte, often potassium hydroxide (KOH), whereas a PEM electrolyser uses a solid membrane, usually a polytetrafluoroethylene-based product (Sapountzi et al., 2017). The AE technology has been used for over a century in the industry, especially in ammonia production, and requires relatively low costs investments (ca. 1000 €/kW for AE vs 2000 €/kW for PEM) (Bertuccioli et al., 2014). AE has already been used before for large-scale hydrogen production in Norway (up to 300 MW) but these installations were closed in 1991 (Graré, 2019). However, the electrolyser's low current density (below 1 A/cm^2) and sensitivity to differential pressures restrict its efficiency (Bertuccioli et al., 2014). In comparison, PEM technology has only been used in small-scale installations (HyBalance, 2018) but offers a stronger potential for further technological developments. For instance, the higher current density in PEM electrolysers (1–3 A/cm^2) enables higher efficiency and the stack can be smaller in size, while maintaining similar production rates. Moreover, the PEM electrolyser's dynamic power response is more flexible than AE technology, making PEM especially suitable to deal with intermittent electricity production. As hydrogen is being promoted in the Netherlands, a detailed comparison between alkaline and PEM electrolysers, both at a large scale, would provide some relevant insights.

2.2. Applied methodology

To assess the impacts of the systems described in section 2.1 we developed a novel ex-ante LCA adding technology analysis and scenario analysis, following Cucurachi et al. (2018). The methodology is shown in Fig. 1 and consists of four phases. In the first

[1] Note for the reader: a distinction is made between the *electrolysis*, which is the chemical process itself where water is split into hydrogen and oxygen, and the *electrolyser*, which is the technological device that operates an electrolysis.

phase, an LCA study of the state-of-the-art for the selected electrolysers' alternatives was conducted. In the second phase, technology analyses were conducted to explore possible evolutions and developments of the selected technologies and the socio-technical system of electricity production and consumption. In Phase 3 these analyses were fed into exploratory scenarios generation using general morphological analysis. Finally, the scenarios were used in the fourth phase to conduct the ex-ante LCA.

In order to make meaningful comparisons between electrolysers and scenarios, SMR is considered in this paper as the incumbent alternative as it is representing ca. 50% of the worldwide production of hydrogen. SMR is a catalysed chemical reaction that produces syngas (hydrogen and carbon monoxide) from hydrocarbons (generally natural gas) requiring steam at high temperature and pressure. Nowadays this is called grey hydrogen, while in combination with Carbon Capture and Storage it is referred to as blue hydrogen. In this study, no research has been conducted on SMR's development over time as it is a mature technology, while the focus is put on electrolyser and the latter is expected to bring more environmental benefits.

2.2.1. *Life cycle assessment of state-of-the-art AE and PEM technologies (phase 1)*

The environmental emissions and impacts from the processes necessary to produce H_2 were evaluated. The approach adopted is "cradle-to-gate", starting from the production of raw materials to the production of hydrogen gas. The Balance of the Plant (e.g. cables, compressor, storage tanks, etc.) and recycling systems are out of the scope of the study, due to lack of data. We considered no evolution in hydrogen demand or market within the LCA model. The functional unit was defined as "1 kg of hydrogen at a pressure of 20 bars produced", for all the systems assessed.

LCA models were developed using the OpenLCA software (GreenDelta, 2018) and the ecoinvent 3.4 (ecoinvent, 2018) database for background processes. Data for foreground processes and for modelling pilot-scale systems were based on recent reviews available in the scientific literature (Koj et al., 2017; Schmidt et al., 2018; Wulf and Kaltschmitt, 2018). Data for foreground processes relating to the large-scale systems originated from the technology analysis (see Section 2.2.2). Full reference to the inventory (LCI) data used is available in the Supplementary Information. The incumbent technology of SMR was modelled based on the work of

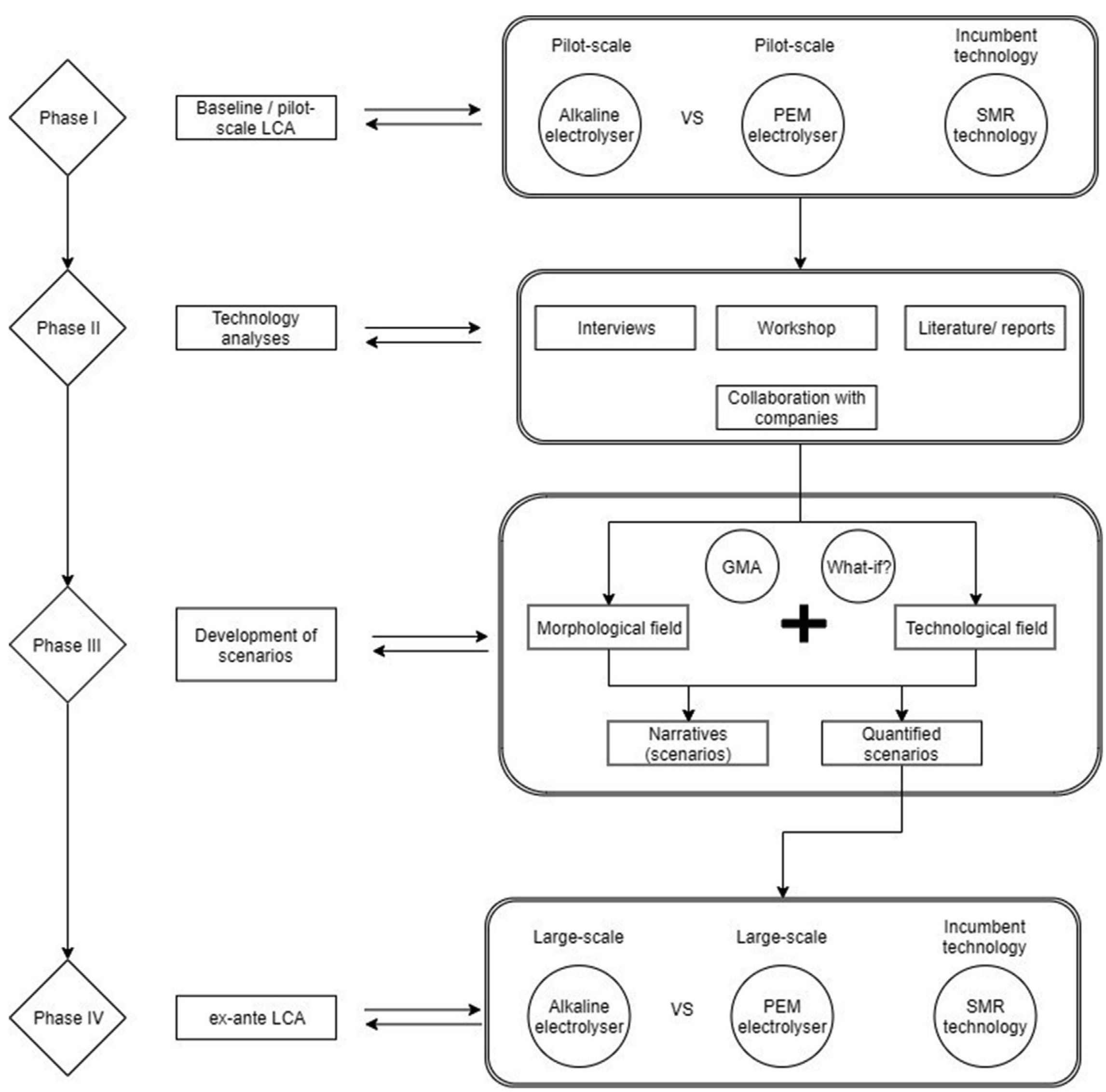

Fig. 1. Visual chart of the methodology used.

Wulf and Kaltschmitt (2018). At the impact assessment phase (LCIA), the ILCD 2011 baseline was used (JRC European commission, 2011).

2.2.2. Technology analysis methods (phase 2)

Phase 2 comprised the technology analysis based on (i) screening of the literature, (ii) attending expert workshops, and (iii) expert consultation using semi-structured interviews and informal communications. Various reports and studies were collected and thoroughly analysed, regarding the two identified electrolysers technologies, possible developments and evolutions. The search criteria consisted of technical parameters about material and energy requirements for the electrolyser under study. Both journal papers and reports were included, key sources included Ball and Wietschel (2009), Bertuccioli et al. (2014), Gigler and Weeda (2018), and Smolinka et al. (2018).

In addition to attending workshops and meetings, four interviews were conducted with (i) a member from an electricity and gas distributor company that runs a pilot installation, (ii) an innovation technologist at a Dutch chemical company, (iii) a director of Business Development for electrolysers, and (iv) a hydrogen envoy from the Dutch government. A full overview of the questions is provided in the supplementary information.

Furthermore, collaboration has taken place with ENGIE and the laboratory CRIGEN in Paris, intending to discuss and refine the technological model. This resulted in additional data for the modelling of the water, though did not lead to significant influences in assessment results. Some sensitivity analyses have also been conducted concerning the requirements of noble metals, but their environmental impacts were negligible (a few percent). To get a current overview of the technological forecasts, some data and documents were also used in the scenario development (Bertuccioli et al., 2014; Smolinka et al., 2018).

2.2.3. Scenario construction (phase 3)

In phase 3 exploratory scenarios were constructed using general morphological analysis (GMA) (Ritchey, 2011), which was applied to ex-ante LCA recently (Rijnsburger, 2016; Honkoop, 2017). Morphological analysis can be described as “a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes” (Ritchey, 2011, p.84).

GMA enables to develop exploratory scenarios in a systematic and transparent way, while bringing in diversity and addressing complexity and uncertainties. The method proposed by Ritchey (2011) was used, but slightly adjusted. Morphological scenario generation consists of 4 steps (Ritchey, 2011): (1) defining dimensions or variables, (2) identifying values for the variables, resulting in a so-called morphological field, (3) consistency analysis, and (4) generate and assess scenarios. However, step (3) was not fully conducted due to time limitations and instead only the most relevant scenarios were considered. For scenario development expert consultation, as well as articles and reports were used. A key input was the recent Dutch vision for a potential green hydrogen technology development (van Wijk, 2017). The hydrogen demand for transport was considered as it may provide a breakthrough for green hydrogen technologies (Ball and Weeda, 2015). Furthermore, other factors influencing technology development (e.g., support from actors, hydrogen distribution framework) were also selected as dimensions, to consider plausible evolutions.

The morphological scenario method resulted in a morphological field where selected dimensions are placed in columns using the inputs from the technology analysis, including non-technological aspects (as reported in Section 3.2 and Table 3). Each dimension shows a range of possible values. The selection of a value for each dimension resulted in a “field configuration”, which is the backbone for a specific scenario. To feed the qualitative scenarios into the quantitative LCA assessment, an additional table the “technological field” was created, showing numbers based on the potential technical evolution of the electrolysers −and used in the ex-ante LCA in phase 4 (see Tables 2 and 5).

Two key scenarios were developed having a clear distinction between “high” development of hydrogen technology (Scenario A), and “low” development (Scenario B). The scenarios provide a context for hydrogen production and the fuel demand in the future. For each scenario, a short narrative describes the future envisioned, in 2050, reflecting the morphological field shown in Tables 3 and 4. The cross-consistency checks made to delete unlikely combinations is given in the Supplementary Information.

2.2.4. Ex-ante LCA (phase 4)

Ex-ante LCA was applied as proposed in Cucurachi et al. (2018). This class of methods focuses on the expansion of the LCA standard framework to assess emerging technology systems. Following recommendations by van der Giesen et al. (2020), information collected in phase 3 was used to quantify the LCI foreground information for the systems under assessment, anticipating its likely operation at a large-scale. The information allows mapping the potential evolution of the system at scale towards 2050 in the Netherlands and provides scenario analysis. The same methodological specifications as in phase 1 were adopted, in relationship with functional units, system boundaries, and other specifications of the LCA model. Technological relevant parameters (e.g. changes in material inputs) were updated using the information resulted from the GMA and shown in Table 5.

3. Results

3.1. Pilot-scale LCA

The first methodological phase consists in conducting the pilot-scale LCA, as described in Section 2.3. The flowcharts for the pilot-scale systems and the graphs with absolute values can be found in the Supplementary Information. The results are shown in Fig. 2, relatively with the maximum result for each impact category.

Remarkably, Fig. 2 shows that the SMR alternative possesses better environmental performances than the two electrolysers. Contribution analyses also showed that electricity production (from the Dutch grid) is responsible for more than 80% of environmental impacts for all impact categories. Moreover, the PEM alternative possesses relatively smaller environmental impacts than AE technology for all impact categories (up to 20%). Further contribution analyses enabled the selection of the most sensitive parameters, which may gain larger influences in up-scaled systems, as listed in Table 1. When developing and analysing the large-scale LCA systems, special attention should be put to these potentially sensitive parameters.

3.2. Technology analysis

The information collected from the technology analysis were injected in the scenario narratives and the list of dimensions and parameters in the morphological and technological fields respectively. The technological field has been developed and reviewed with inputs from industrial reports, literature review, and technology analyses (see Section 2.2.2). The following technical

Table 1
Parameters relevant for upscaling of PEM and AE technologies.

System AE	System PEM
Electricity production Water consumption Materials: Nickel and tetrafluoroethylene	Electricity production Water consumption Materials: membrane (often named "Nafion") Noble metals (Platinum, Iridium, Titanium)

Table 2
Electrolyser technological field.

Parameters	AE		PEM	
	2019	2050	2019	2050
Lifespan of the electrolysis plant	20–25 years	30 years	20 years	30 years
Lifespan of the stack	80,000 h	120,000 h	60,000–80,000 h	130,000 h
Plant capacity	A few MW	100 MW - 1 GW	A few MW	100 MW - 1 GW
Stack capacity (power)	2–4.5 MW	20 MW	1 MW	20 MW
Electrical consumption	50 $kWh_e/kg\ H_2$	47-50 kWh_e/kg of H_2	50 $kWh_e/kg\ H_2$	50-55 kWh_e/kg of H_2
Water consumption	10 kg/kg H_2	9–10 kg/kg H_2	10 kg/kg H_2	9–10 kg/kg H_2
Steel consumption	10–30 kg/kW	10–30 kg/kW	7–10 kg/kW	7–10 kg/kW
KOH consumption (AE)	1–2 g/kg H_2	1–2 g/kg H_2	NA	NA
Nickel consumption (AE)	0.2–2 kg/kW	0.2–2 kg/kW	NA	NA
Iridium load (PEM)	NA	NA	0.7 g/kW	0.01–0.05 g/kW
Nafion consumption (PEM)	NA	NA	0.016 kg/kW	0.002 kg/kW
Platinum load (PEM)	NA	NA	0.1–0.3 g/kW	0.01–0.03 g/kW
Titanium load (PEM)	NA	NA	450–500 g/kW	35/kW

Table 3
Configuration field selected (in orange) for scenario A "Full hydrogen power".

Level of electrolysis implementation	Transport market penetration by H_2 (in % of car fleet)	Policy support	Technology development	Stakeholders involvement	Production/distribution framework	Technology promoted for H_2 production	Main origin of electricity (for electrolysis)
Implemented in all regions • National scale	70%	Strong policy support • R&D subsidised • Carbon tax • Laws adjusted for H_2	Strong development • Reduced noble metals consumption • Large-scale systems	Strong collaboration • Clusters, supply chain construction, coalitions	Mostly centralised	Electrolysis	Wind • Construction of large wind parks
Implemented in few regions (mostly North)	50%	Limited policy support (electrification, blue hydrogen)	Limited development	Limited collaboration	Mostly decentralised	Anion Exchange Membrane electrolyser	Solar
Not significantly implemented	30%	No support (electrification, blue hydrogen)	No significant change	Dispersed efforts	Parallel evolution • Backbone (1 GW) and decentralised frameworks	SMR (blue hydrogen)	Nuclear
	10%					Coal gasification (blue hydrogen)	

parameters were considered: the lifespan of the plant and the electrolysers, the system and stack capacities, the efficiency of the electrolyser and the material consumption. Using the technology analysis results, a "technological field" has been created (see Table 2) to provide technical and quantified values for the scenario in the next step, including the parameters from Table 1. For each parameter presented in Table 2, values were defined for the current situation and extrapolated for 2050 (for more details on data sources, see Supplementary Information). For each scenario, the best or worst-case situation was considered.

3.3. *Scenario construction*

3.3.1. *Scenario A "full hydrogen power"*

In "Scenario A", the most ambitious development path for 2050 has been selected for hydrogen technology and the electrolyser technology will have been implemented in all potential regions (van Wijk, 2017). Scenario A essentially describes the implementation of a green hydrogen economy in the Netherlands, at a national scale, while key elements of the scenario are shown in Table 3.

Table 4
Configuration field selected No to wind-based Hydro (in orange) for scenario B "Without wind-based hydrogen".

Level of electrolysis implementation	Transport market penetration by H2 (in % of car fleet)	Policy support	Technology development	Stakeholders involvement	Production/distribution framework	Technology promoted for H_2 production	Main origin of electricity (for electrolysis)
Implemented in all regions	70%	Strong policy support	Strong development	Strong collaboration (clusters, supply chain construction)	Mostly decentralised • No strong trend of evolution (up to 100 MW)	Electrolysis	Wind
Implemented in few regions (mostly North)	50%	Limited policy support (electrification, blue hydrogen)	Limited development	Limited collaboration (specific on locations)	Mostly decentralised	Anion Exchange Membrane electrolyser	Solar
Not significantly implemented • Only at some "hotspots" locations	30%	No support • Electrification • Blue hydrogen • Support for other alternatives	No significant change • Status quo on the performance	Dispersed efforts • Few coalitions exist but no main leader or trend	Parallel evolution	SMR (blue hydrogen)	Nuclear • Nuclear-based electrolysis = the alternative promoted
	10%					Coal gasification (blue hydrogen)	

Table 5
Electrolyser parameters' values adopted from the technological field in relation to the scenarios.

Parameters	Scenario A (2050)		Scenario B (2050)	
	AE	PEM	AE	PEM
Lifespan of the electrolysis plant	30 years	30 years	20 years	20 years
Lifespan of the stack	120,000 h	130,000 h	80,000 h	80,000 h
Plant capacity	1 GW	1 GW	100 MW	100 MW
Stack capacity (power)	20 MW	20 MW	5 MW	5 MW
Electrical consumption	47 $kWh_e/kg\ H_2$	50 $kWh_e/kg\ H_2$	50 $kWh_e/kg\ H_2$	50 $kWh_e/kg\ H_2$
Water consumption	9 $kg/kg\ H_2$	9 $kg/kg\ H_2$	10 $kg/kg\ H_2$	10 $kg/kg\ H_2$
Steel consumption	10 kg/kW	7 kg/kW	30 kg/kW	10 kg/kW
KOH consumption (AE)	1 $g/kg\ H_2$	NA	2 $g/kg\ H_2$	NA
Nickel consumption (AE)	0.2 kg/kW	NA	2 kg/kW	NA
Iridium load (PEM)	NA	0.01 g/kW	NA	0.7 g/kW
Nafion consumption (PEM)	NA	0.002 kg/kW	NA	0.016 kg/kW
Platinum load (PEM)	NA	0.01 g/kW	NA	0.3 g/kW
Titanium load (PEM)	NA	35 g/kW	NA	500 g/kW

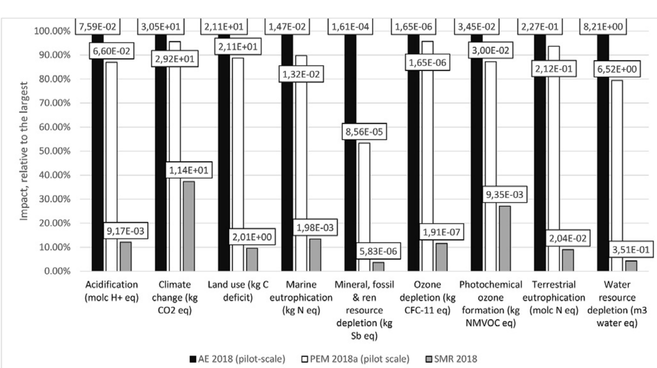

Fig. 2. Relative comparison of environmental impacts from the pilot-scale AE and PEM models, with the SMR alternative (ILCD 2011 family).

In this scenario, GW-scale plants for hydrogen production will have been built in different places in the Netherlands. The ex-ante large-scale LCA model for "Scenario A" considers the production of 1 kg oh H_2 from a 1 GW-scale plant, fed by electricity from wind turbines. It is also assumed that different hydrogen coalitions and clusters will have been built and that the Dutch government will have implemented the required measures to promote green hydrogen development, contributing to improving and optimising the different electrolyser technologies.

This scenario also assumes that an ambitious program would have been applied to make a shift towards 100% hydrogen transport in the gas network. For this, the Dutch law has been adjusted to allow the transport of hydrogen in the national pipeline infrastructure. The construction of the large offshore wind parks has enabled the increase of the capacity of centralised green hydrogen production with electrolysers. Therefore, electrolysis has become the most used technology for hydrogen production in the NL and large electrolysis plants will have been constructed at the GW-scale. In parallel, a decentralised and smaller scale of hydrogen production and transportation networks have been deployed. The latter has been implemented in more isolated regions, such as the countryside or islands.

All these developments will have resulted in a transport market penetration by hydrogen cars of 70%, by 2050. The remaining 30% of the Dutch transport fleet is mostly composed of oil-based cars or battery-based electric cars. For hydrogen production, the most important competitor to wind-based electrolysis is solar-based electrolysis, used on a lower scale. Solar- and wind-based electrolysis is used to supply energy in transports, industry, built environment, agriculture, etc.

3.3.2. Narrative for scenario B "without wind-based hydrogen"

"Scenario B″ was selected as a more pessimistic path for 2050 for green hydrogen development. In this scenario, none of the massive Dutch projects for hydrogen would have been successfully achieved and other technologies would have been promoted instead. Nevertheless, a few electrolysis plants will have been built with a capacity reaching 100 MW. Key elements of this scenario are shown in Table 4, while the ex-ante large-scale LCA model for "Scenario B″ considers the production of 1 kg of H_2 from a 100 MW-scale plant, fed by electricity from wind turbines.

This scenario assumes that the Dutch government will not have been convinced by hydrogen perspectives and will have supported other alternatives. Massive electrification will have occurred in different consumption sectors with large renewable energy systems installed (wind turbines and solar panels). A large implementation of battery-based electric cars will have occurred in the vehicle sector instead of hydrogen vehicles. The different offshore wind parks will have been constructed but will be used to feed the electricity grid.

When only electrolysers are considered, it is assumed that nuclear-based electrolysis is the largest competitor, as it avoids the intermittency problem and is especially useful as a backup system in case of a mismatch between supply and demand. Apart from this, when hydrogen is necessary for industrial processes, SMR and coal gasification remain the most used option, with Carbon Capture System to limit the environmental impact.

Due to the lack of political and industrial support, no significant technological improvement will have been achieved in electrolysers. Several green hydrogen projects have been implemented in a dispersed and decentralised way. As battery-electric vehicles will dominate, hydrogen cars will only have reached a market share of around 10%. Some hydrogen coalitions will still exist and try to promote green hydrogen technology, but no strong collaboration will have been established with leading stakeholders required for large-scale development and implementation.

In sum, due to a combination of various failures (from the tests, change in legislation, communication) the hydrogen option has been rejected in favour of electrification of the transport sectors and nuclear energy use for electrolysers for 2050.

3.4. Combination adopted and LCA

Qualitative visions are given with scenarios and quantitative data are provided in the technological field. To prepare phase 4, the qualitative scenarios must be combined with quantitative elements to conduct the ex-ante LCA. The "technological field" has been used in combination with scenarios and values for the technical evolutions have been selected in coherence for Scenario A and B. Table 5 shows the combination adopted for implementing the scenarios in the LCA software, with the ex-ante large-scale systems. Consistent with the narratives, in scenario A, the most optimal technical values were considered. In scenario B, the most pessimistic values were selected.

The parameters values from Table 5 have been implemented in the LCA models and results were analysed with the ILCD family in the next section.

3.5. Large scale LCA models

The large-scale LCA models are based on the pilot-scale LCA models. The maximum amount of details was kept but some irrelevant flows were deleted when shifting from the pilot-scale to the large-scale systems (see Supplementary Information). The values of the concerned flows were adjusted based on Table 5. The goals of the ex-ante large-scale LCA are the following:

1) The environmental impacts from the large-scale hydrogen production with AE or PEM electrolysers are studied in comparison with the pilot-scale models. The SMR is treated as the incumbent technology and used as a benchmark.
2) The environmental performances are compared between the two electrolysers' alternatives considered (PEM and AE), within a common scenario.
3) Contribution analyses from each electrolyser alternative (PEM and AE) are studied in order to understand the influence of each production steps.

Finally, these goals aim to provide relevant conclusions and recommendations concerning green hydrogen production based on electrolysers.

Fig. 3 shows the flowchart of the large-scale PEM and AE systems considered. The functional unit is the production of 1 kg of Hydrogen (the plant type varies depending on the scenario considered).

3.6. Present vs future and scenarios comparison

In Fig. 4, the environmental impacts of the pilot-scale and large-scale systems for AE and PEM electrolysers are compared, relatively with the maximum result for each impact category. The electricity for SMR and pilot-scale models come from the Dutch market, whereas ex-ante large-scale systems are fed with Dutch wind energy. For clarity, only the pilot-scale models from Wulf and Kaltschmitt (2018) and scenario A are shown.

A shift from electricity from the grid to electricity from wind turbines induces a large decrease in environmental impact for all impact categories (around 90% of decrease), except in "Mineral, fossil & renewable resource depletion". For the latter, the largest values from ex-ante large-scale systems come mostly from the lead consumption for the wind turbines. Another prominent result from Fig. 4 is that pilot-scale AE and PEM electrolysers perform worse than SMR in all impact categories with electricity coming from the grid. When electricity for electrolysers comes from the wind, SMR performs better than ex-ante large-scale AE and PEM models in "Water resource depletion" and "Mineral, fossil & renewable resource depletion". This result shows that the primacy of electrolysers over SMR depends on the impact category considered. Overall, from a sustainability perspective, operating a shift from electricity from the grid to electricity from wind energy would decrease significantly the environmental impact of hydrogen production.

A detailed comparison is made between ex-ante large-scale AE and PEM alternatives, for scenarios A and B. The environmental results are shown in Fig. 5, relatively with the maximum result for each impact category.

Comparing the electrolysers, the variations between the four alternatives are relatively low (<7%), except in "Ozone depletion" in Scenario A, where AE possesses a larger environmental impact of 43.8% compared to PEM, mostly due to polytetrafluoroethylene consumption.

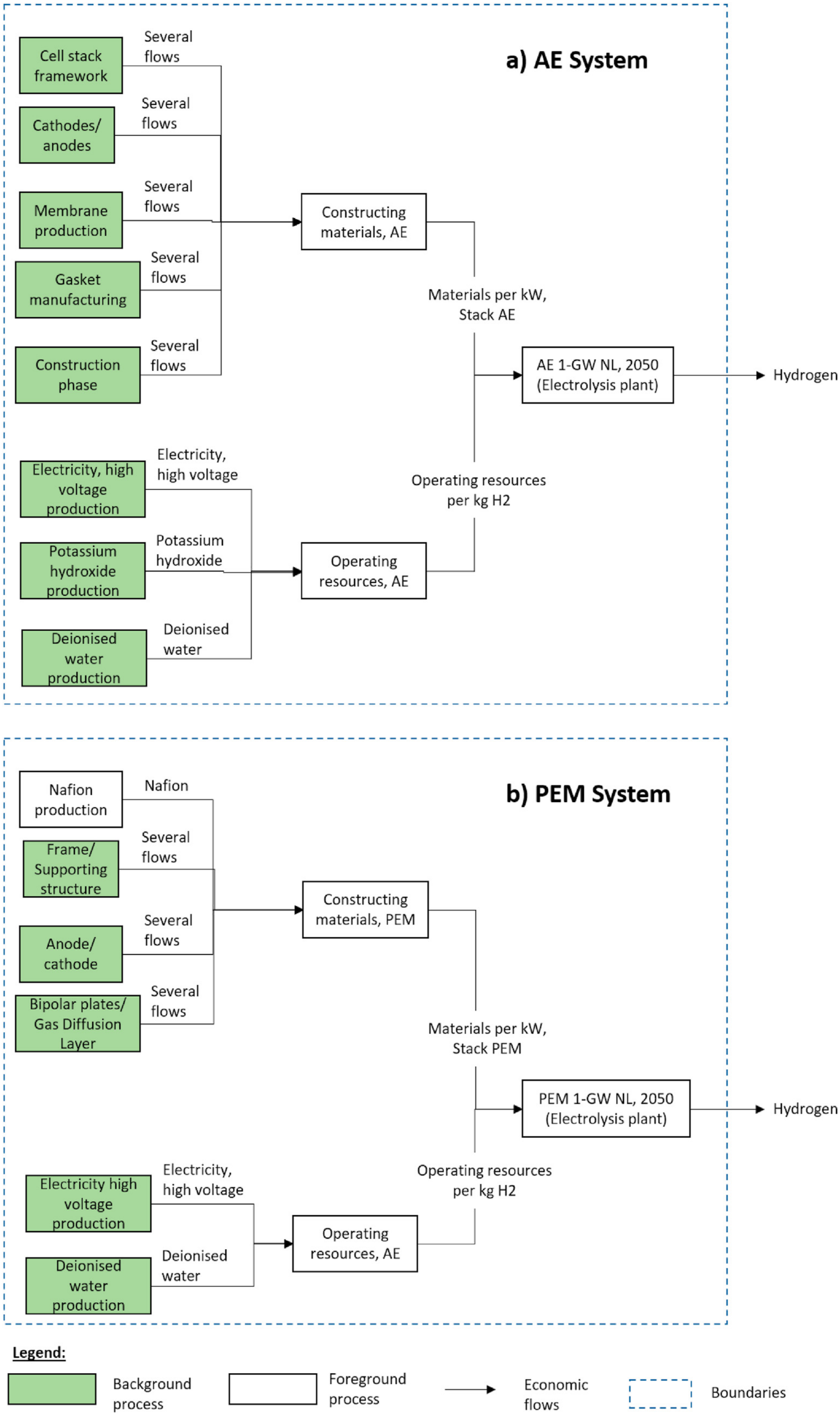

Fig. 3. Flowchart for the ex-ante large-scale LCA model of the AE (a) and PEM (b) electrolysers.

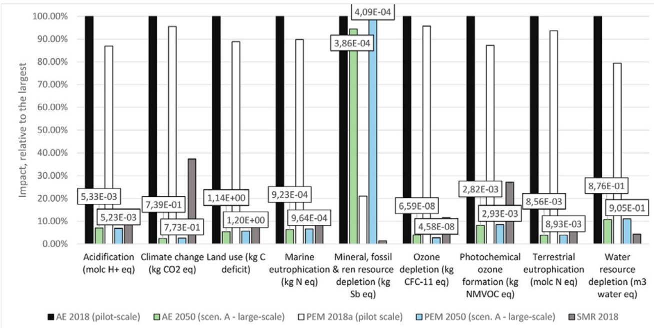

Fig. 4. Relative comparison of environmental impacts from the pilot-scale and ex-ante large-scale AE and PEM models, with the SMR alternative (ILCD 2011 family) (remaining absolute values can be found in Fig. 2).

Comparing scenarios, Scenario A provides lower (<6%) or equivalent environmental performances than Scenario B, showing the interest of upscaling. Only the impact category "Ozone depletion" shows scenario A performing worse than Scenario B (+39.5% for AE and +2.3% for PEM). This difference is mainly explained with the plant construction emissions and is connected to the scale considered (1 GW for Scenario A, 100 MW for Scenario B).

Overall, in scenario A, the PEM alternative has larger environmental impacts than AE for all impact categories, except for "Acidification" and "Ozone depletion", even though the differences are non-significant. In scenario B, the opposite situation appears (PEM performs better than AE) with no exception on impact categories. These results show the importance of the scale considered and may suggest that AE systems could benefit slightly more from upscaling effects than PEM electrolysers.

3.7. Contribution analysis

Contribution analyses were conducted for ex-ante large-scale AE (Fig. 6) and PEM (Fig. 7) alternatives, in scenario A, to show how the different unit processes contribute to the environmental performances.

In both alternatives, the electricity production from wind turbines remains by far the largest contributor to environmental results, with values ranging from 84 to 98%. Within the electricity production from wind turbines, the major process contributors are the glass fibre reinforced plastic production and steel and concrete needed for the wind turbines' construction. One noticeable exception is found with the impact category "Ozone depletion" for AE where the market for tetrafluoroethylene (used for gasket manufacturing) accounts for 37.3% of the environmental performance. The market for water shows some influences (5–8%) for AE and PEM in "Ozone depletion" and the market for nickel influences the "Acidification" for AE at 6%. Otherwise, the constructing materials and the electrolyser materials show low influences. The use phase is then the most important aspect to consider for environmental performances.

4. Discussion

With a combination of ex-ante LCA with scenarios from GMA, we highlighted some upscaling aspects of electrolysers' technologies. The ex-ante LCA models show that, overall, large-scale AE and PEM systems lead to very similar results. The main contributor to their environmental performances is the production of electricity that is sent to the electrolyser, during the use-phase.

Several criticisms can be raised, such as the data's age, its consistency or completeness. In order to limit these criticisms, the most recent sources, technology analyses and scenarios were used to conduct the LCA as consistently as possible.

Despite the paper's limitations, our results are in line with the available literature on the systems assessed. For instance, Koj et al. (2017) assessed the environmental impacts of alkaline-based hydrogen production with the same impact assessment family as in this paper (ILCD 2011). For all impact categories, Koj et al. (2017) found environmental performances of the electrolysers 10 times lower than in the models in this paper. A possible explanation for the difference is the geographical context considered by Koj et al. (2017), namely Spain, Germany and Austria. Also, Bareiβ et al. (2019) evaluated the evolution of PEM electrolysers in the future and claimed that electricity production is responsible for a considerably larger share of impacts in comparison to the influence of the electrolyser itself, which is confirmed in this paper. (Biswas et al., 2013) also highlighted the influence of the electricity origin in AE electrolyser environmental profile.

This paper has applied a step-by-step methodology using a combination of LCA with technology analysis and scenario development, which, to the best of our knowledge, has not yet been reported in the literature, using both scenarios and detailing the

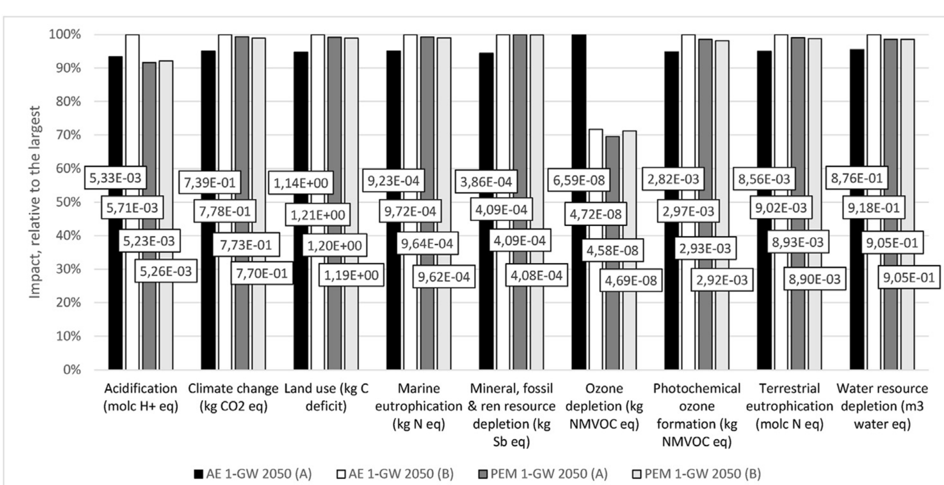

Fig. 5. Relative comparison of environmental impacts from the ex-ante large-scale AE and PEM models, with the 2 scenarios (A & B) (ILCD 2011 family).

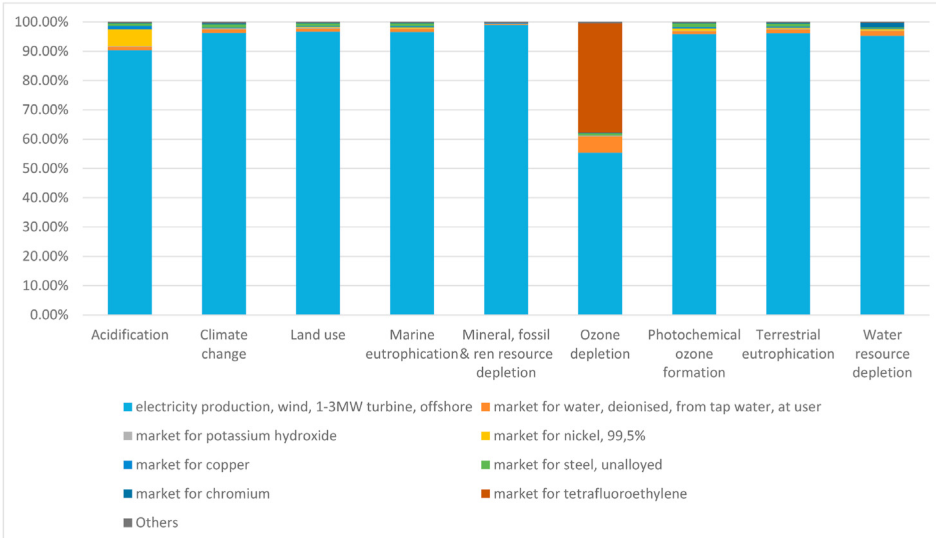

Fig. 6. Contribution analysis AE 1-GW 2050 (“Scenario A”) (ILCD 2011 baseline).

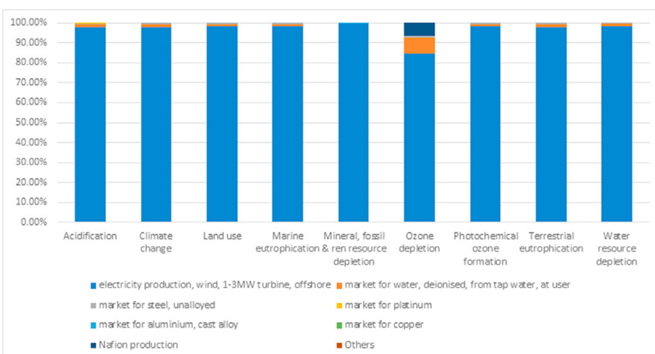

Fig. 7. Contribution analysis PEM 1-GW 2050 (“Scenario A”) (ILCD 2011 baseline).

evolution of technological parameters. This approach could be extended to any comparison between a quantified system analysis tool and scenarios and could consist of the following phases.

Phase 1: Construction of a baseline model with the quantitative environmental tool. This analysis provides a state-of-the-art of the current situation.
Phase 2: Technology analysis is conducted using several methods to identify the basic elements for constructing scenarios and making quantitative estimates taking into account future improvements of the technology.
Phase 3: Based on the inputs from the first two phases, the scenarios for the future can be developed, for which different scenario methods can be used.
Phase 4: The scenarios constructed are converted into quantified inputs in the quantitative environmental tool. Comparisons can then be made on the system performances between the present and future cases.

Furthermore, the GMA methodology for exploratory scenario development considers general trends and societal aspects, whereas the LCA methodology evaluates specific elements and detailed systems. To combine these two perspectives, this paper used a specific methodological tool, named the “technological field”, which was used to indicate the potential evolution of the electrolysers. In this way, the results of the study provided a detailed comparison of environmental performances from hydrogen production, at present pilot-scale and future large-scale. The results enabled us to conduct deep analyses, to fulfil a knowledge gap and to support different recommendations, such as a focus on the electricity’s origin impact.

Further development of the proposed methodology is recommended. Other scenario methods than GMA are available and can provide additional insights on the future visions, while the Delphi method can be used for expert consultation (Höjer et al., 2008). The study of the transition processes to reach the futures envisioned (e.g. backcasting, see Quist, 2013) is another example that allows for further methodological development. Adding economic perspectives may also be valuable (e.g. Cost-Benefit Analysis or lifecycle costing).

It can be mentioned that other types of electrolysers exist, but the focus was put on AE and PEM technologies, currently the two most common alternatives. For instance, anion exchange membrane (AEM) also possesses strong potentials but is still under lab studies and faces different design challenges (Vincent and Bessarabov, 2018). Due to the limited availability of data AEM was not included in the current study. Moreover, the SMR environmental performances could also be analysed in further studies as Wismann et al. (2019) indicate that only 17–41% of CO_2 emissions come from hydrocarbon combustion, while the rest could be supplied with renewable-based resources. Another option would be to consider SMR with a Carbon Capture System that could decrease by 60% the CO_2-emissions (Nazir et al., 2020). In the context of a transition phase where SMR would be needed, efforts to reduce its environmental impacts would be useful.

More generally, the modelling in our study was restrained to a topic where hydrogen could be quite significantly used, namely in transport, following from literature study and expert consultation. However, other applications can be considered too, such as in various industries. The perspective of cars using hydrogen can also be challenged, as in the future of vehicles could possibly consume synthetic hydrocarbons (methanol, kerosene …) made from CO_2 and renewable H_2, biofuels or electricity. These options were out of the scope of this paper but would deserve further comparisons. Another assumption made in the scenarios concerns hydrogen transport where we assumed a completely new transportation network is massively used. However, an interviewed expert suggested that the "conversion" of the gas network for hydrogen transportation may be more feasible as it provides a "business-as-usual" scenario building on the existing natural gas distribution infrastructure in the Netherlands.

The geographical dependency may also have influences on some electrolysers' parameters. For example, if electrolysers are to be deployed in desert countries – such as Arabic countries, Saharan regions or Australia – water consumption can become a more critical factor than in the Netherlands. These regions possess a lot of potential for solar-based electrolysis but also water resource scarcities. It could be noted that the consumption of noble metals for the PEM electrolysers does not seem to possess a significant environmental impact but could raise further geopolitical tensions or investment costs regarding resource criticality.

Finally, focusing on one country-level enables to highlight the potential benefit of energy independence, local job creations and optimal use of national resources. However, the geographical scope of the study could also be extended and consider possibilities for cross-border collaborations between neighbouring countries, as mentioned in the "2 × 40 GW" Initiative. This perspective would add further stakeholders' analysis at a State-level. Due to the limited resources of the paper, such a "cross-border" scale could not have been applied but the topic could lead to further research.

5. Conclusion and recommendations

In this paper, an ex-ante LCA was combined with scenario development and technology analysis enabling an extended comparison between pilot-scale and large-scale electrolysers. With a strong focus on the electrolyser potential evolution, we have shown that large-scale AE and PEM systems possess virtually the same environmental impacts, with minor differences (apart from "Ozone depletion"). The contribution analyses indicated that the origin of electricity remains the largest contributor to environmental performances, even when renewable energy sources are considered. The electrolysers themselves possess only limited environmental influence within the scope considered in the paper. Nevertheless, hydrogen production from electrolysis shows globally environmental benefits compared to SMR. Other criteria, such as economic or political context could be assessed in further researches.

One major challenges was to combine an ex-ante LCA, a quantitative tool, with GMA scenarios, a qualitative tool. To combine these two elements, a technological field has been created (see Table 2), summarising parameters' evolutions which can be selected depending on the future considered. To the best of our knowledge, this kind of bridging element has not yet been commonly defined and used in ex-ante LCA and this paper seeks to provide an example and potential guidance in this direction. This type of tool, combined with LCA, would provide some significant flexibility and enable the exploration of a wide range of scenarios, based on different parameters selection.

Some recommendations can be extracted. Firstly, a focus should be put on renewable energy systems in further research to see how their environmental impacts can be even more decreased. Typically, an ex-ante LCA, similar to the study, which assesses the technical evolution of wind technology or solar modules with better environmental performances would be relevant. Secondly, the combination of LCA and scenario tools should be more implemented with emerging alternatives or other products that are planned to be implemented on a large-scale. By doing so, a consistent framework can be developed. Thirdly, some deeper research would be recommended regarding the problem of the water consumption from electrolysers and/or the noble metals consumption of PEM systems. The last point should consider probably more geopolitical perspectives with critical raw materials problematics. Fourthly, more studies would be necessary to explore the potential and technical feasibility of converting the existing gas infrastructure for hydrogen use. Fifthly, an aspect that has not been dealt with in this paper is the recycling technologies, especially concerning the electrolysers, where there is a lack of data. The results from HyTechCycling, a European project can provide the basis for more extended research (HyTechCycling, 2016). Finally, the social dimension is lacking in this study and could be explored with, for example, social LCA. The benefits of a hydrogen economy regarding energy independence, local job creation, and increased awareness of environmental responsibility are some factors that could then be assessed.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Mathieu Delpierre: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing. **Jaco Quist:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **Jan Mertens:** Validation, Resources, Data curation, Writing – review & editing. **Anne Prieur-Vernat:** Validation, Data curation, Resources, Data resources, Technical feedback. **Stefano Cucurachi:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision.

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.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors would like to thank the interviewees for their granted time to discuss hydrogen futures. The authors thank all the members at ENGIE France (lab CRIGEN) who kindly helped in developing LCA models.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126866.

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