An ex-ante LCA study on wind-based hydrogen production in the Netherlands

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Executive summary

Life Cycle Analysis (LCA) is a common tool used to assess the environmental impacts, in several categories, of a product or service over its entire lifespan. However, most of the time, LCAs are conducted on existing products with comparative perspectives. When the results recommend some change, the latter are generally hard to apply in practice. That is why, for a few years, more research has been conducted in order to apply LCAs on emerging technologies. In this sense, LCAs seek to model the potential environmental impacts of the system in the future, when the technology is implemented on a large-scale for example. The outcomes of these "prospective" LCAs would enable to guide the technology evolution and avoid potential mistakes.

Naturally, making models about future states of the technologies imply a large amount of uncertainties due to predictions and assumptions. The use of scenarios for future developments of the technology under study appears as a logical tool to limit this issue. As a matter of fact, scenarios can help to structure the future visions and the potential developments of an emerging technology. Then, the potential environmental impacts of the technology under study can be modelled within the boundaries of a scenario. Naturally, other uncertainties methodologies exist as well but the scenarios remain a communicative tool that provide rather clear contexts. Connections with broader topics such as societal trends or economies can be made then. Despite the interests in combining LCAs with scenarios, no clear standardised methodology exists for it so far.

In this Master thesis, a framework combining LCAs and scenarios has been developed and applied on a particular function: the production of sustainable hydrogen in the Netherlands. The General Morphological Approach (GMA) has been used for the construction of the scenarios. A focus was put on the electrolysis technology which is considered for now as the most sustainable way for producing hydrogen. In more details, two electrolysers alternatives have been considered, both fed with wind energy: the alkaline and PEM electrolysers. Both of these technologies are based on the same principle: water is split with electricity into oxygen and hydrogen. To produce green hydrogen, the electricity comes from wind energy, the largest renewable energy source potential in the NL. Both electrolysers are currently at a pilot-scale for hydrogen production and are the most promising options for a large-scale production of sustainable hydrogen. The presence of massive projects in the Netherlands to promote a hydrogen economy by 2050 reinforces the necessity to understand, in advance, the potential environmental impacts from both electrolysers. As a consequence, the following research questions were studied in the thesis:

<u>Main Research Question:</u>

What are the environmental impacts for a large-scale hydrogen fuel production from wind-based electrolysis in the Netherlands and the options to improve them?

<u>Sub-questions:</u>

1) *What are the environmental profiles of the two electrolysers' alternatives (pilot-scale)?*
2) *Which parameters are the most relevant for the transition from a pilot-scale to a large-scale perspective?*
3) *What are possible scenarios for a large-scale production of sustainable hydrogen in the Netherlands?*
4) *How will the environmental profiles evolve between the pilot-scale (current situation) and the large-scale implementation (scenario situation)?*

The structure of the thesis can be divided into 5 phases.

- The first phase consists in constructing baseline/pilot-scale LCA models, based on literature review, desk research or contacts with experts. These pilot-scale LCA models are based on existing studies or systems (pilot or lab-scale). The outcomes of these LCAs provide an overview of the current situation and indications on the potential parameters to consider during upscaling processes.
- The second phase consists of technology's analyses. Different kind of activities was conducted during the Master thesis work: participation to a workshop, interviews and contacts with stakeholders from different backgrounds (scientific, political…), collaboration with a scientific company, desk research and report studies. These technology analyses provide inputs for the construction of scenarios and enable a better understanding of the technology under study and its potential development. The list of the relevant parameters found in the first phase can be adjusted as well based on these inputs.
- The third phase consists of the construction of the scenarios. The GMA approach was adopted to structure the construction with a "morphological field". The latter enables to develop visions and narratives for the state of the technology in 2050. Then, these scenarios were quantified as LCA inputs. For this, a new element, the "technological field", was specifically developed for the thesis' needs and is not normally a part of the GMA methodology. The "technological field" enables to connect the scenarios created with the GMA and the technological LCAs.
- The fourth phase consists of creating the ex-ante large-scale LCA models, with the help of scenarios, where the electrolysers are implanted massively in the future. Different sensitivity, comparison and uncertainty analyses can be made, depending on the scenario considered. The software used (OpenLCA) enables some flexibility to adjust some parameters' values and then evaluate how the latter can influence the environmental profiles. The outcomes of these prospective LCAs are to give recommendations or interpretations on the potential evolution of electrolysers.
- The fifth phase consists of a critical reflection of the previous steps. All possible interpretations and recommendations must be wisely considered with recontextualization, with perspective and the uncertainties acknowledged. This phase is even more necessary than with "traditional" LCAs as prospective studies are conducted.

The framework used in the thesis enabled an innovative approach to combine GMA and LCA, with the creation of some specific elements, such as the "technological field". A combination of a quantitative environmental tool (LCA) with scenarios (GMA) provides new insights and enables to study future evolutions in a structured way. Some lacks and weaknesses are still present but can be fixed with more investments and additional studies.

The works achieved in the thesis showed that feeding electrolysers (PEM and alkaline) with renewable energy source instead of electricity from the grid decreases significantly the environmental impacts. A shift towards renewable energy sources makes then sense from a sustainability perspective. Furthermore, when renewable energy sources are considered, alkaline electrolysers, globally, possess lower environmental impact than PEM to produce hydrogen, even though the two alternatives possess virtually the same environmental performances. Monte-Carlo projections showed that the relative differences between PEM and alkaline electrolysers are non-significant.

The origin of electricity for operation (wind energy in the thesis) remains the largest contributor to environmental impacts and a focus should be put on it in further research. On the contrary, the electrolyser system itself possesses only a negligible influence, despite its potential technological evolution. Some lacks in modelling are still pointed out during the thesis, such as the Nafion membrane

used for PEM electrolysers, the recycling technologies for rare metals or the water consumption which can become a sensitive topic.

From a methodological perspective, more research could be made on the technology analyses to conduct and combine with LCAs. Moreover, more scenarios could be elaborated after the three main ones developed in the thesis. The transitional aspects should also be more discussed as the thesis considered final states and not the transition process itself. Concerning LCAs, several background processes were used from ecoinvent, such as electricity production, and may require some deeper research to update them in a future state.

Overall, a combination of LCA and GMA methodologies has been applied in the thesis to assess the environmental performances for two electrolysers in 2050, for green hydrogen production. Using renewable energy source decreases significantly the environmental impacts but the electricity production will likely remain the biggest contributor. The electrolysers are unlikely to influence significantly the environmental profile of green hydrogen production. A focus should be put primarily on electricity’s production.

Keywords: hydrogen, electrolysis, PEM, alkaline, ex-ante LCA, GMA, cars

Summary table

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List of abbreviations

AE	Alkaline Electrolyser
AEM	Anion exchange membrane
BAU	Business as Usual
BPP	Bipolar plates
BoP	Balance of the plant
CAPEX	Capital Expenditure
CCA	Cross-Consistency Assessment
CCM	Catalyst-coasted membrane
CCS	Carbon Capture System
CL	Catalyst layer
ECN	Energy Research Centre of the Netherlands
EoL	End-Of-Life
FCEV	Fuel Cell Electric Vehicle
GMA	General Morphological Analysis
HER	Hydrogen Evolution Reaction
HHV	Higher Heating Value
ILCD	International Reference Life Cycle Data System
Ir	Iridium
IX	Ion-exchanger
KOH	Potassium hydroxide
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating value
MC	Monte Carlo
MEA	Membrane Electrode assembly
MEM	Membrane
NHST	Null Hypothesis Significance Testing
NL	Netherlands

OEM	Original Equipment Manufacturer
OER	Oxygen Evolution Reaction
Pd	Palladium
PEM	Proton Exchange Membrane
Pt	Platinum
PTFE	Polytetrafluoroethylene
PTL	Porous Transport Layer
PVC	PolyVinyl Chloride
R&D	Research and Development
SMR	Steam Methane Reforming
SOE	Solid Oxide Electrolysis
TA	Technology Assessment
Ti	Titanium
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
SDE+	Stimulering Duurzame Energieproductie
SSI	Semi-Structured Interview
SWOT	Strengths, Weaknesses, Opportunities and Threats

1) Introduction

1.1) Problem definition

The goal as defined in the Paris Agreement to limit global warming to 2°C embodies the urgent need to tackle sustainability issues (UNFCCC, 2015). One of the largest actions that must be taken is to massively decarbonize several energy-consuming sectors. Some of these sectors, such as transports, are highly dependent on fossil fuels. Nowadays, gasoline and diesel account for 96% of the total fuel consumption and are responsible for 21% of the total carbon emissions (Hydrogen Council, 2017; IPCC, 2014). Finding new solutions to improve the situation and enhance its sustainability is then even more challenging. Nevertheless, new alternatives have appeared for a few decades, such as hydrogen fuels (Ball & Wietschel, 2009).

Hydrogen possesses several advantages such as a higher energy density (120 MJ/kg) than gasoline (44 MJ/kg), making it interesting for fuel use (Acar & Dincer, 2014). Furthermore, hydrogen can be produced from renewable energy resources and its combustion releases heat and water, so there are no carbon emissions. Finally, hydrogen has a strong potential to increase the autonomy from fossil fuels resources (Acar & Dincer, 2014; Ball & Wietschel, 2009). However, hydrogen cannot be found in nature and needs to be produced. Currently, around 96% of hydrogen's production in the world is based on fossil fuels (Ball & Wietschel, 2009, p.279). Different methods exist such as coal gasification, partial oxidation but the Steam Methane Reforming (or Reformation) (SMR) remains the most used technology to produce hydrogen and accounts for ca. 50% of worldwide production (Ball & Wietschel, 2009). SMR is the cheapest technology for producing hydrogen but produces also several problematic environmental emissions such as carbon dioxide (Gielen & Simbolotti, 2005; Singh et al., 2015). On average, the production of 1 ton of hydrogen from fossil fuels induces 10 tons of CO_2 emissions (Hydrogenics, 2018a). Consequently, a paradigm shift in the hydrogen production approach is necessary for more sustainability. Some studies have already compared different ways of producing hydrogen and concluded that water electrolysis combined with renewable energy sources offer the most promising environmental performances (Acar & Dincer, 2014).

In this perspective, in the Netherlands, two main types of electrolysers[1] offer the biggest potentials for the future: the alkaline (AE) and PEM electrolysers. The wind energy also possesses large power capacities and would be an important renewable energy source to develop sustainable societies. Nevertheless, this type of electrolysis based on wind energy is still at a pilot scale and requires larger implementations (Nikolaidis & Poullikkas, 2017). Before doing so, it is relevant to assess and compare the environmental performance of these two electrolysers (alkaline and PEM) on a large scale, in order to ensure that wind-based electrolysis does contribute to a more sustainable society.

1.2) Research questions

A knowledge gap has been found with the need for a prospective environmental assessment on large-scale production of hydrogen fuel, with a special focus on the electrolysers. Therefore, the main Research Question will be:

What are the environmental impacts for a large-scale hydrogen fuel production from wind-based electrolysis in the Netherlands and the options to improve them?

[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

The main Research Question is subdivided into the corresponding sub-questions along the thesis:

5) *What are the environmental profiles of the two electrolysers' alternatives (pilot-scale)?*
6) *Which parameters are the most relevant for the transition from a pilot-scale to a large-scale perspective?*
7) *What are possible scenarios for a large-scale production of sustainable hydrogen in the Netherlands?*
8) *How will the environmental profiles evolve between the pilot-scale (current situation) and the large-scale implementation (scenario situation)?*

1.3) Problem approach

To answer the main Research Question and the sub-questions, the thesis will combine modelling and qualitative approaches. The modelling approach is used to evaluate the environmental impacts from the electrolysers with the different steps being based on the framework from Cucurachi et al. (2018). The qualitative approach enabled to construct scenarios for 2050.

Modelling approach:

Through the years, several tools were developed to conduct environmental assessments such as Life Cycle Assessment (LCA). Its methodology provides a framework which compiles and evaluates the inputs, outputs and the potential environmental impacts of a product through its whole lifecycle (Guinée, 2002).

An ex-ante (prospective) LCA approach is useful to solve sustainability issues at the very early stage of a process. This approach has the significant advantage to adopt an anticipatory perspective and not a retrospective one when the technology (and its potential problems) has already been implemented. By doing so, the prospective LCA can promote responsible innovation for emerging technologies (Wender, 2016). An ex-ante LCA is then particularly suitable to assess the environmental impacts of producing hydrogen on a large scale from Dutch wind turbines. Several types of ex-ante LCAs were distinguished by Cucurachi et al. (2018):

- *Prospective*: the study is about future potential technologies and their impacts
- *Consequential*: this type considers the effects of a change in the technology landscape (e.g. introduction of a new technology or a change in policies)
- *Dynamic*: the study highlights the importance of the temporal aspect in the technology developments and the emissions related
- *Anticipatory*: the study focuses on the decision aspects to integrate the values of decision-makers
- *Mixed*: the study combines several aspects of the previous types described above.

The thesis focuses on the future state and use of the electrolyser's technologies and is, therefore, a "prospective" type. The ex-ante LCA on electrolysers will consider a cradle-to-gate approach, from the production of electricity from wind turbines to the hydrogen gas ready to be distributed in a network. By conducting an ex-ante LCA analysis, the hotspots for hydrogen's technology can be found and therefore mistakes can be avoided during the upscaling process. A hotspot is defined in this thesis as a sensitive factor/element from a system that can possess a high influence on environmental impacts. Nevertheless, the ex-ante perspective remains challenging because of the lack of data or the relatively high degree of uncertainties inherently linked with future visions.

Qualitative approach:

In order to describe a future where the technology under study works at full operational scale, Cucurachi et al. (2018) recommend using scenarios. A scenario perspective is applied to upscale the technology under study with the General Morphological Analysis (GMA). This methodology enables to structure the development of scenarios through a 'morphological field'. A 'technological field' is also created to strengthen connections between the scenario's narratives and the quantified LCA models. To support the construction of the two 'fields', some technology analyses were made. Technology analyses are defined in the thesis as all the processes which contributed to understanding different perspectives connected to the technology under study and helped to assess its potential impacts on society and the environment. Technology analyses were achieved through interviews, a collaboration with a company, a workshop and a literature review.

In the end, each scenario developed with GMA will represent a possible future state and can be a strategy to deal with the data uncertainties by providing desirables situations. The scenarios will be implemented in the ex-ante large-scale LCA models. Comparisons between alkaline and PEM electrolysers in the ex-ante large-scale LCA models and pilot-scale LCA models will be made. Some uncertainty analyses (Monte-Carlo projections and sensitivity analyses) will be conducted to keep a critical mind on the results. In this way, informed conclusions can be drawn.

Overall, a combination of ex-ante LCA, General Morphological Analysis and some technology analyses are applied in the thesis. A summary of the problem approach is provided for each sub-question below.

Sub-question 1: An LCA model for alkaline and PEM technologies is developed, based on a literature review and on the current knowledge.

Sub-question 2: Based on the results from sub-question 1 and some technology analyses, the most relevant technological parameters are considered for the technology's upscaling.

Sub-question 3: Based on the inputs from sub-questions 1 and 2, the most relevant scenarios for the thesis are generated with the GMA approach.

Sub-question 4: Implementing the future scenarios in LCAs enable to achieve the ex-ante analysis and to draw interpretations.

The general goal of the thesis is to critically evaluate the environmental impacts of a potential energy solution and its large-scale implementation. The aim here is not to predict the future but rather to study certain variables to build a sustainable society.

1.4) Outline of the thesis

The next chapter narrows the problem and describes the electrolyser's system in details and the methodology used through a literature review. The pilot-scale LCA models are developed based on the state-of-the-art of the technology in Chapter 3. Scenarios for the future are developed and described in Chapter 4. The hotspots identified for the upscaling processes are combined with the scenarios for implementation in LCA models in Chapter 5. An ex-ante large-scale LCA on hydrogen's production in the Netherlands, from wind-based electrolysis, is conducted in Chapter 6. Discussions and potential improvements on the thesis' work are elaborated in Chapter 7. The final conclusions and recommendations are indicated in Chapter 8.

2) Methodology and literature overview

2.1) Setting the context

First, the different elements that are studied are clearly defined and the reasons to consider them specifically are provided.

2.1.1) The use of hydrogen as a fuel

Despite the large potential from hydrogen's production from an environmental and economic perspective, different papers highlight that this technology is still considered as emerging (Acar & Dincer, 2014; Singh et al., 2015). Some studies expressed the potential of hydrogen technology in transport saying that "it is primarily as an alternative fuel in the transport sector that hydrogen will find its way into the energy system", mainly because of that state-of-the-art of the technology and the political goals set (Ball & Weeda, 2015, p.7917). Ball & Wietschel also consider that hydrogen will likely replace "oil-based fuels in the transport sector" (Ball & Wietschel, 2009, p.638). One of the biggest challenges and key drivers for hydrogen fuel technology is the development of an infrastructure for production (Ball & Wietschel, 2009; Dincer & Acar, 2017). This challenge is usually referred to as the "chicken-and-egg" dilemma. As explained by Ball & Wietschel (2009) for the automobile industry, the question is which actor will first take the move for a large-scale implementation: the customers by buying hydrogen cars and increasing the demand or the stakeholders responsible for the infrastructure availability (supply)? In this perspective, the existence of a dense gas network in the Netherlands can be part of the solution and provide potentials for hydrogen fuel use, as explained later.

2.1.2) Renewable hydrogen's production in the Netherlands

As the Netherlands aims to be natural gas-free before 2050, hydrogen can be an interesting alternative as an energy carrier. The current production of hydrogen depends almost exclusively on fossil resources. In this section, the different production possibilities based on renewable energy sources will be reviewed in order to select the most relevant one for the Dutch situation. Fossil fuel-based hydrogen's production possesses obvious problems mentioned in the introduction. As recalled by Ball & Wietschel, "renewable hydrogen is […] the ultimate vision" (Ball & Wietschel, 2009, p.628). In this perspective, an option remains water electrolysis where an electrolyser splits the water with electricity into oxygen and hydrogen but it accounts only for 4% of the ca. 60,000 kt produced worldwide (see **Figure 1**) (Ball & Weeda, 2015; Bhandari, Trudewind, & Zapp, 2014; Gielen & Simbolotti, 2005). Furthermore, Biswas, Thompson, & Islam (2013) highlighted the influence of the electricity origin in the electrolyser's environmental profile. These authors considered wind-based electrolysis which led to a decrease up to 99% of global warming and eutrophication impacts, in comparison with the scenario where the electricity came from the grid. Electricity from the grid results from a mix of different production's technologies, most of the times dominated by fossil-fuels based system. In the case of the Netherlands, the electricity production mix is dominated by natural gas and hard coal processes (Treyer & Ruiz, 2014). Consequently, the composition of the electricity mix can be a highly influential factor in the environmental profile of a technology. Combining electrolysers with renewable energy sources can be relevant in two ways. Firstly, the use of renewable energy sources would decrease the system's environmental emissions. Secondly, the electrolysers cope efficiently with load shifts, so they offer advantages when it comes to deal with intermittent supply. Overall, reviews indicate that wind energy is the most sustainable way to produce hydrogen (Bareiß, de la Rua, Möckl, & Hamacher, 2019; Bhandari et al., 2014; Bockris, 2013; Ghandehariun & Kumar, 2016; Hussain & Dincer, 2005; Koroneos, Dompros, Roumbas, & Moussiopoulos, 2014; Patterson et al., 2014; Wulf & Kaltschmitt, 2018).

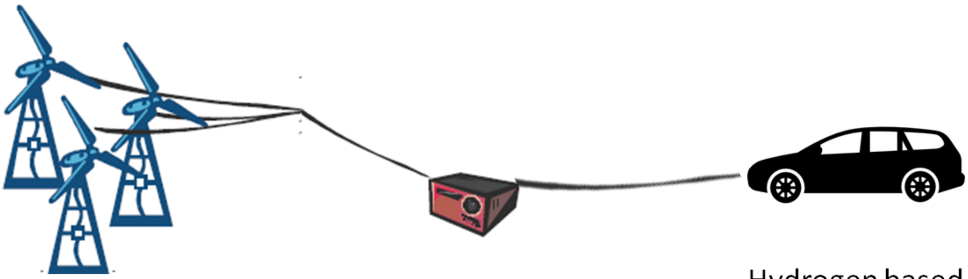


Figure 1: Principle of sustainable hydrogen fuel production for transportation from wind turbines (adapted from Spath & Mann, 2004)

However, Dincer & Acar (2017) promoted geothermal and biomass technologies. Geothermal energy use requires the presence of natural potential, and biomass can be considered as the only sustainable source for carbon, thus there can be conflicts with other usages. As biomass can be a source for heat, power generation and biofuels, competitions for use can rise (Ball & Wietschel, 2009). Therefore, geothermal and biomass technologies will not be considered further. Furthermore, Acar & Dincer (2014) promoted nuclear energy-based production for hydrogen. Here again, there is an implied requirement to possess a nuclear plant and the technology involves other issues (nuclear waste, etc…). In this perspective, the Netherlands possesses only one commercial nuclear reactor in Borssele.

Solar energy can be an interesting alternative but suffers from serious reductions in panels' efficiency through time (Gahleitner, 2013). Furthermore, in the case of the Netherlands (NL), van Wijk (2017) predicts that wind turbine will provide 4,000 MW for the Northern Netherlands Hydrogen Economy. Solar energy will provide "only" 2,000 MW and in a more decentralised way than what could be expected with wind power. ECN/TNO also presented wind energy as an opportunity from the Netherlands to develop green hydrogen economy (see **Erreur ! Source du renvoi introuvable.**). Moreover, the Global Wind Atlas gives an average of the wind power density in the NL of 400 W/m² (with offshore density up to 900 W/m²) (World Bank Group, ESMAP, DTU, & Vortex, 2018). The Global Solar Atlas shows that the NL possesses a global horizontal irradiance of around 1050 kWh/(m².year) equivalent to 119.78 W/m² (ESMAP & Solargis, 2016). These figures clearly show that wind energy possesses a stronger potential in the NL in comparison to solar energy. Thus, it can be deduced that wind provides the most promising perspective for hydrogen production with relatively high efficiency and with the least harmful emissions possible.

2.1.3) The need for upscaling the hydrogen's technology

Many pilot installations for hydrogen production already exist, but only a few are connected to the grid and a large-scale project has yet to be implemented (Gahleitner, 2013).

However, according to the Noordelijke Innovation Board (van Wijk, 2017) and Bockris (2013), only a large-scale production will make the technology economically viable (2 to 5 €/kg of H_2). Van Wijk, van der Roest & Boere (2017) claim that the only way for the Netherlands to produce hydrogen on a large scale is through water electrolysis. Dincer & Acar stated in their paper that: "There is now a strong need to work on scaling up these studies for large-scale applications [since] scaling up can reduce unit costs of production, delivery, and storage of H2" (Dincer & Acar, 2017, p.14850). In the transport sector, at the pilot scale, the hydrogen technology for cars is ready to be used (Ball & Weeda, 2015; Dincer & Acar, 2017). The next necessary step is to reach commercialization scale (or large-scale) through major societal changes such as political support, public acceptance, legislation adjustment and network construction. Better collaboration between the main stakeholders (producers, distributors, suppliers, consumers, politicians and others) is also required (Ball & Weeda, 2015; Dincer & Acar, 2017; Thomas, Mertens et al., 2016).

Consequently, conducting an environmental assessment, such as an LCA, on large-scale wind-based electrolysis makes sense when considering the need for upscaling trends. Unfortunately, Burkhardt, Patyk, Tanguy, & Retzke (2016) recall that one of the main issues concerning LCA studies on hydrogen produced from wind is the lack of primary data. Also, they recommend conducting further research on larger plant sizes. Similarly, Patterson et al. (2014) recommended conducting further research on large-scale hydrogen production from wind farms (on- and offshore).

The potential hotspots and environmental impacts which can vary in the upscaling process must be wisely managed. An ex-ante LCA is adapted for this task since it aims to analyse and study the potential impacts of an emerging technology in a future state, usually implying a change in use's scale (Cucurachi et al., 2018).

2.1.4) The electrolyser issue

Conducting an ex-ante LCA on large-scale production of sustainable hydrogen is necessary, especially since the production from wind electrolysis is "the least used renewable energy-based systems" (Bhandari et al., 2014, p.151) despite its sustainability potential. The LCA from Spath & Mann (2004) already considered hydrogen output from wind turbines and concluded that the majority of environmental emissions from hydrogen's production came from the production stage. They claimed that "any increase in wind turbine or electrolyser efficiency" will lead to a reduced amount of environmental impacts (Spath & Mann, 2004, p.7). However, the study from Spath & Mann (2004) only considered a theoretical approach and no large-scale perspectives. Numerous studies have already been conducted on existing offshore wind parks (e.g. Gemini in the Netherlands in 2017), including LCAs. Thus, it is more relevant to look at a technology that can still be adapted and mentioned by Spath & Mann (2004): the electrolyser.

The two most developed electrolyser technologies are alkaline and PEM, both available commercially at a MW scale but some improvements and optimisation are still possible (Gigler & Weeda, 2018). In most of the assessment studies on water electrolysis, only the alkaline type of electrolysers was considered (Bhandari et al., 2014). This situation is not a surprise since alkaline electrolysers are the most mature and developed electrolyser's technology in the world. If alkaline technology has been developed since the end of the 18th century, another technology, PEM (Proton Exchange Membrane) has emerged since the 1960s. PEM electrolysers have seen an increasing production during the last decades. Thanks to its power range (see Appendix 7.7), the PEM electrolyser has shown interesting potentials to overcome the intermittency issue from renewable energies sources (Carmo, Fritz, Mergel, & Stolten, 2013; Zeng & Zhang, 2010). Until now, little research has been conducted on this technology and its potential impacts (Carmo et al., 2013). Another potential electrolyser path is the high-temperature electrolysis. However, no relevant case studies using this technology has been found. As it is also at an earlier stage of development than PEM or alkaline electrolysers, this option has not been further investigated in this thesis.

Still, some studies have been conducted on PEM (Carmo et al., 2013) and on alkaline electrolysers (Zeng & Zhang, 2010) and each time they indicate the bottlenecks to solve. Comparisons can be found between alkaline and PEM electrolysers, though mainly from an economic perspective. Wulf et al. (2018) do consider both electrolysers but not in high detail since they consider also other technologies. These authors indicate that both electrolysers have very similar performances. However, there is no clear consideration of upscaling effects or large production. Thus, no comparative LCA has been conducted specifically between alkaline and PEM electrolysers on large scale and it is still unclear which technology fits the best for sustainable hydrogen production. Hence, if a choice was to be made between the two electrolysers, “a more detailed assessment would be necessary” (Wulf & Kaltschmitt, 2018, p.17). Therefore, when conducting the ex-ante LCA for this thesis, a special focus will be put on the electrolyser technologies to deal with this knowledge gap.

An LCA by Bareiß, de la Rua, Möckl, & Hamacher (2019) considered a similar topic than in the thesis. The authors’ intentions were to compare the PEM electrolyser (alone) with the Steam Methane Reforming (SMR) option considered as the incumbent technology. The authors also considered how the PEM technology could evolve in the near future (probably within a decade) and they estimated how several technical parameters may evolve such as electrodes loading, stack lifetime, voltage, etc. Bareiß et al. (2019) also make some estimations by 2050 in Germany for the use of different raw materials, such as platinum or iridium. The authors made their projections based on data from industrial partners or laboratory experiments. Nevertheless, the alkaline electrolyser was not considered in their LCA study. Personal contact made with the authors gave some more information. Among other, the authors’ opinions are that the main difference between the current situation and the future will be found in the stack level, especially concerning the material needs and the current density (linked to efficiency). Most of the improvements presented by Bareiß et al. (2019) are cost-driven, thus they are more likely to occur in the future.

2.1.5) Description of the system

As the focus of the thesis is on the electrolyser, a clear description of the system under study is provided below.

Globally, an electrolyser splits electrochemically the water (H_2O) into oxygen (O_2) and hydrogen (H_2). An electrolyser is composed of several parts. The cell is the fundamental component of an electrolyser. A certain number of cells define one stack and one electrolyser may contain several stacks. Different types of electrolysers exist but the focus will be put on the alkaline and PEM technologies. Solid oxide cells can be an option to consider but are less mature in their developments than the two other alternatives. Anion exchange membrane (AEM) also possesses strong potentials and is a sort of mix between PEM and alkaline. However, this technology is still under lab studies and face different design challenges as described by Vincent & Bessarabov, (2018). Therefore, AEM and solid oxide cells will not be further considered in the thesis. The main differences between electrolyser’s technologies consist of the operating conditions (temperature, pressure, etc.) and the type of electrolyte used.

An alkaline electrolyser contains a liquid electrolyte, often potassium hydroxide (KOH) whereas a PEM electrolyser possesses a solid membrane, usually a polytetrafluoroethylene-based product. In both cases, there are two bipolar plates, one on each side of the electrolyte: the anode and the cathode with different metals.

The chemical reaction that occurs within an electrolyser is described with the equation 1:

$$H_2O \rightarrow H_2 + {}^{1}/_{2}\, O_2 \ (Eq. 1)$$

The previous reaction is actually the sum of two half-reactions occurring at the electrodes. For the alkaline case, Equation 2, the oxygen evolution reaction (OER), takes place in the anode, and Equation 3, the hydrogen evolution reaction (HER), takes place in the cathode:

$$2HO^- \rightarrow H_2O + 2e^- + {}^{1}/_{2}\, O_2 \ (Eq. 2)$$

$$2H_2O + 2e^- \rightarrow 2HO^- + 2H_2 \ (Eq. 3)$$

For the PEM case, Equation 4 takes place in the anode (OER) and Equation 5 takes place in the cathode (HER):

$$H_2O \rightarrow 2H^+ + {}^1/_2\, O_2 + 2e^- \; (Eq. 4)$$

$$2H^+ + 2e^- \rightarrow H_2 \; (Eq. 5)$$

The alkaline electrolyser can generate an output pressure of H_2 around 10-20 bars whereas the PEM electrolyser is able to reach an output pressure of 80-100 bars (but can also work on lower pressure). Getting high-pressurised hydrogen as an output may be relevant for transportation with a lower need for further compression steps. **Figure 2** below provides a visual description of electrolysers.

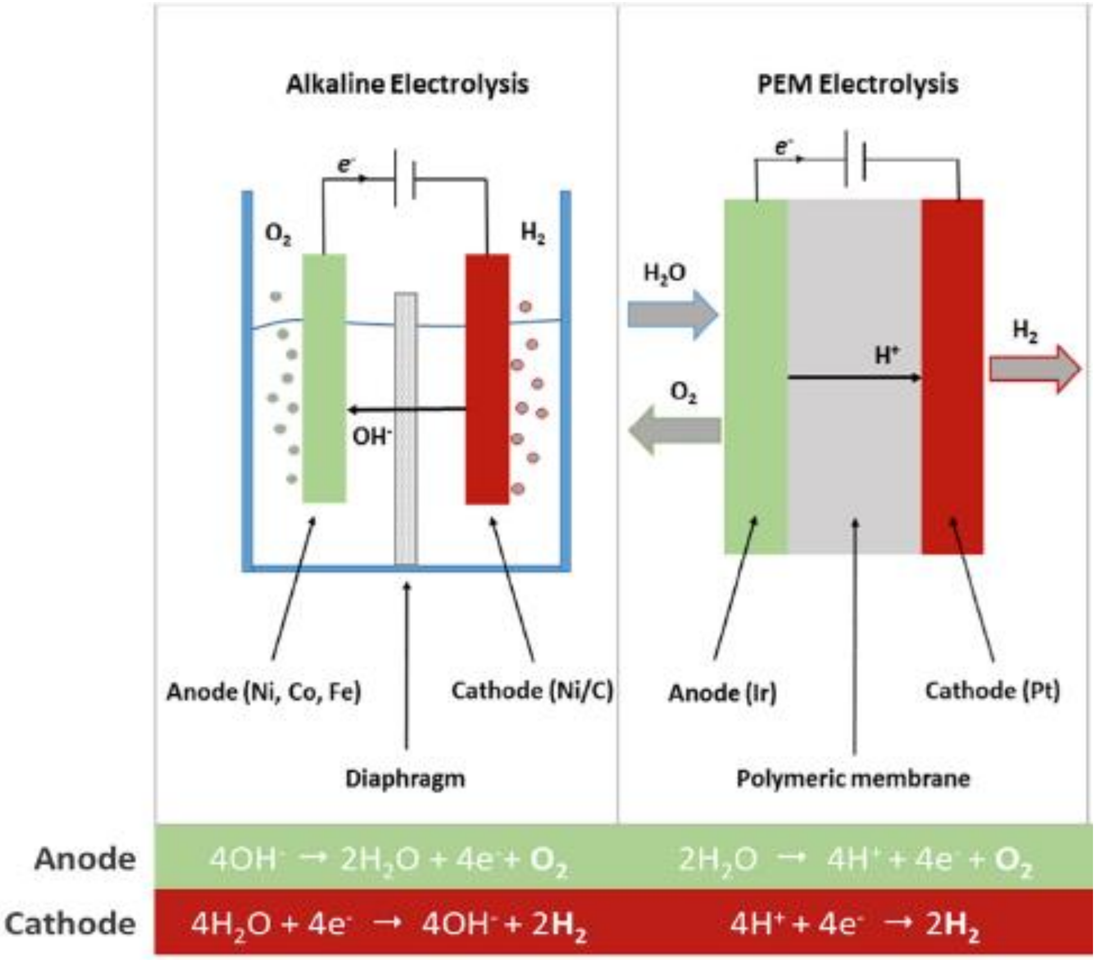


Figure 2. Visual representation of the operating principles of the alkaline and PEM electrolysers. The oxygen evolution reaction occurs at the anode and the hydrogen evolution reaction occurs at the cathode (extracted from Sapountzi, Gracia, Weststrate, Fredriksson, & Niemantsverdriet, 2017).

The alkaline technology has been used for over a century in industries, especially in ammonia production. Alkaline electrolysers were used at large scales, reaching 135 MW (Nel Hydrogen, 2016). The alkaline technology possesses relatively low costs investments, making it interesting for stakeholders. However, the electrolyser's low current density (below 1 A/cm²) and sensitivity to differential pressures limit its efficiency (Bertuccioli et al., 2014). PEM technology has been developed since the 1960s, is more flexible for technological adjustments than alkaline and is used in small scale installations (HyBalance, 2018). PEM electrolysers are likely to be used in larger-scale installations within the next decade. PEM technology offers some advantages in comparison to alkaline. The higher current density in PEM electrolysers (1-3 A/cm²) enables higher efficiency and the stack can be smaller in size with the same production rate. Moreover, the PEM electrolyser's dynamic power response is more flexible than alkaline technology, making PEM especially suitable to deal with intermittent electricity production, such as renewable energy resources. In this perspective, the PEM technology may be valuable in a sustainable energy production system. Still, the use of noble and rare metals (such as platinum and iridium) raises questions on resources scarcities and high investment costs.

In **Table 1** & **Table 2** are presented several technical characteristics for the alkaline and PEM electrolysers respectively. The tables provide orders of magnitude of the performances that can be expected from commercial models. When no range of value is provided, the single value applies for nominal conditions.

Table 1. Technical characteristics of alkaline electrolysers

Name of the product	A150	A3880	McLyzer 10-10	McLyzer 400-30
DC energy consumption	3,8-4,4 kWh_e/Nm^3	3,8-4,4 kWh_e/Nm^3	5,25 kWh_e/Nm^3	4,5 kWh_e/Nm^3
Hydrogen production range	50-150 Nm^3/h	2400-3880 Nm^3/h	10 Nm^3/h	400 Nm^3/h
Nominal power	ca. 660 kW	ca. 17 MW	57 kW	2 MW
Output pressure	19 mbar	ca. 20 bar	10 barg	30 barg
Source for the data /company	(Nel Hydrogen, 2019)		(McPhy, 2017)	

Table 2. Technical characteristics of PEM electrolysers

Name of the product	ME 100/350	ME 450/1400	HyLYZER-1	HyLYZER-2
DC energy consumption	4,9 $kWh_e/Nm3$	4,9 $kWh_e/Nm3$	6,7 kWh_e/Nm^3	6,7 kWh_e/Nm^3
Hydrogen nominal production	100 kg/day <=> 47 Nm^3/h	450 kg/day <=> 210 Nm^3/h	1 Nm^3/h	2 Nm^3/h
Nominal power	225 kW	1 MW	6.7 kW	13.4 kW
Output pressure	30 bar	30 bar	1 - 8.9 bar	1 - 8.9 bar
Source for the data/ company	(H-TEC, 2019a)	(H-TEC, 2019b)	(Hydrogenics, 2018b)	

2.2) Methodology overview

For a clear understanding of the different parts that compose the thesis, a methodological overview is provided with **Figure 3**. The latter gives an overall visual representation of the different steps conducted through the thesis and shows that different main phases can be extracted from the whole process. A small description for each phase is provided in the next sections. Despite the visual representation, the chronology of these phases can be much more intertwined or miscellaneous. For example, in the thesis, phase 2 overlapped with phase 3 and even 4, with experts' contacts being kept for new comments or some interviews still being made.

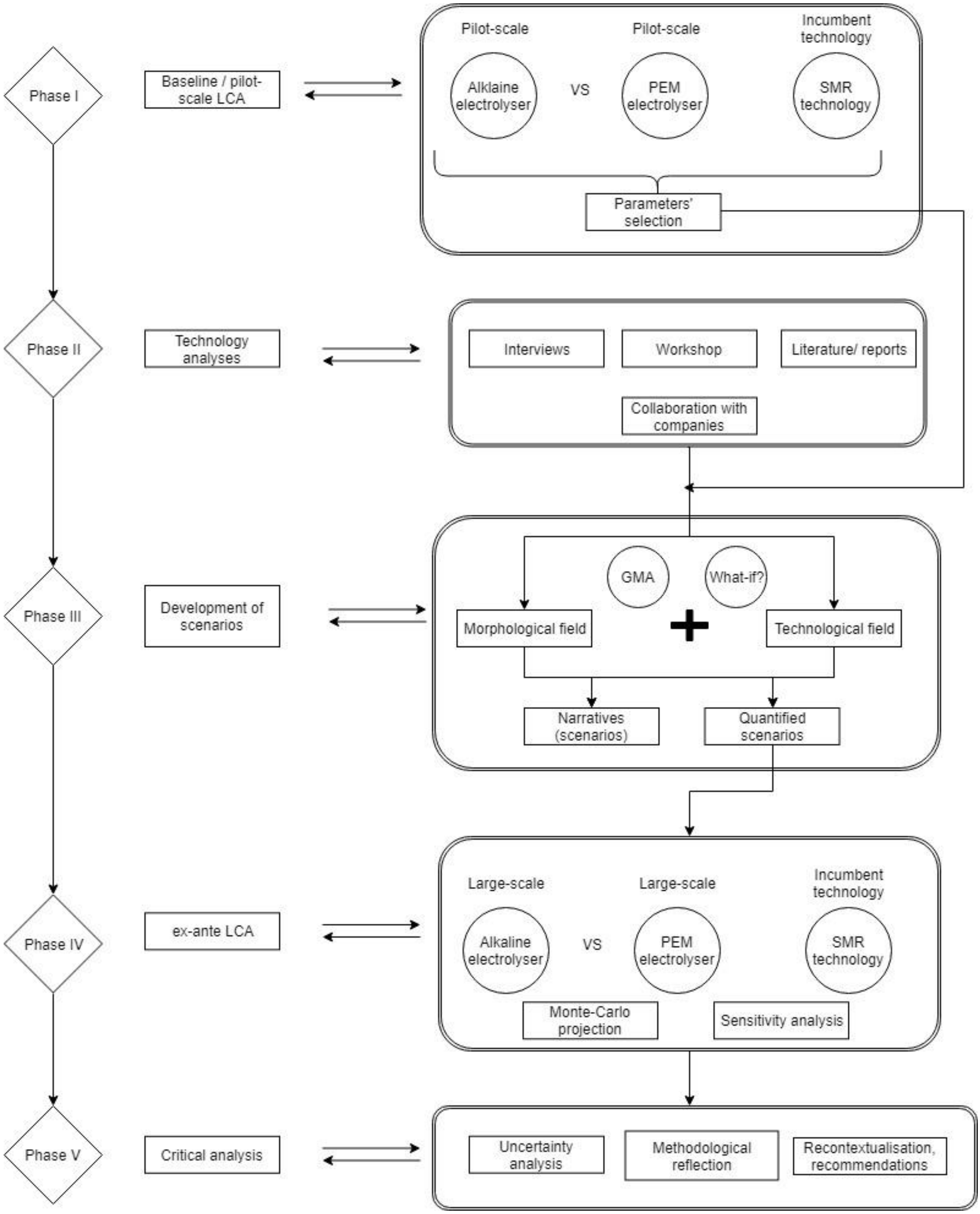


Figure 3. Methodological framework overview.

2.3) Phase 1: Pilot-scale LCA models

Sub-question 1: "*What are the environmental profiles of the two electrolysers' alternatives?"*

To begin with, LCA models at pilot-scales are constructed. They provide a list of relevant parameters to consider during the upscaling process and serve as the basis to construct the ex-ante large-scale models.

Following the methodology defined with the ISO 14040 framework (Guinée, 2002), four main phases are defined for the LCA. Firstly, the "goal & scope" defines the aim of the study, its breadth and depth. Secondly, the "Life Cycle inventory" compiles all the relevant data (material and energy flows) quantified for the system, throughout its lifecycle. Thirdly, the "Impact assessment" evaluates all the potential environmental impacts of the system under study. Lastly, analyses of the results, conclusions and recommendations consistent with the goal and scope definition will be made in the "Interpretation" phase. These four steps describe the main phases of any LCA studies. However, as mentioned by Cucurachi et al. (2018), the majority of the LCA studies consider existing systems, with hindsight. This position can become problematic since the potential conclusions or recommendations may be hard to apply in reality. On the contrary, making an LCA study on emerging technologies (lab or pilot-scale) enables to make decisions early in the development process. Despite its uncertainty due to the prospective approach, an ex-ante LCA can provide valuable insights for emerging technologies and avoid burdens and regrettable investments.

In the thesis, LCA models are developed with the OpenLCA software which enables good flexibility concerning the definition of parameters and their values' manipulation. The latter will be especially helpful for the sensitivity analyses or scenario evaluations (phase 4). The database that is used is ecoinvent 3.4, one of the most common LCA database. Ecoinvent seeks to provide well-documented process data for many products in order to assess their environmental impacts in lifecycle inventories (ecoinvent, 2018). Ecoinvent also provides uncertainty distribution laws (lognormal distribution) for all its flows. This element helps to implement the Monte-Carlo method (conducted in phase 4 as part of the ex-ante large-scale LCA model) to deal with uncertainties in model's calculations

In phase 1, a simplified LCA model at pilot-scale is developed in order to get relevant order of magnitudes of the different electrolyser's alternatives (PEM and alkaline technology) with the Steam Methane Reforming (SMR), considered as the incumbent technology. The incumbent technology consists of the most used technology available to perform the same function than the emerging technology under study (Cucurachi et al., 2018). In the thesis, two levels can be defined for the incumbent technology. Firstly, at the broadest level, the incumbent technology is the SMR since it is the most used technology worldwide to produce hydrogen, and the emerging one is the electrolyser (subdivided into PEM and alkaline). Secondly, at the electrolyser's field level, the incumbent technology is the alkaline which is more developed than PEM, the emerging technology. Depending on the section, the first or second levels for the incumbent technology will be considered.

The production of electricity required for the electrolyser is considered and either comes from the Dutch grid in the Business-as-Usual (BAU) case or from offshore wind turbines, in order to produce sustainable hydrogen. The point in considering electricity from wind turbines in the pilot-scale models is to decrease the environmental impacts from electricity's production and make the potential parameters for the upscaling process more prominent. Several LCA studies and data about wind turbines can be found in the literature (Birkeland, 2011; Huang, Gan, & Chiueh, 2017; Weinzettel, Reenaas, Solli, & Hertwich, 2009). As this topic is particularly well known and studied, the LCA model developed within the ecoinvent database for the Dutch wind turbines will be used for the electrolyser stage. The data for the electrolysers will be collected from the literature review with Life Cycle

Inventories (Schmidt, Topriska, Kolokotroni, & Azapagic, 2018; D. Thomas et al., 2016; Topriska, Kolokotroni, Dehouche, & Wilson, 2015; Wulf & Kaltschmitt, 2018).

Based on the results from this first LCA model and some sensitivity analyses, the relevant technological parameters to consider in upscaling processes are found and used for the next steps (see **Table 9**). Some technology analyses conducted in Phase 2 provided deeper analyses and understanding on which and how parameters may evolve. From a strictly scientific point of view, all technological parameters should be considered with no exception. However, due to time and practical limitations, a selection was made, based on the resources available and the parameter's characteristics. For example, the consumption of noble metals is deemed relevant to consider since these elements are connected to criticality's problems. In the thesis, a focus was put on a limited number of parameters (13 for both electrolyser's alternatives).

2.4) Phase 2: Technology analyses

Sub-question 2: "*Which parameters are the most relevant for the system transition from a pilot-scale to a large-scale perspective?*"

The sub-question has already partly been answered in phase 1. However, further inputs can be added during phase 2. This phase consists of conducting different activities/analyses in connection with the technology under study.

The presence of parameters that evolve over time, especially for emerging technologies, is one of the main factors that induce uncertainty related to any work on future situations. Miller & Keoleian (2015) discuss the issue of the inherent lack of data and uncertainties that exist within an LCA on emerging technologies. These authors describe 10 factors in 3 categories that can have influences on the technology performances. These factors are summarised in **Figure 4** below.

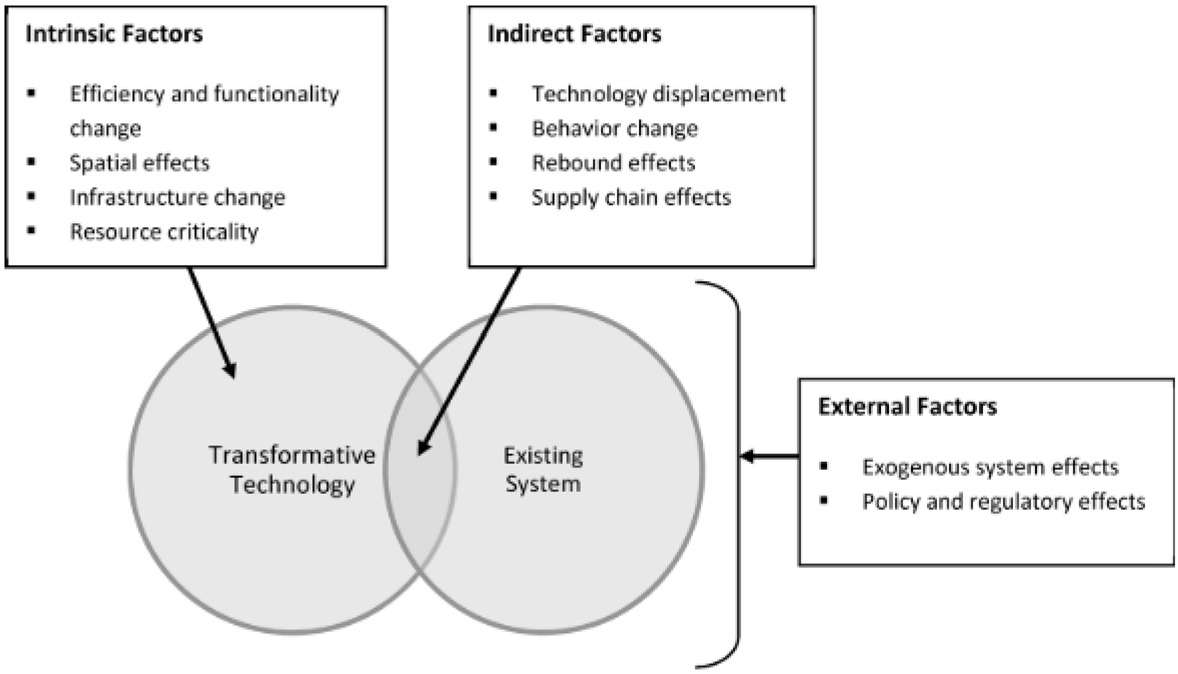


Figure 4. 10 factors in 3 categories that are key influencers for the LCA results from a transformative technology (extracted from Miller & Keoleian, 2015).

Miller & Keoleian (2015) describe quickly each of the factors and then apply the latter in 2 case studies. The authors' framework was partly used in the thesis, with the factors "Efficiency and functionality change" and the "Resource criticality". The former since the electrolysers are expected to improve their efficiencies, the latter since some rare metals are used, especially in the PEM case. These factors and the "Policy and regulatory effects" are discussed in Chapter 4. The other factors do not fit in the scope of the thesis.

To deal with the uncertainty on parameters' evolution, some technology analyses were conducted. The goal of the thesis is to describe potential situations with the hydrogen production in 2050, so no focus will be put in the *transition* process itself, but on the *final* state. Information was collected on the electrolyser's efficiency, the material requirements' evolutions, the number of plants expected and so on. The effects of scaling-up were primarily based on experts' knowledge, companies' reports and data when available. The different activities conducted are described below.

Several conversations and interviews were conducted throughout the thesis to get feedback from experts. The latter provides some information from different points of view and enable to get a clearer idea on the present (and future) context of the technology under study. Usually, interviews are separated into three categories:

- Structured interviews which mainly consist of a specific set of questions with no flexibility, as a survey for example.
- Unstructured interviews which use open-ended questions and possess much more elasticity, like a brainstorming session.
- Semi-structured interviews (SSI) are a kind of mix of the two previous categories. They possess some cornerstone questions, but the structure allows some flexibility in the topics discussed.

For the purpose of the thesis, the interviews followed a semi-structured pattern to enable some flexibility and adaptation. In this way, some important questions were still dealt with systematically. At the same time, some room was present for flexibility and remarks about potential new perspectives or ideas. This flexibility is especially relevant when an emerging technology is under consideration. Adams (2015) describes the different steps to conduct a semi-structured interview (SSI). Among other things, the use of an interview guide with the cornerstone questions written is recommended to keep some structure during the discussion. Furthermore, SSIs provide the advantage of understanding the visions of different stakeholders and their independent thought, they avoid the "group-effect" by conducting individual interviews and SSIs are especially suitable for exploring "uncharted territory with unknown but potential" problems (Adams, 2015, p.494). Several suggestions are given by Adams (2015) to prepare the interview, such as selecting the questions, paying attention to potential translations, the management of possible sensitive questions, etc. Adams (2015) claims that despite all the preparations made, the interview guide should be considered as a work in progress along the process that can evolve and be adjusted depending on the stakeholders' input. This evolution can also be interesting in the development of scenarios. The website tools4dev (2014) also strongly suggest using an interview guide. Furthermore, this website recommends contacting stakeholders from different horizons and scales. Finally, Zorn (2008) also gives 11 advice on the preparation and application of SSIs. The two main advantages for SSIs promoted by Zorn (2008) are to avoid imposing meaning or leading effects and to create a comfortable atmosphere for discussion (Zorn, 2008). For all the reasons previously mentioned and to develop the scenarios in Phase 3, semi-structured interviews with stakeholders were achieved.

The list of the questions (the “interview guide”) used in the interviews can be found in Appendix 5. The main outcomes of the different interviews are described in Appendix 6. The interviewee list is provided below:

- Albert van der Molen, Expert Asset Management at Stedin, an electricity and gas distributor company that runs a Power-to-Gas station in Rozenburg.
- Thijs de Groot, Innovation technologist at Nouryon, a chemical company based in the Netherlands.
- Steve Szymanski, Director of Business Development at Nel Hydrogen, an American company which produces alkaline and PEM electrolysers.
- Noé van Hulst, Hydrogen envoy at Ministerie van Economische Zaken en Klimaat. Based on a common agreement, no detailed description of the interview is provided in the thesis. Only the relevant information was used in the scenario’s development and mentioned as “Personal communication, van Hulst, 2019”.

Furthermore, going or organising a workshop can also be really efficient in collecting opinions and scientific information. In the case of the thesis, the author could join a workshop organised by ECN/TNO about PEM electrolyser (see Appendix 6.1). This is a typical example of a relevant workshop that provides fruitful inputs for the thesis. The workshop from Volta Chem (a group from TNO), entitled “Developing the supply chain for electrolysis” enabled to discuss with several stakeholders for the PEM technology. The workshop was the first attempt to make contacts between distinct companies in order to create collaborations for further development of a hydrogen economy in the NL.

Moreover, collaboration with companies through exchanges or internships can also be helpful. For this thesis, a collaboration was made with the laboratory CRIGEN, in Paris, from ENGIE France, one of the main French energy company. This laboratory possesses specialised teams in electrolysers and LCA studies (see Appendix 8). An example of output that came from this collaboration is that the academic world promotes more the PEM technology whereas the industries rely more on alkaline electrolysers. Several industrial reports were also transmitted through ENGIE and were used as a basis for the projections on parameters. The workshop and collaboration with ENGIE enabled to discover a new point of views, from diverse stakeholders and also collect data from real-world applications.

Finally, a literature review was conducted with several reports from companies or academics where some deep analyses or forecast were made concerning different parts of the electrolysers.

All these activities and technology analyses sought to provide consistent data and knowledge for the further steps, for refining the models established in phase 1 and improving the list of parameters to consider during the upscaling process. The opinions collected from experts enabled to understand more how the two electrolysers technologies (alkaline and PEM) will evolve in the future. The list of parameters is used during the scenario’s development and implementation in the ex-ante large-scale LCA models.

2.5) Phase 3: Development of scenarios

Sub-question 3: “*What are possible scenarios for a large-scale production of sustainable hydrogen in the Netherlands?”*

Based on the potential technical evolutions and combined with the inputs from experts on the political and societal trends, a limited number of scenarios for 2050 are framed.

The use of scenario can be relevant to describe potential futures of the technology's implementation. Wender (2016) applies scenarios as well, in order to avoid unintended consequences from large implementation of an emerging technology. Some LCAs were conducted without explicitly considering scenarios though, such as the LCA on solar panels from Pehnt (2006). In this case, only some parameters for the solar panels were used and their values adjusted (on assumptions from official German scenarios' studies). Nevertheless, Pehnt (2006) does not develop a scenario's methodology in his paper, showing that different approaches are possible.

The combination of scenarios' use and different environmental analyses tools has been discussed by Höjer et al. (2008) and is deemed especially relevant with LCAs. Using scenarios in combination with LCAs would justify some strategic decisions or planning. The authors point out the fact that most LCAs consider "What-if?" scenarios for the future. Further use and research in the combination of environmental tools with scenarios would enhance their usefulness and relevance.

Scenarios have already been used in different LCA studies such as the one on transports made by Spielmann, Scholz, Tietje, & Haan (2005). The latter have used matrix modelling with technical and socio-economic variables to define a set of scenarios. Matrices of consistencies were also used to reduce the number of scenarios to some called "cornerstones". These cornerstones scenarios are meant to represent future developments of an entire LCI product system. By doing so, the authors could compare different future paths with changes in the political decisions (promote more one transportation path than another) and technical parameters (technological evolution), in order to find the most sustainable alternative (Spielmann et al., 2005). Another example of combination between LCA and scenarios is provided by Ravikumar, Sinha, Seager, & Fraser (2015) where they use scenarios to compare the environmental performances of CdTe solar panels' recycling. The authors considered some parameters such as the distance to the recycling factory, the level of materials recycled and sent to the landfill and others.

As stated by Ball & Wietschel: "Whether hydrogen can solve most of the energy issues in the long-term needs to be evaluated through well-defined deployment scenarios, which can provide quantitative information on the opportunities and risks related to large market introduction" (Ball & Wietschel, 2009, p.386). The literature review conducted on the combination of scenarios and LCA shows the relevance of this approach and supports scenarios' implementation in the thesis.

The scenarios are usually divided into three categories (Höjer et al., 2008):

- *Predictive scenarios*: the goal is to make predictions of the future with the help of surveys, statistics or stakeholders' analyses.
- *Explorative scenario*: the goal is to consider a range of possible evolutions with their potential impacts.
- *Normative scenario:* the goal is to define a desirable endpoint first. Then, through backcasting usually, pathways to reach the mentioned endpoint are defined.

In the thesis, as the scenarios for the future will be based on real Dutch projects, the predictive scenario approach will be considered for the thesis. Explorative scenarios would require a larger scope. The thesis' goal is not to describe a pathway to reach a desirable endpoint, so a normative scenario would not be suitable.

Predictive scenarios can be subdivided into 2 categories: "forecast" and "What-if?". Most of the time, forecasts consider the most likely development of a certain field, considered as a reference. Therefore, they are particularly suitable for short-term predictions. What-if scenarios consider how the development of a certain field may depend on specific external events or internal decisions (Höjer et al., 2008). One scenario for the thesis will be based on Dutch projections for the green hydrogen technology's development. In addition to that, some alternatives considered as "deviations" from the original Dutch predictions (goal not reached, delays, etc.) will be studied as well. Therefore, the "What-if?" approach will be adopted further on.

Moreover, the General Morphological Analysis (GMA) framework will be used to restrain the development of scenarios and avoid dispersal. The GMA "is a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes" (Ritchey, 2011, p.84). This approach can also be suitable and adapted for a sustainability issue.

Effectively, a technology development does not depend only on technical aspects but also on non-quantifiable elements such as political decisions, public acceptance, companies' orientations and more. Furthermore, all actors are interdependent, increasing the analyses' complexity even more. The GMA methodology consists in creating a morphological field where selected dimensions are placed in columns beside each other as in **Table 3**. Each dimension must be connected to a range of possible values or conditions. At this step, the relevant parameters found in the pilot-scale LCA models can be used. Finally, the selection of a single value for each dimension defines a "field configuration" which is equivalent to a specific scenario. Obviously, a number as small as 5 or 6 dimensions can already provide a huge number of scenarios possibilities. To limit this number, consistency assessments are conducted, based on logical contradictions and empirical constraints (i.e. conjunctions which are highly unlikely). For the thesis, a total of 3 main field configurations ("scenarios") will be considered. One scenario will be subdivided in 2 ("Scenario B" and B1) due to methodological reasons, explained later.

Table 3. A simplified example of a morphological field. The cells coloured indicate a possible field configuration ("scenario").

Dimension 1	Dimension 2	Dimension 3	Dimension 4	Dimension 5	Dimension 6
Value 1.1	Value 2.1	Value 3.1	Value 4.1	Value 5.1	Value 6.1
Value 1.2	Value 2.2	Value 3.2	Value 4.2	Value 5.2	Value 6.2
Value 1.3	Value 2.3	Value 3.3	Value 4.3	Value 5.3	Value 6.3

Globally, sub-questions 2 and 3 are highly interconnected. For example, a massive development of hydrogen production systems (scenario) is unlikely to occur if the technology does not benefit from some technical improvements (technology analyses). The scenarios developed in phase 3 are implemented in the ex-ante large-scale LCA models in phase 4.

2.6) Phase 4: Ex-ante large-scale LCA model

Sub-question 4: "*How will evolve the environmental profiles between the pilot-scale (current situation) and the large-scale implementation (scenario situation)?*"

This phase consists in constructing the ex-ante large-scale LCA models.

Once again, the same methodology than for "traditional" LCA is applied (cf. phase 1). Before that, reflexion must be conducted in order to define the constituents of the large-scale LCA model. The pilot-scale LCA models developed in phase 1 are used as a base but they possess differences in life cycle inventories or in details, due to the specific context considered. Contrary to the pilot-scale, the ex-ante large-scale LCA model is supposed to provide a reference model that could be applied in "any location" and possess a more "neutral" perspective. Obviously, each location may require some minor adjustments depending on the context considered. A balance must be found between creating a general model that would be valid at a national scale and the level of details for the elements' description. Caduff, Huijbregts, Althaus, Koehler, & Hellweg (2012) did a similar work with harmonizing Life Cycle Inventories regarding the background processes and the system boundaries. In the thesis, the higher degree of details is recommended without getting in too location-dependent elements, even though these are arbitrary choices. Then, the choices and construction of the model must be clearly explained, and the use of each element should be described as much as possible. In the ex-ante large-scale LCA models developed, the "Constructing materials" and "Operating resources" were considered for both electrolysers to construct the plant. Some flows from the pilot-scale were deleted in the ex-ante large-scale LCA models due to a lack of data or precisions. The list of the flows adjusted or changed is given in Appendix 12.

The future scenarios from phase 3 combined with the different relevant parameters from phases 1 & 2 must be translated into quantified inputs in OpenLCA. Reflection on the implementation in OpenLCA (cf. section 5.2) enable to translate scenarios and parameters into numerical values with transparent assumptions. For example, a political subsidy can enable scientists to improve the electrolysers in order to reduce tenfold the consumption of a noble metal. The scenarios implemented enable to analyse the evolution of the environmental impacts from the hydrogen's production technology at a large-scale.

Once the ex-ante large-scale LCA system is constructed, the traditional steps from LCA methodology are followed: impact assessment, result inventories, analyses and interpretation. New levels of analyses are added at this level, with comparisons with the pilot-scale LCA models or comparisons between different scenarios, with SMR taken as a "Business-as-usual" case.

One of the main issues in LCA studies concerns the management of uncertainty in data and results. Many reasons can justify some assumptions and generate uncertainties in an LCA model: a lack of data, time consideration, modelling choices, impact categories' definition, aggregation, etc. In theory, any process in an LCA study should be modelled with empirical data from cradle-to-grave. In reality, this path is impossible to achieve for every single step. Furthermore, in an ex-ante LCA, no certain vision for the future can be developed. In general, regardless of the means deployed to conduct the LCA, some uncertainties will always be implied in the data or the results. However, some description can be provided concerning the uncertainties in order to perform informed interpretations. For example, as Lesage, Mutel, Schenker, & Margni (2019) indicate, ecoinvent is an LCI database that provides uncertainty information on its parameters. The default distribution that describes the parameter's value uncertainty is the lognormal distribution, one of the most common probabilistic distribution due to mathematical reasons.

In order to generate the most productive conclusions, several options exist to deal with uncertainties and take them into account. A tool commonly used in LCA models is the Monte-Carlo method and the approach used in the thesis is similar to the one described by Henriksson et al. (2015). Monte Carlo (MC) projection consists of sampling randomly values to a certain number of variables, following the distribution law that defines the variables. This step is repeated a large number of times (usually ca. thousands of runs) and at each iteration, the values given are aggregated into LCA results. This procedure generates a range of LCA possible values which can be evaluated through a series of statistical tests (mean, median, variable, quartile…) or define a new distribution law. This way, a consistent consideration of uncertainties is applied, and more relevant interpretations can be drawn. In the sampling procedure from MC, the variables can be either independent or dependent. If they are independent, each variable is based on a uniquely drawn set of random samples. If they are dependent, the variables are based on the same set of random samples. Uncorrelated variables generate hardly comparable results as they come from different sampled values. As the goal of the thesis is to compare two potential alternatives (PEM and AE) which possess differences *and* similarities, some variables must be correlated in order to avoid "unfair" comparisons. Thus, when a shared process between the two electrolysers' technology (the production of electricity for example) is randomly attributed to an unusually high value, both alternatives will likely possess a high environmental profile. In this case, only the relative difference between the alternatives considered is valuable and can be interpreted. **Figure 5** illustrates the concept of correlated/uncorrelated alternatives.

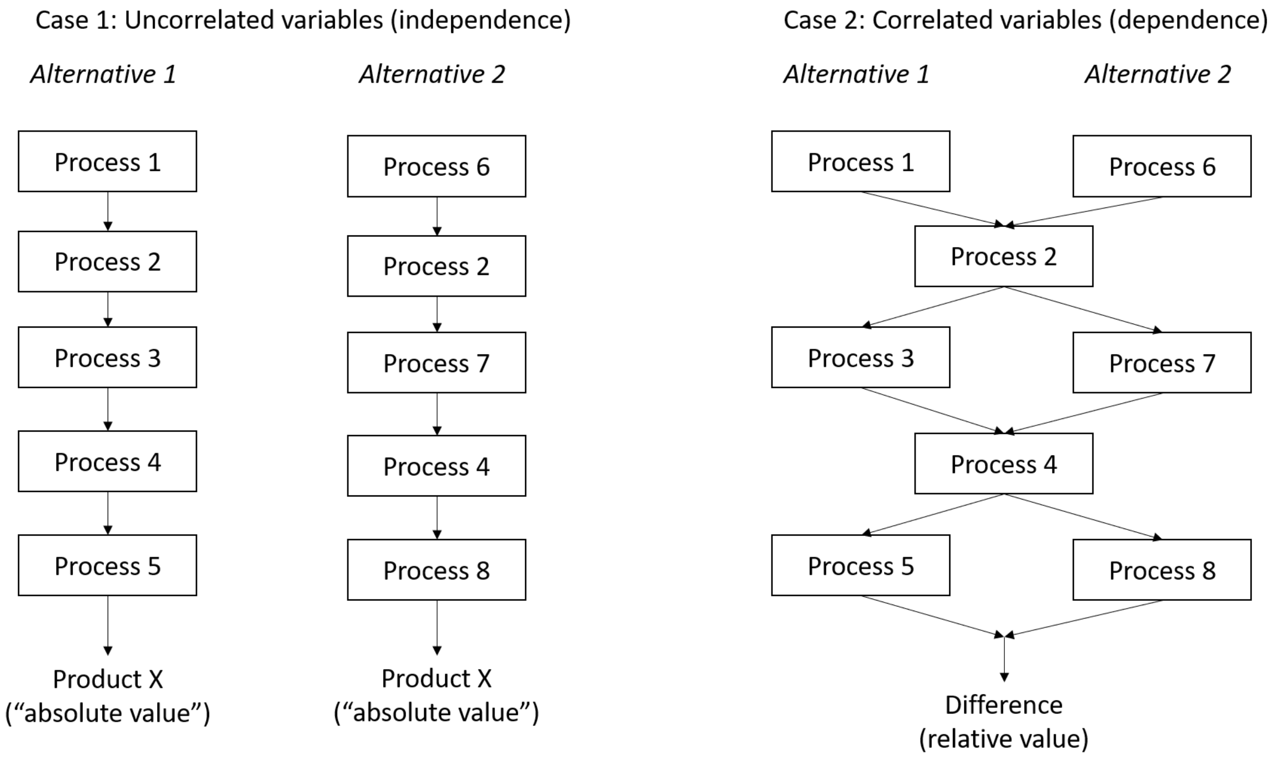


Figure 5. Illustration of the correlated/uncorrelated approach that can be adopted with MC. In case 1, each alternative will have its own drawn set of samples, which can lead to "unfair" comparisons. In case 2, both alternatives possess the same set of samples. So, all common processes will adopt the same values for both alternatives and all specific processes will adopt its own value.

This approach is also promoted by Heijungs, Henriksson, & Guinée (2017), who stated that each LCA study should generate Monte-Carlo samples, dependently sampled in order to make consistent comparisons, without overestimations of the results' uncertainties. Lesage et al. (2019) also concluded that independent sampling tends to exaggerate the results' uncertainty. More precisely, these authors indicate that if the same material is used for several alternatives, then the variables linked to them should be dependent. From a practical point of view, the MC option is already implemented in OpenLCA, facilitating its implementation.

Finally, contribution and sensitivity analyses will be conducted in OpenLCA between the two electrolysers' technologies (PEM and alkaline), with a comparison between the two-time points (current situation in 2019 and 2050) with SMR taken as a "Business-as-usual" scenario. Interpretations and recommendations will be drawn from these analyses.

2.7) Phase 5: critical analyses

This phase discusses the assumptions taken for the thesis and reflects on the whole process conducted.

Firstly, the limitations of the study itself are discussed. Uncertainty issues and strategies adopted to deal with them in the LCA models and scenarios are recalled. Uncertainty analysis has started to attract attention only for a few years in the LCA field and started to be considered in phase 4 with the MC projections. Different methodologies can be applied to analyse the uncertainties connected to an LCA model, and even more with an *ex-ante* LCA model. Beltran et al. (2018) and John, Henriksson, Guinée, & Heijungs (2014) provide a decision tree to guide LCA practitioners to select the most relevant tests that should be conducted, including Monte-Carlo projections, weighting means and the Null Hypothesis Significance Testing.

Other elements of the LCA are discussed. For example, the definition of the system under study can also be reconsidered with the boundaries. In the thesis, recycling aspects were introduced and started to be modelled for a sensitivity analysis.

Scenarios and uncertainties can also be dealt with different strategies such as backcasting. The consistency of the scenarios needs to be debated about its advantages and drawbacks. The GMA approach is interesting but one of its limits is that the number of field configurations increases exponentially (or in a factorial way) with the number of parameters, making it extremely time-consuming (Ritchey, 2011b).

Methodological reflection is made at this phase in order to keep perspective with the different choices made in the thesis and the potential alternatives that exist, such as Technology Assessment or other types of scenarios. To assess the relevance of the work conducted, comparisons are made with the existing literature to see what the added-values are. A methodological framework that could be reused in further similar researches will be extracted then. Broader perspectives are also considered to put again the system under study into context, showing the importance and influence of the point of view adopted.

Finally, a list of recommendations ends the critical analyses. Overall, the goal is to consider an overview of the whole work achieved and the possibilities for further works.

To conclude, all these methodological phases will be implemented within the overarching ex-ante LCA study and will enable to answer the main Research Questions with coherent and relevant methods. In this sense, a structured modelling approach is being considered all along the thesis.

3) Pilot-scale LCA models

As described in the Methodology, the first step is to develop pilot-scale LCA models from a literature review or based on experts' inputs (phase 1). The contribution analysis of these firsts LCA models will enable to find out the relevant parameters that may play a significant role in upscaling processes. To create these firsts LCA models, several papers were chosen, as described below. The LCA methodology is based on the ISO 14040 and the recommendations from "Handbook on Life Cycle Assessment" (Guinée, 2001).

3.1) Goal and scope definition

To begin with, the goal of the LCA study is defined. The scope of the LCA and the different levels of coverages are clarified. The products of the study are described as functions.

3.1.1) Goal

The goal of the pilot-scale LCAs is to develop some models based on the literature review and existing machines. A comparison of the environmental performances will be conducted between 2 electrolysers, the alkaline and the PEM. Other hydrogen's production technology from water exist as well, like the photo-reduction, but the alkaline electrolysis and PEM remain the two most promising technologies.

The results will enable to conduct detailed analysis in order to find which technological parameters may be the most relevant for large-scale implementation. The list of the most relevant parameters will be considered during the scenario's development and the ex-ante large-scale LCA construction. Moreover, the environmental profile from the pilot-scale installations will be used later for comparisons with the ex-ante large-scale LCA models.

The results from the pilot-scale LCA models are intended to be used within the thesis' research process. The target audience is made of all the relevant stakeholders involved in the thesis developments (Leiden University and TU Delft, experts contacted, supervisors, etc.) and the persons interested in the study's outcomes.

3.1.2) Scope

The scope will be from cradle-to-gate, going from the extraction of raw materials to the production of hydrogen gas. The environmental emissions connected to these processes will be considered and assessed. The technology level will be based on the current knowledge and the most recent data available for the electrolyser (from 2017 onwards). When other background processes or flows were necessary, the database ecoinvent v3.4 was used. The resources used considered the electrolysis technology in different countries such as Germany, Jamaica or Ghana. However, for the thesis' pilot-scale LCA models, the technologies are relocated in the Netherlands. The adjustments made are the following:

- All the different material/energy inputs come from the European market when available, or from the global market.
- A special focus is put on electricity origin for the electrolysers (except for SMR). The first results consider electricity from the Dutch national grid. Then, the electricity's origin is switched to originate from Dutch offshore wind turbines because the thesis seeks to consider wind-based electrolysis. By doing so, processes different than the electricity production will become more prominent as wind-based electricity possesses lower impacts. The analysis of the parameters relevant for upscaling processes will be facilitated.

For the pilot-scale LCAs models, 2 main foreground processes are modelled: the construction of the electrolyser plant, with cells and stacks, and the operating conditions, with the consumption of water, electricity and electrolyte (when suitable). The electrolysis plants possess an average lifespan of 20 years. The Balance of the Plant (storage tank, heat exchanger, compressor, etc.) is not considered in the thesis, due to a lack of data. No transport process is modelled in the pilot-scale LCA model, since in most of the hydrogen fuel projects, the product is created on-site, and clients collect it themselves. In this sense, the "transport of H_2" is considered to be out of the scope. The end-of-life (EoL) aspects are out of the scope of the study as well as only a few information is available. An attributional approach is considered for the pilot-scale LCA models, as no dynamic assumption is made on potential demand's evolutions.

3.1.3) Function, functional unit, alternatives, reference flow

The function defines the purpose of the system under study. In the thesis, the function is the production of hydrogen in kilogram (kg). The functional unit describes the function in quantifiable terms and is defined as "1 kg of hydrogen produced". More characteristics may be considered such as temperature, pressure. However, only a mass perspective is considered for simplification. Furthermore, the literature used did not always provide information about the compressor or other equivalent systems. The alternatives of the technology are the PEM and the alkaline electrolyser. For each electrolyser's alternative, two models were developed, as described below:

- For **alkaline electrolyser**:
  - The paper from Koj, Wulf, Schreiber, & Zapp (2017) was used to develop the first version of the alkaline electrolyser. The model is referred later on as "AE NL 2017".
  - The paper from Wulf & Kaltschmitt (2018) was used to model the second version of the alkaline electrolyser. The model is referred later on as "AE NL 2018".
- For **PEM electrolyser:**
  - The paper from Wulf & Kaltschmitt (2018) was used to develop the first model of PEM electrolyser. The model is referred later on as "PEM NL 2018a".
  - The paper from Schmidt, Topriska, Kolokotroni, & Azapagic (2018), supported by Topriska, Kolokotroni, Dehouche, Novieto, & Wilson (2016), was used to develop the second model of PEM electrolyser. The model is referred later on as "PEM NL 2018b".
- For **Steam Methane Reforming:**
  - The paper from Wulf & Kaltschmitt (2018) was used to develop the SMR model. The model is referred later on as "SMR NL 2018". The SMR is considered as the incumbent technology. In this respect, SMR NL 2018 will not be as deeply analysed as the electrolyser's models.

Based on these 5 models, the reference flows describe the different ways of obtaining the functional unit. They are consequently defined as:

- To provide 1 kg of hydrogen from the model AE NL 2017
- To provide 1 kg of hydrogen from the model AE NL 2018
- To provide 1 kg of hydrogen from the model PEM NL 2018a
- To provide 1 kg of hydrogen from the model PEM NL 2018b
- To provide 1 kg of hydrogen from the model SMR NL 2018

The global environmental impacts between PEM and AE are studied and some comparisons are also conducted between the two models possible for each electrolyser's technology.

3.2) Life Cycle Inventory

In the second phase of an LCA, the product system must be defined with its boundaries and a flowchart. The associated inputs and outputs must be listed and quantified.

In theory, in an LCA study, all the flows should be considered with a cradle-to-grave perspective. However, in practical, this is impossible to achieve due to a lack of data and knowledge at some process' level. Therefore, some cut-off may be applied even though they should be avoided as much as possible. For the pilot-scale LCA models, due to its structure, no more cut-offs were applied than the one already implemented in background processes from ecoinvent or in the literature resources.

Due to the construction of the LCA models, no unit process possesses more than one product of interest. Consequently, no unit process possesses multifunctionality with several outcomes and no allocation of the environmental impacts between the products of interests was necessary to implement.

The data for the energy and materials requirements come from the papers mentioned in the alternatives' description. The database used is ecoinvent 3.4. The most fundamental energy/mass flows were taken from background processes, already available in ecoinvent 3.4 and are subjected to average values or estimations. In some cases, the economic or environmental flows could not be found in the database. Therefore, the closest proxies were selected. The detailed information on the change applied can be found in the electronic Excel file "Appendix, Life Cycle Inventories, Pilot-scale LCA files".

Succinct descriptions of the four electrolyser's models are provided below.

For the model *AE NL 2017:*

The system from Koj, Wulf, Schreiber, & Zapp (2017) is a 6 MW alkaline installation, using a novel Zirfon membrane, made of four cells with 139 cells each (total of 556 cells). Zirfon is an anion exchange membrane developed by the Afga-Gevaert group. It contains 85 wt% of hydrophilic zirconium dioxide (ZrO_2) and 15 wt% polysulfone (Poggi-varaldo & Romero-casta, 2017). The 6 MW scale was not yet available on a commercial scale at the time of the paper. Therefore, the authors of the paper made some projections based on existing 3.5 MW electrolysers. The authors assumed a load factor of 95% (8300h/year). The origin of electricity is not clearly stated but assumed to be from the national grid. The installation's lifetime is estimated to be 20 years, the stack's and electrolyte's lifetime are worth 10 years before replacement. The data provided for the constructing materials were per AEL (Alkaline water ELectrolysis) plant, so it is assumed that the time scope equals 20 years and the data consider all the necessary replacements (cells and electrolytes) (Franetzki, 2008).

For the model *AE NL 2018:*

Not many specific details are available on the description of the electrolyser from Wulf & Kaltschmitt (2018). However, contacts with the authors confirmed that the lifetime of the electrolyser system is supposed to be 20 years. The plant has a capacity production of 26 kg H_2/h, with a stack lifetime of 10 years and a full load hours value of 7500 h/y (availability of ca. 86%). Again, the electricity's origin is not clearly defined and assumed to be from the grid. The life cycle inventories tables provide the construction materials, assumed to be the total necessary for all cells during their entire lifetime use.

For the model *PEM NL 2018a:*

The first PEM model comes from the same paper of Wulf & Kaltschmitt (2018) than the model AE NL 2018. Therefore, there are not so many details provided. Nevertheless, the lifetime of the PEM system is supposed to be 20 years and the production capacity is worth 48 kg H_2/h. The stack lifetime is worth only 8 years and the full load hours value is equal to 4000 h/y (availability of ca. 46%). The same remark for electricity than in AE NL 2018 applies. The life cycle inventories tables provide the construction materials amount, assumed to be the total necessary for all cells during their entire lifetime use.

The PEM electrolyser uses different kind of membranes with one of the most common ones being the Nafion. Despite the Nafion being a commercial membrane, no specific production process information has been found. However, several sources – such as the book "Nafion: properties, structure and applications" (Sutton, 2016) – indicates that the membrane is made of a hydrophobic polytetrafluoroethylene backbone. As no "Nafion" input is available in the ecoinvent database, the "tetrafluoroethylene" input has been used instead of "Nafion" for the model PEM NL 2018a.

For the model *PEM NL 2018b:*

The PEM electrolyser system studied by Schmidt, Topriska, Kolokotroni, & Azapagic (2018) is made of 4 stacks, each of them containing 20 cells (80 cells in total) with an outlet hydrogen pressure at 13.8 bar and a continuous average production of 1.14 Nm^3/h. The water flow is 9.3×10^{-4} m^3/h. Contacts with one of the authors, Ximena Schmidt Rivera, confirmed that the lifetime of the PEM electrolyser is worth 60,000h and that the lifetime of the electrolyser plant is estimated for 20 years. This would give an average full load hours value of 34%. This value is relatively low but is explained by the fact that the system under study is fed by solar panels. Furthermore, two PEM electrolysers were considered in the study to fulfil the cooking energy needs for Jamaican village of 20 households. This information provides some background context for the final use of the system. For the pilot-scale LCA models, a shift has been operated from electricity from solar panels to electricity from wind turbines, but the full load hours value has been kept the same. Calculations showed that the global average production for one PEM electrolyser is 0.22 kg H_2/h (so equivalent to 1.14 Nm^3/h).

For the model *SMR 2018:*

The SMR technology is already applied on a large-scale and cannot be considered at a "pilot-scale". Nevertheless, a comparison is made for 1 kg of H_2 production between PEM and AE technologies and SMR.

3.2.1) Economic-environment boundaries

A distinction is made between the product system and the environment and between environmental flows and economic flows. In the thesis, an environmental flow is defined as a flow leaving or entering the product system without prior or further human intervention. In this sense, environmental flows can be considered as "free" and "unlimited". The wind energy for the wind turbines is a typical example of an environmental flow considered as virtually unlimited and free. An economic flow is a flow that is treated or used by human factors. Hydrogen is considered as an economic flow as it is barely available in nature. The product system considers all the unit processes to fulfil the function of the LCA (production of hydrogen). The environment is the background where the environmental flows originate from. The flowcharts provide a visual representation of the boundaries. One noteworthy flow must be discussed in connection with boundaries definition's issue:

- The iridium is a noble metal necessary for the PEM electrolyser. However, iridium is modelled in ecoinvent only as an environmental flow. Consequently, when a unit process consumes iridium, it is implied that the process extracts directly iridium from nature, which is unlikely the case in reality. Due to the constraints of the thesis, iridium was modelled as an environmental flow, with full awareness of the modelling limitations.

3.2.2) Flowcharts

The flowcharts are provided below for a visual interpretation of the different pilot-scale LCA models.

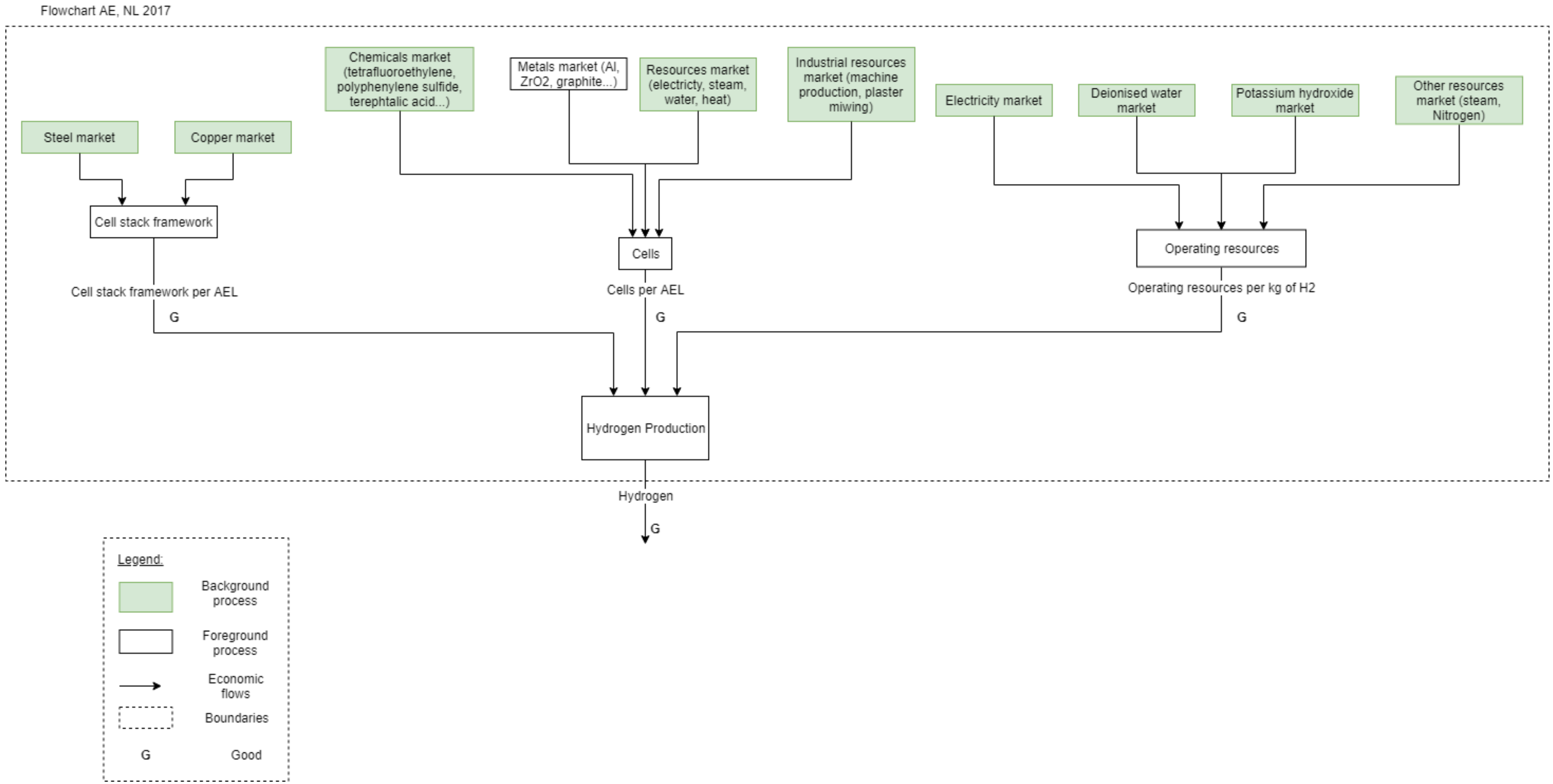


Figure 6. Flowchart of the model AE NL 2017

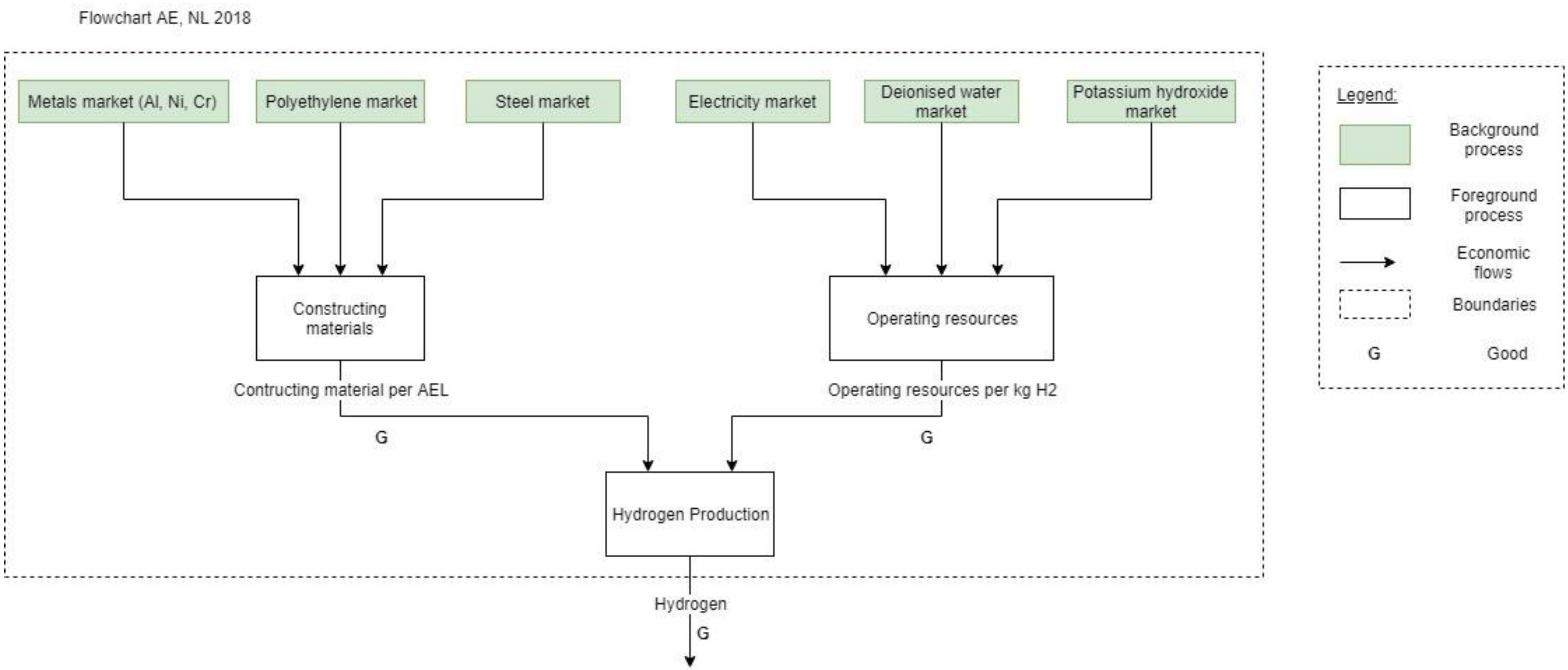


Figure 7. Flowchart of the model AE NL 2018

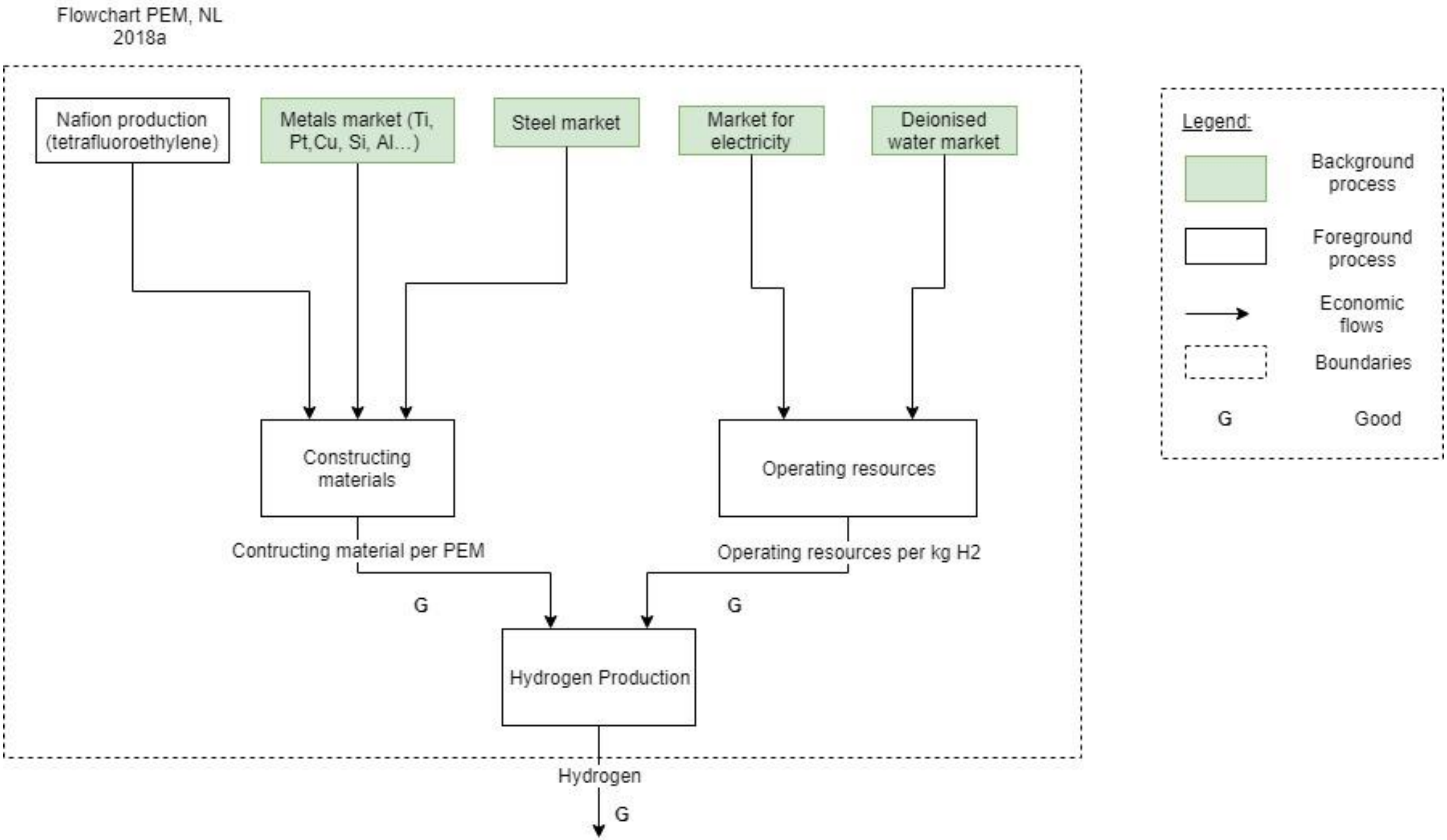


Figure 8. Flowchart of the model PEM NL 2018a

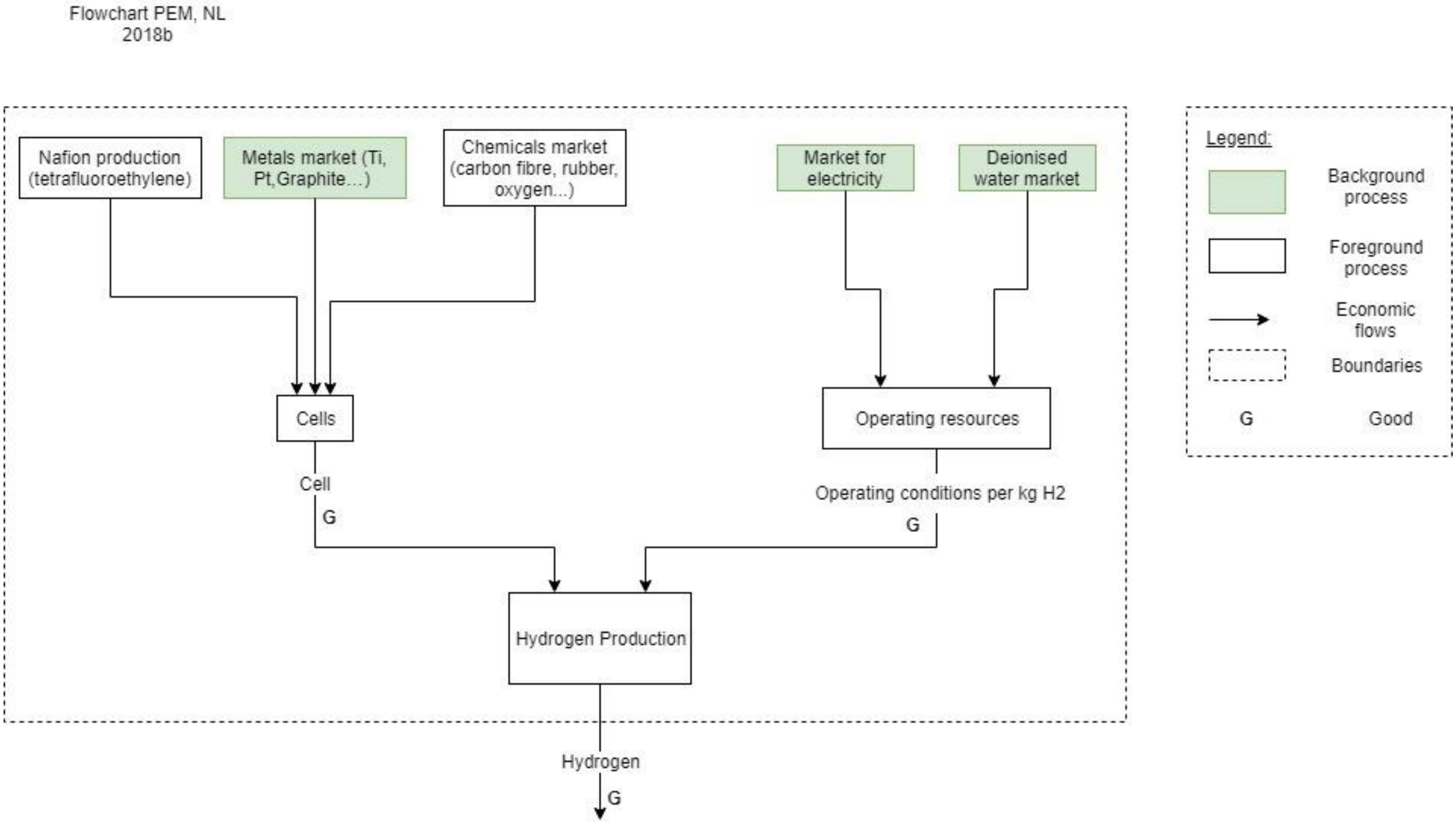


Figure 9. Flowchart of the model PEM NL 2018b

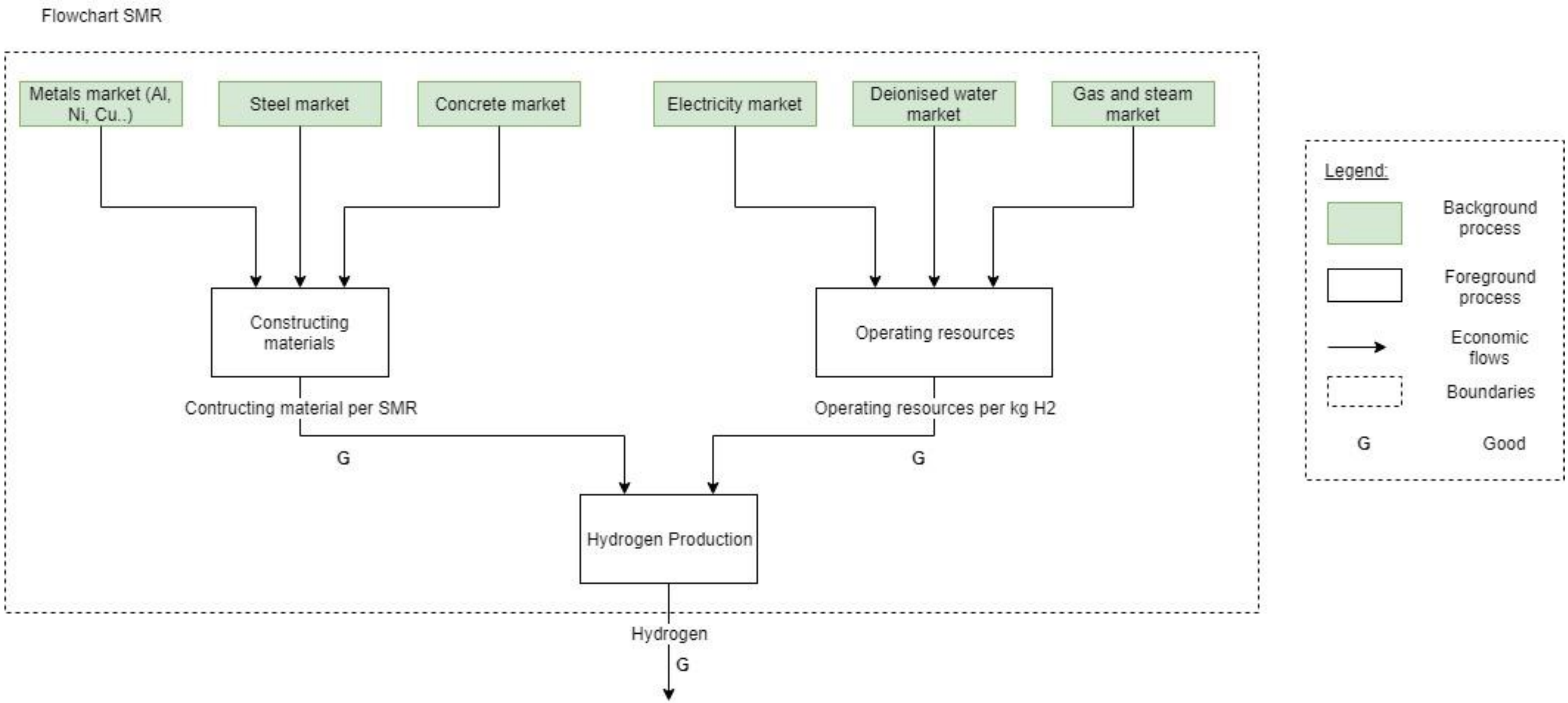


Figure 10. Flowchart of the model SMR

3.2.3) Comparability of the models:

Obviously, one of the main limits of the study is the question of comparability. Even though all the electrolyser plants mentioned above are considered to possess a lifespan of 20 years, they possess differences in their capacities and sizes. **Table 4** summarizes the main differences and gives an overview of the different models.

Table 4. Different characteristics between the pilot-scale electrolyser's models.

Model	**AE NL 2017**	**AE NL 2018**	**PEM NL 2018a**	**PEM NL 2018b**
Installation capacity	6 MW	1.23 MW	ca. 2.3 MW	ca. 11.4 kW
Total hydrogen production (20 years)	1.95×10^7 kg	3.90×10^6 kg	3.84×10^6 kg	1.34×10^4 kg (for two electrolysers)
Hydrogen production rate	118 kg/h	26 kg/h	48 kg/h	0.44 kg/h (for two electrolysers)
Number of cells	556	NA	NA	160 (for two electrolysers)
System use through one year	95%	86%	46%	34%

As shown in **Table 4**, the electrolyser's models possess differences regarding the total amount of hydrogen produced, the production rate or the system use through the year (in percentage). From this point of view, comparisons between the models must be taken with perspective and cautions. However, some elements can be mentioned in favour of comparisons:

- The functional unit for all the systems is "1 kg of hydrogen produced". In this sense, the LCA software disaggregates all the inputs and outputs in order to get the environmental impacts of only 1 kg of hydrogen. On the one hand, if a "big" plant – such as AE NL 2017 – can produce a lot of hydrogen, it also requires a lot of materials. On the other hand, "smaller" plant – such as PEM NL 2018b – produces less hydrogen but also require less energy/materials. That is why some kind of balancing effect may occur. As a matter of fact, when all the results are compared in Section 3.3, no significant change of scale is shown, except for some impact categories, supporting the "balancing-effect" assumption.
- The differences in scale and production capacity also reflect partly the state-of-the-art of the technology, highlighting the fact that PEM electrolyser is still a technology on evolution for reaching the large-scale system. On the contrary, alkaline technology is more mature and less flexible for technological change.
- Comparisons are valuable between the models "AE NL 2018" and "PEM NL 2018a". As a matter of fact, both models come from the same paper (Wulf & Kaltschmitt, 2018) and the total production values are similar (3.90×10^6 kg for AE and 3.84×10^6 kg for PEM).
- Finally, the goal of these pilot-scale LCA models is less to make actual comparisons between the models than to conduct contribution analyses in order to detect the potential hotspots parameters to consider for large-scale implementation. The proper ex-ante LCA will model a 1 GW-scale plant for PEM and alkaline electrolysers, improving at the same time the comparability aspect. With the ex-ante large-scale LCA models, comparisons will be more consistent.

3.3) Impact assessment

In the third phase of an LCA process, the results of the Life Cycle Inventory are given and connected to environmental impacts.

3.3.1) Impact categories, characterization and classification

Life cycle impact assessment provides the results of the inventory analysis in terms of environmental impacts. Several models exist to calculate the impacts, usually defined by acronyms such as ILCD, CML-IA, ReCiPe and others.

Depending on the impact assessment method selected, different impact categories are provided to describe the environmental impacts in several categories, such as climate change, eutrophication, acidification, eutrophication, resource depletion, etc.

Each of the environmental flows (CO_2, methane, nitrous oxides…) are connected to a characterization factor in order to aggregate their emissions into one common unit for each impact category where the mentioned flows possess impacts. This step is named the classification. For example, the unit of the impact category "climate change" is in "CO_2-eq", with the CO_2 emissions taken as a reference value. Methane (CH_4) emissions are one type of environmental flows that have impacts on climate change and the characterisation factor provides the following equivalence: 1 kg CH_4 ⇔ 25 kg CO_2 éq. So, if a process emits 2 kg of CO_2 and 3 kg of CH_4, its total impact in "climate change" will be worth 77 kg CO_2-eq (2 + 3 x 25).

All unit processes from the LCA model generate emissions flows. The latter are aggregated into common units so consistent results are given. In the thesis, the ILCD 2011 baseline has been chosen as an impact assessment method (also named 'family'). ILCD 2011 enables to consider quite a large scope of impact categories, with considering global warming, human toxicity, water resource depletion or freshwater eutrophication. The analyses of the environmental profiles and some contribution analyses enable to detect the potential hotspots or parameters that will be important to consider in the upscaling process for the electrolysers. **Table 5** provides the list of the different impact categories defined by the ILCD method.

Table 5. Overview of the different impact categories considered by the ILCD impact assessment method.

Impact category	**Unit**
Acidification	molc H^+ eq
Climate change	kg CO_2 eq
Freshwater ecotoxicity	CTUe
Freshwater eutrophication	kg P eq
Human toxicity, cancer effects	CTUh
Human toxicity, non-cancer effects	CTUh
Ionizing radiation E (interim)	CTUe
Ionizing radiation HH	kBq U_{235} eq
Land use	kg C deficit
Marine eutrophication	kg N eq
Mineral, fossil & ren resource depletion	kg Sb eq
Ozone depletion	kg CFC-11 eq
Particulate matter	kg $PM_{2.5}$ eq
Photochemical ozone formation	kg NMVOC eq
Terrestrial eutrophication	molc N eq
Water resource depletion	m^3 water eq

The ILCD Handbook provides a full description of the different impact categories (EC-JRC, 2010).

3.3.2) Flows without a characterization factor

Due to practical considerations, in all impact assessment methods, only a limited number of flows possess a characterization factor that enables to calculate the environmental impact. These flows are considered in the environmental profiles and characterization results. Some flows lack characterization factors and therefore, their impacts are not assessed, even though the flows are numerically calculated. The list of the flows lacking a characterization factor can be found in the analysis results in the software OpenLCA (OpenLCA sheet "LCIA checks" in the product systems). The latest OpenLCA version available did not enable to extract the flows lacking a characterisation factor and to copy them in some other electronic file (Excel or equivalent). The list of these environmental flows can indicate which flows are not taken into account for the environmental profile and also show the limitations of the model. For example, in the "Human toxicity, non-cancer effect" impact category, the "carbon monoxide, fossil" flow is not connected to a characterization factor and is therefore not taken into account. However, carbon monoxide is known to be toxic to human health. This is one of the limitations that must be acknowledged with the LCA model.

3.3.3) Characterization results

The complete characterization results, i.e. the complete emissions per environmental flow, are present in the Excel appendix attached to the thesis "Appendix, Inventory results, pilot-scale LCA models".

3.3.4) PEM and AE comparisons (Dutch grid)

To begin with, a comparison between an alkaline and a PEM electrolysis has been conducted, with the electricity feed for the electrolyser coming from the Dutch national grid. To do so, only the models AE NL 2018 and PEM NL 2018a were compared, with SMR NL 2018 taken as BAU case, as the three models come from the same paper. This way, their comparison is deemed more consistent than a comparison with models coming from distinct sources.

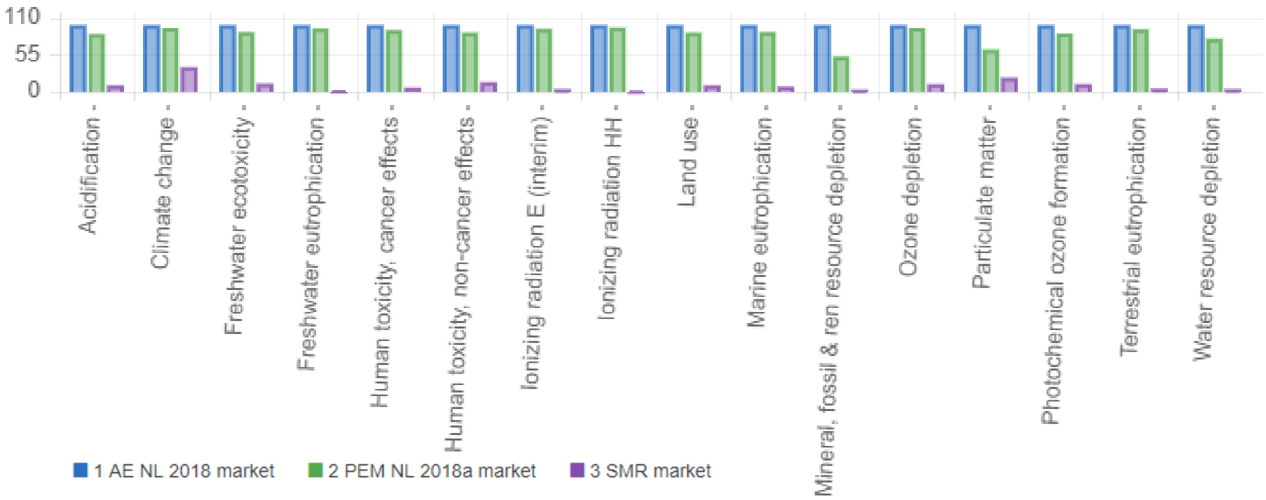


Figure 11. Relative environmental results of the 2 electrolyser's technologies (PEM and AE) and SMR with the ILCD family (models from Wulf & Kaltschmitt (2018)). The electricity comes from the Dutch grid mix.

Table 6. LCIA results of the 2 electrolysis technologies (PEM and AE) and SMR with the ILCD family (models from Wulf & Kaltschmitt (2018)). The electricity comes from the Dutch grid mix.

Impact category	1 AE NL 2018 market	2 PEM NL 2018a market	3 SMR NL market	Unit	Factor change AE/SMR	Factor change PEM/SMR	Differences between AE and PEM
Acidification	7.59E-02	6.60E-02	9.17E-03	molc H^+ eq	8.27	7.19	13.04%
Climate change	3.05E+01	2.92E+01	1.14E+01	kg CO_2 eq	2.68	2.56	4.45%
Freshwater ecotoxicity	1.22E+02	1.10E+02	1.51E+01	CTUe	8.12	7.26	10.54%
Freshwater eutrophication	1.26E-02	1.20E-02	2.97E-04	kg P eq	42.49	40.31	5.15%
Human toxicity, cancer effects	1.18E-06	1.09E-06	7.57E-08	CTUh	15.64	14.43	7.75%
Human toxicity, non-cancer effects	4.46E-06	3.99E-06	6.38E-07	CTUh	7.00	6.25	10.67%
Ionizing radiation E (interim)	8.51E-06	8.02E-06	3.53E-07	CTUe	24.10	22.70	5.78%
Ionizing radiation HH	3.78E+00	3.65E+00	8.35E-02	kBq U_{235} eq	45.24	43.78	3.23%
Land use	2.11E+01	1.87E+01	2.01E+00	kg C deficit	10.48	9.30	11.21%
Marine eutrophication	1.47E-02	1.32E-02	1.98E-03	kg N eq	7.42	6.66	10.24%
Mineral, fossil & ren resource depletion	1.61E-04	8.56E-05	5.83E-06	kg Sb eq	27.52	14.68	46.65%
Ozone depletion	1.65E-06	1.58E-06	1.91E-07	kg CFC-11 eq	8.62	8.25	4.31%
Particulate matter	4.52E-03	2.89E-03	9.56E-04	kg $PM_{2.5}$ eq	4.73	3.02	36.13%
Photochemical ozone formation	3.45E-02	3.00E-02	9.35E-03	kg NMVOC eq	3.69	3.21	12.80%
Terrestrial eutrophication	2.27E-01	2.12E-01	2.04E-02	molc N eq	11.13	10.42	6.36%
Water resource depletion	8.21E+00	6.52E+00	3.51E-01	m^3 water eq	23.41	18.58	20.60%

A prominent result from **Figure 11** and **Table 6** is that PEM and alkaline electrolysers perform worse than SMR in all impact categories, usually by a factor 10 or 20. These first results seem to favour the use of the SMR technology when the electricity comes from the Dutch national grid. From **Table 6**, PEM electrolyser performs better than alkaline electrolysers in all impact categories as well, with average variations of ca. 15%. Nevertheless, variations can be substantial, reaching 46.65% with the "Mineral, fossil & ren resource depletion" impact category.

The same comparison is reiterated, with the electricity feed for the electrolyser coming from the Dutch offshore wind turbines (no change for SMR). In **Figure 12** and **Table 7**, the results of the comparison are provided.

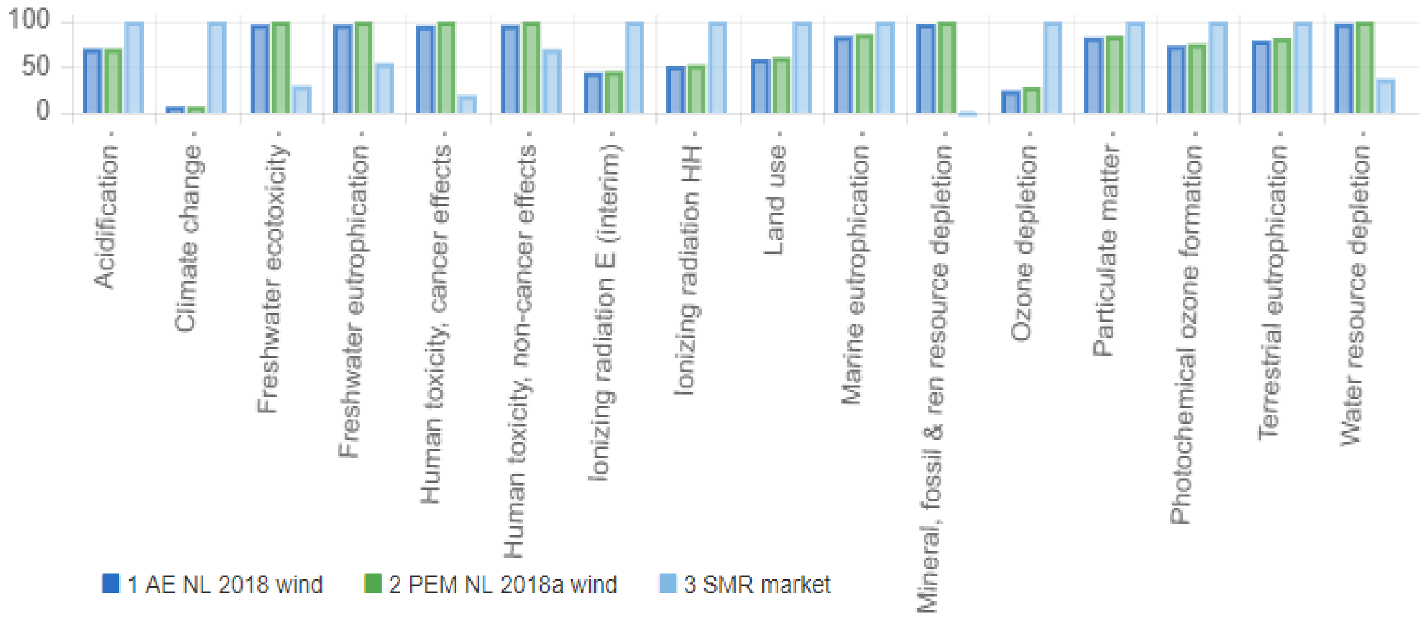


Figure 12. Relative environmental results of the 2 electrolyser's technologies (PEM and AE) and SMR with the ILCD family (models from Wulf & Kaltschmitt (2018)). The electricity comes from the Dutch grid mix for SMR and from Dutch offshore wind turbines for the electrolysers.

Table 7. LCIA results of the 2 electrolysis technologies (PEM and AE) with the ILCD family (models from Wulf & Kaltschmitt (2018)). The electricity comes from the Dutch grid mix for SMR and from Dutch offshore wind turbines for the electrolysers.

Impact category	1 AE NL 2018 wind	2 PEM NL 2018a wind	3 SMR market	Unit	Differences between AE and PEM
Acidification	5.37E-03	5.52E-03	9.17E-03	molc H^+ eq	-2.77%
Climate change	7.70E-01	7.95E-01	1.14E+01	kg CO_2 eq	-3.23%
Freshwater ecotoxicity	5.02E+01	5.19E+01	1.51E+01	CTUe	-3.39%
Freshwater eutrophication	5.30E-04	5.53E-04	2.97E-04	kg P eq	-4.32%
Human toxicity, cancer effects	3.82E-07	4.00E-07	7.57E-08	CTUh	-4.65%
Human toxicity, non-cancer effects	8.80E-07	9.22E-07	6.38E-07	CTUh	-4.69%
Ionizing radiation E (interim)	1.56E-07	1.60E-07	3.53E-07	CTUe	-2.49%
Ionizing radiation HH	4.30E-02	4.39E-02	8.35E-02	kBq U_{235} eq	-2.29%
Land use	1.19E+00	1.23E+00	2.01E+00	kg C deficit	-3.23%
Marine eutrophication	9.59E-04	9.90E-04	1.98E-03	kg N eq	-3.15%
Mineral, fossil & ren resource depletion	4.01E-04	4.11E-04	5.83E-06	kg Sb eq	-2.57%
Ozone depletion	4.63E-08	5.38E-08	1.91E-07	kg CFC-11 eq	-16.04%
Particulate matter	7.77E-04	8.02E-04	9.56E-04	kg $PM_{2.5}$ eq	-3.27%
Photochemical ozone formation	2.91E-03	3.01E-03	9.35E-03	kg NMVOC eq	-3.42%
Terrestrial eutrophication	8.92E-03	9.22E-03	2.04E-02	molc N eq	-3.28%
Water resource depletion	9.22E-01	9.40E-01	3.51E-01	m^3 water eq	-1.98%

Figure 12 and **Table 7** prove that the electricity's origin plays a significant role in the environmental profile from the three alternatives (AE, PEM and SMR). As a matter of fact, SMR performs worse than any electrolyser in 10 out of 16 impact categories. If a shift is to be made to renewable energy systems, electrolysers become much more relevant to increase the sustainability of hydrogen's production.

From **Table 7**, the performances' differences between AE and PEM are smaller than in **Table 6**. Only the "ozone depletion" impact category shows a non-negligible variation (16.04%). PEM possesses a larger impact than AE in all the impact categories from ILCD 2011 baseline with electricity from Dutch wind turbines, whereas PEM had lower impacts than AE with electricity from the grid. The contribution analyses provide some guidelines to understand this change in results. **Figure 12** and **Table 7** favour the use of the alkaline technology when the electricity for operation comes only from Dutch offshore wind turbines and this interpretation is coherent with some stakeholders' opinions (Nouryon, 2018, personal contact).

Further contribution analyses show which parameters could become more relevant when an upscaling process is considered for the electrolyser and a shift operated to renewable energy systems. For the alkaline electrolyser, the nickel market and water consumption become non-negligible contributors to several impact categories. For the PEM electrolyser, the market for tetrafluoroethylene (used in the Nafion membrane) and the market for water become non-negligible contributors for some impact categories. The contribution analyses conducted in section 3.4.3 and 3.4.4 describe with some more details the different parameters that will be considered in the upscaling process for the ex-ante large-scale LCA model.

3.3.5) PEM, AE and SMR comparisons (Dutch wind turbines)

The next analysis compares all models for AE (AE NL 2017 and AE NL 2018), PEM (PEM NL 2018a and PEM NL 2018b) and SMR (SMR NL 2018), even though the comparability factor is debatable (see section 3.2.3). In **Figure 13** and **Table 8**, the electricity for operation comes only from Dutch offshore wind turbines for AE and PEM. Again, to adjust the situation to the Netherlands, the electricity for SMR is coming from the Dutch electricity market (e.g. the grid). The electricity from Dutch wind turbines is not considered for the SMR alternative since there is no plan considered in the thesis to make SMR plants connected to wind energy. The goal of **Figure 13** and **Table 8** is to compare the relative performances of wind-based electrolysis with SMR.

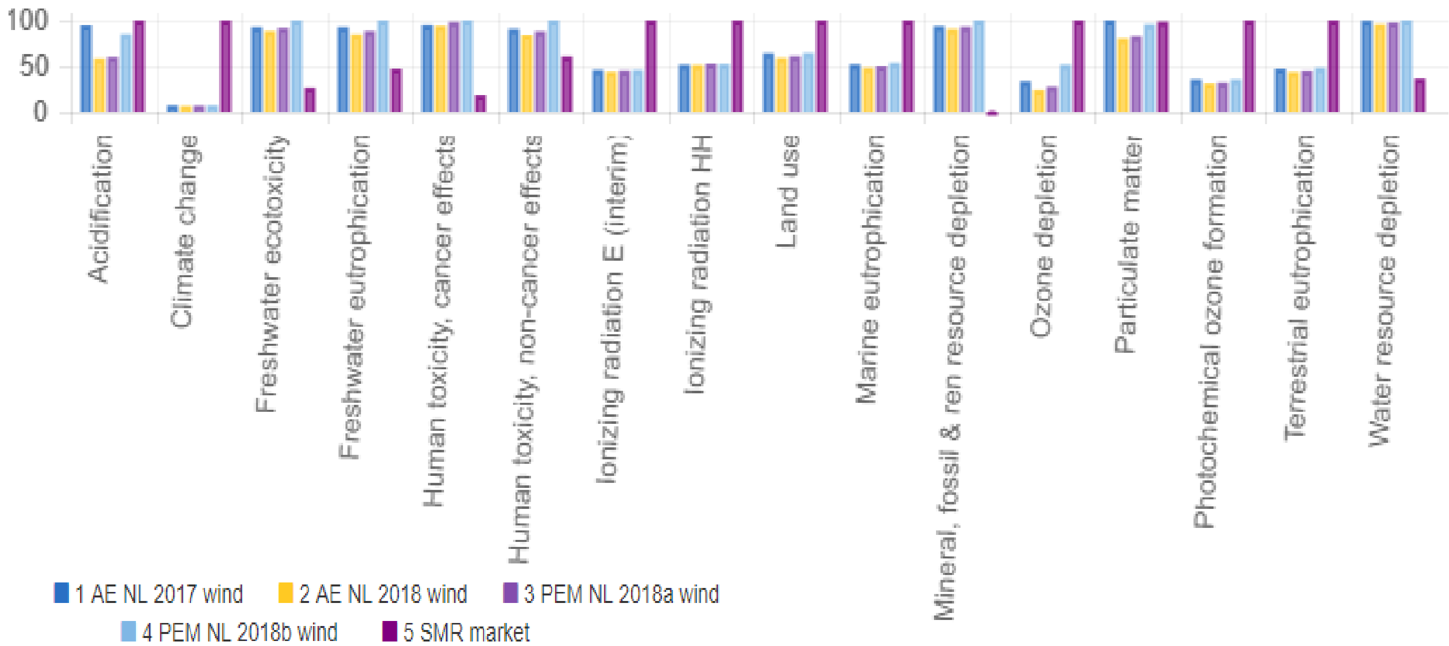


Figure 13. Relative environmental results of the 2 electrolysis technologies (PEM and AE, 2 models each) with the Dutch offshore wind turbines electricity and the SMR with the Dutch electricity market (ILCD family).

Table 8. LCIA results of the 2 electrolysis technologies (PEM and AE, 2 models each) with the Dutch offshore wind turbines electricity and the SMR with the Dutch electricity market (ILCD family).

Impact category	**1 AE NL, 2017**	**2 AE NL, 2018**	**3 PEM NL, 2018a**	**4 PEM NL, 2018b**	**5 SMR, NL**	**Unit**
Acidification	8.70E-03	5.37E-03	5.52E-03	7.81E-03	9.17E-03	molc H^+ eq
Climate change	8.40E-01	7.70E-01	7.95E-01	8.40E-01	1.14E+01	kg CO_2 eq
Freshwater ecotoxicity	5.26E+01	5.02E+01	5.19E+01	5.66E+01	1.51E+01	CTUe
Freshwater eutrophication	5.80E-04	5.30E-04	5.53E-04	6.25E-04	2.97E-04	kg P eq
Human toxicity, cancer effects	3.86E-07	3.82E-07	4.00E-07	4.06E-07	7.57E-08	CTUh
Human toxicity, non-cancer effects	9.52E-07	8.80E-07	9.22E-07	1.05E-06	6.38E-07	CTUh
Ionizing radiation E (interim)	1.63E-07	1.56E-07	1.60E-07	1.62E-07	3.53E-07	CTUe
Ionizing radiation HH	4.32E-02	4.30E-02	4.39E-02	4.37E-02	8.35E-02	kBq U_{235} eq
Land use	1.29E+00	1.19E+00	1.23E+00	1.30E+00	2.01E+00	kg C deficit
Marine eutrophication	1.03E-03	9.59E-04	9.90E-04	1.06E-03	1.98E-03	kg N eq
Mineral, fossil & ren resource depletion	4.14E-04	4.01E-04	4.11E-04	4.42E-04	5.83E-06	kg Sb eq
Ozone depletion	6.46E-08	4.63E-08	5.38E-08	9.90E-08	1.91E-07	kg CFC-11 eq
Particulate matter	9.69E-04	7.77E-04	8.02E-04	9.27E-04	9.56E-04	kg $PM_{2.5}$ eq
Photochemical ozone formation	3.32E-03	2.91E-03	3.01E-03	3.32E-03	9.35E-03	kg NMVOC eq
Terrestrial eutrophication	9.64E-03	8.92E-03	9.22E-03	9.86E-03	2.04E-02	molc N eq
Water resource depletion	9.59E-01	9.22E-01	9.40E-01	9.63E-01	3.51E-01	m^3 water eq

No obvious "most sustainable option" can be found from **Figure 13** and **Table 8**, even though the model AE NL 2018a seems to be on average the most sustainable option. The model AE NL 2017 possesses relatively high impacts compared to other electrolysers, such as in "Acidification" and "Particulate matter". A contribution analysis has been conducted in order to explain these relatively high results. The main difference from AE NL 2017 with the other electrolyser's models comes in the level of details for the cell's construction. The model AE NL 2017 provides more details for specific elements than the model AE NL 2018 and the two PEM models. This difference in description likely induces the difference in environmental performances for "Acidification" and "Particulate matter".

The results from **Figure 13** and **Table 8** indicate that the primacy of the electrolysis (even wind-based) on the SMR is not so obvious and depends on the impact category considered. SMR performs relatively well in general, except in "Climate change", "Ionizing radiation E", "Ionizing radiation HH", "Land use", "Marine eutrophication" and "Ozone depletion" where its environmental impacts are much more massive than the other alternatives.

3.4) Interpretation

The "Interpretation" stage analyses the results for their consistencies, soundness and robustness. Based on these evaluations, interpretations, recommendations and conclusions can be drawn. Some consistency and completeness checks are made in order to see how some chemical aspects could be better modelled or implemented. For the pilot-scale LCA models, contribution analyses are conducted.

3.4.1) Consistency check

A check on whether the assumptions, methods, models and data are consistent with the goal and scope defined is necessary. Two main elements can be mentioned:

- *Differences in data sources*: the pilot-scale LCA models were based on different studies, except for AE NL 2018, PEM NL 2018a and SMR 2018b. The last three come from the same resource (Wulf & Kaltschmitt, 2018). This fact increases the comparability factor which has also been discussed in Section 3.2.3. The use of different resources can limit the comparability but enable to consider more general trends.
- *Differences in technology's knowledge*: alkaline electrolysers are more mature and used than PEM electrolysers. Consequently, more detailed data inventories and studies are available for alkaline than PEM electrolysers. The relevance, accuracy and comparability of data can be questioned then. To counterbalance this effect, a similar LCA framework (see flowcharts) was adopted for both electrolysers, with comparable unit processes and boundaries.

Apart from the two points mentioned above, no other serious consistency issue was found.

3.4.2) Completeness check

The completeness check verifies that all relevant data are available and complete. Again, two main points can be discussed:

- *Data reliability*: the data came from ecoinvent, one of the most prominent LCA databases, from academics' papers or were adjusted based on experts' contacts. Some data from ecoinvent may be rather old (up to the 1990s) but it would be the case for both alternatives (common processes for alkaline and PEM electrolysers). In this perspective, the consistency between the alternatives considered is deemed as strong enough.
- *Comparison with other similar LCAs*: even though no LCA can be properly compared to another, some considerations can still be achieved with the works from Koj et al. (2017), Schmidt et al. (2018) and Wulf & Kaltschmitt (2018). Overall, the pilot-scale LCA models from the thesis possess lower environmental impacts than the ones from the literature review, except for a few impact categories ("Human toxicity" and "Photochemical ozone formation"). Depending

on the literature resource considered, conclusions can vary and the presence of several factors can make the comparison even more delicate to conduct (electricity from the grid or the wind, AE or PEM). The most likely reasons that justify the variations are the geographical differences between the literature review and the Dutch case considered in the thesis (e.g. the electricity comes from the Dutch grid or Dutch wind turbines) and differences in impact assessment methods used (CML 2001, ReCiPe or others). Even though the impact assessment methods may possess "equivalent" impact categories such as "acidification", the calculations methods can be different and provide different interpretations.

3.4.3) Contribution analysis of the AE models

The goal of this section is to conduct a contribution analysis of the alkaline electrolyser's models. By doing so, relevant parameters can be selected for the upscaling stage afterwards. As no critical technological change is expected from the offshore electricity production in the future and as the goal of the thesis is to focus on the electrolysis technology, the contributor processes linked to electrolysers will be considered more deeply than the ones linked to wind turbines.

3.4.3.1) Model AE NL 2017:

An alkaline electrolyser has been modelled based on the paper from Koj, Wulf, Schreiber, & Zapp (2017). This paper considers a large-scale pressurized 6 MW alkaline system with a novel Zirfon membrane. Two stages were considered for this model: the "cell stack construction" (subdivided into cells and cell stack framework) and "Operating resources". The functional unit is 1 kg of H_2 and the electricity comes from the Dutch offshore wind turbine.

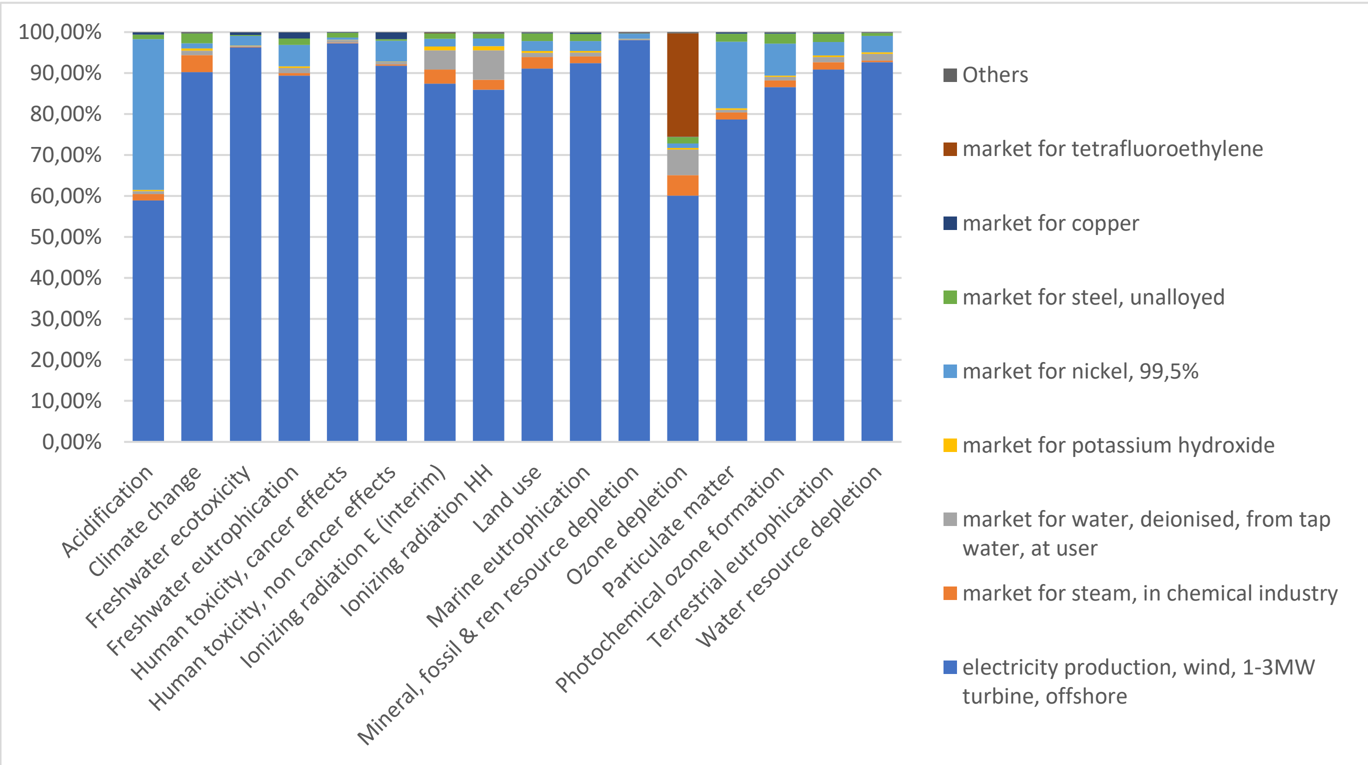


Figure 14. Contribution analysis for AE NL 2017 (based on Koj, Wulf, Schreiber, & Zapp) for the different impact categories from ILCD 2011 baseline.

As shown in **Table 32** (Appendix 3) and **Figure 14**, in most of the impact categories, the highest contributor to the environmental impact is the electricity production system. However, around 37% of the "Acidification" impact and 16% of the "Particulate matter" impact come from the nickel market (used for the electrodes) and 25% of the “Ozone layer depletion” comes from the tetrafluoroethylene market (used for the gasket manufacturing).

Therefore, an interesting aspect would be to consider how the nickel and tetrafluoroethylene requirements for the AE system may be dealt with or improved in the future. Both elements appear in the cell’s construction.

3.4.3.2) Model AE NL 2018:

Another alkaline electrolyser has been modelled based on the paper from Wulf & Kaltschmitt (2018). This paper considers an alkaline electrolyser directly installed at a hydrogen refuelling station, in Germany. For the following results, the functional unit is 1 kg of H_2 and the electricity for operation comes from the Dutch offshore wind turbine.

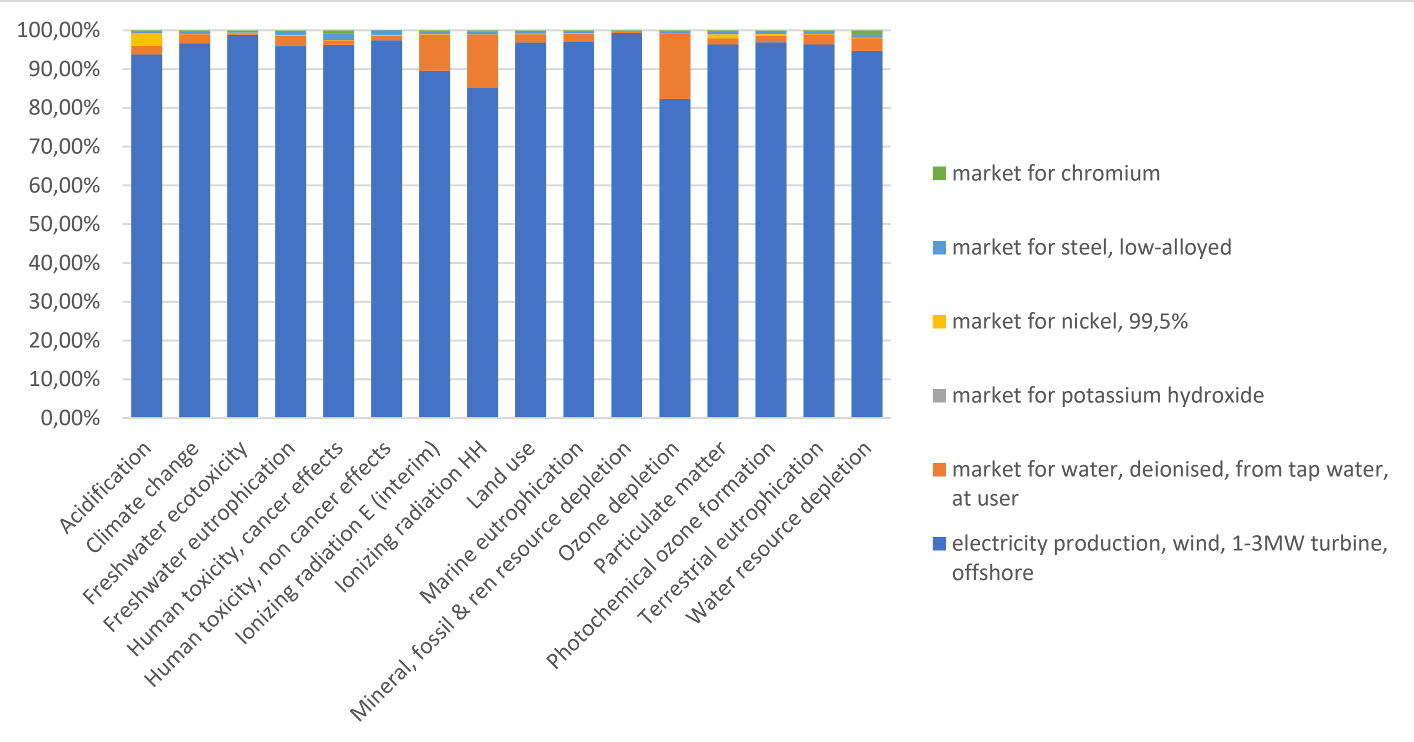


Figure 15. Contribution analysis for AE NL 2018 (based on Wulf & Kaltschmitt) for the different impact categories from ILCD-2011 baseline.

As shown in **Figure 15** and **Table 33** (Appendix 3), the two main contributors to the environmental impacts are the electricity production and the market for deionised water. The water consumption for the electrolyser possesses a non-negligible impact in “Ionizing radiation E” (9%), “Ionizing radiation HH” (14%) and “Ozone depletion” (17%). Quite surprisingly, the water use for the electrolyser is not a significant contributor in the “Water resource depletion” category. The water consumption for the wind turbine’s construction is more predominant in this model. In comparison to other factors, the constructing materials (e.g. steel, chromium, nickel…) for the electrolyser possess only limited impacts (a few per cent).

3.4.3.3) Comparison of the two models of AE:

A comparison between 2 LCAs must be kept with a lot of perspectives because many reasons can explain the differences in results. However, the two papers used to model the AE systems considered construction needs and operating needs, thus the boundaries are normally the same. It can be noted that in both previous models, nickel and potassium hydroxide were used for the electrolyser. However, the nickel market possesses a much more noticeable impact in the model AE NL 2017 (from Koj et al.

(2017)) and the electricity production possesses a slightly lower contribution impact in comparison with the model AE NL 2018 (from Wulf & Kaltschmitt (2018)).

3.4.4) Contribution analysis of the PEM models

The goal of this section is to conduct a contribution analysis on the PEM electrolyser's models. By doing so, relevant parameters can be selected for the upscaling stage afterwards.

3.4.4.1) Model PEM NL 2018a:

A PEM electrolyser has been modelled based on the paper from Wulf & Kaltschmitt (2018). Like the model AE NL 2018, the authors consider a PEM electrolyser system directly installed at a hydrogen refuelling station, in Germany. For the following results, the functional unit is 1 kg of H_2 and the electricity comes from the Dutch offshore wind turbine.

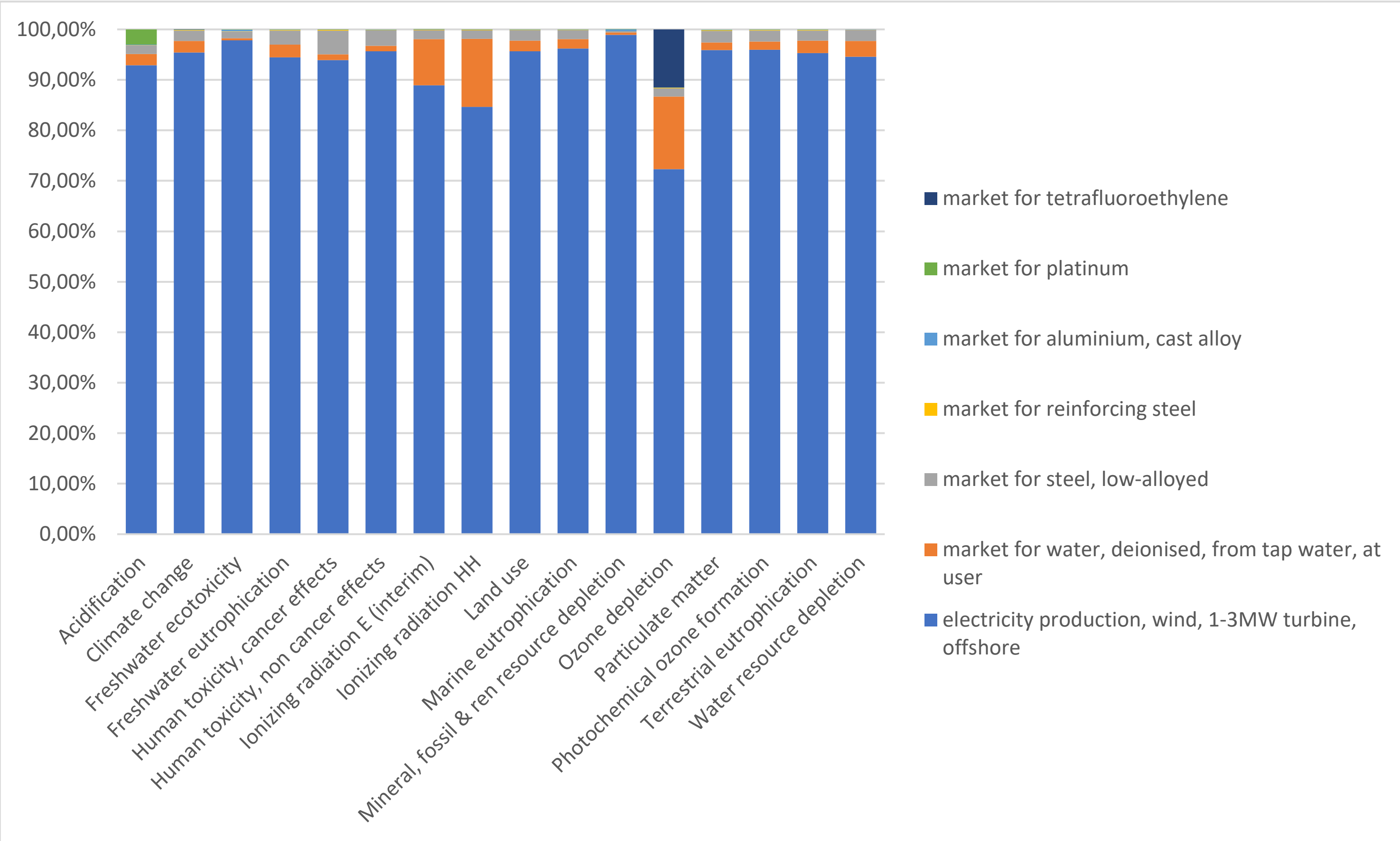


Figure 16. Contribution analysis for PEM NL 2018a (based on Wulf & Kaltschmitt) for the different impact categories from ILCD 2011 baseline.

As shown in **Figure 16** and **Table 34** (in Appendix 3), the "electricity production" is the main contributor to the environmental impact for all impact categories. However, the "market for deionised water" possesses again a non-negligible impact "Ionizing radiation E" (9%), "Ionizing radiation HH" (13%) and "Ozone depletion" (14%). Furthermore, in the "Ozone layer depletion" impact category, the market for tetrafluoroethylene shares 11.5%. The tetrafluoroethylene comes from the Nafion product required for the PEM electrolyser. Nafion is a sulfonated tetrafluoroethylene based fluoropolymer-copolymer, a membrane, produced among others by DuPont and used by PEM electrolysers as an electrolyte. Some database, such as GaBi, possess a "Nafion" input. However, no "Nafion" input is available in the ecoinvent database. Therefore, in the model PEM NL 2018a, the membrane has been modelled as a "tetrafluoroethylene" input, based on the description found in the literature. Overall, the tetrafluoroethylene requirements and the water need for the PEM system should be considered for the upscaling process.

3.4.4.2) Model PEM NL 2018b:

Another PEM electrolyser's model has been developed based on the work from Schmidt et al. (2018). These authors consider a system containing 80 cells, with an average production rate of 0.22 kg H_2/h (for one electrolyser, equivalent to 1.14 Nm^3/h in their paper). The LCA model considers the whole installation, i.e. 2 PEM electrolysers, as described by Schmidt et al. (2018). Originally, the system is fed with solar power. In the model PEM NL 2018b, a shift was operated to wind turbine electricity. Again, the functional unit is 1 kg of H_2.

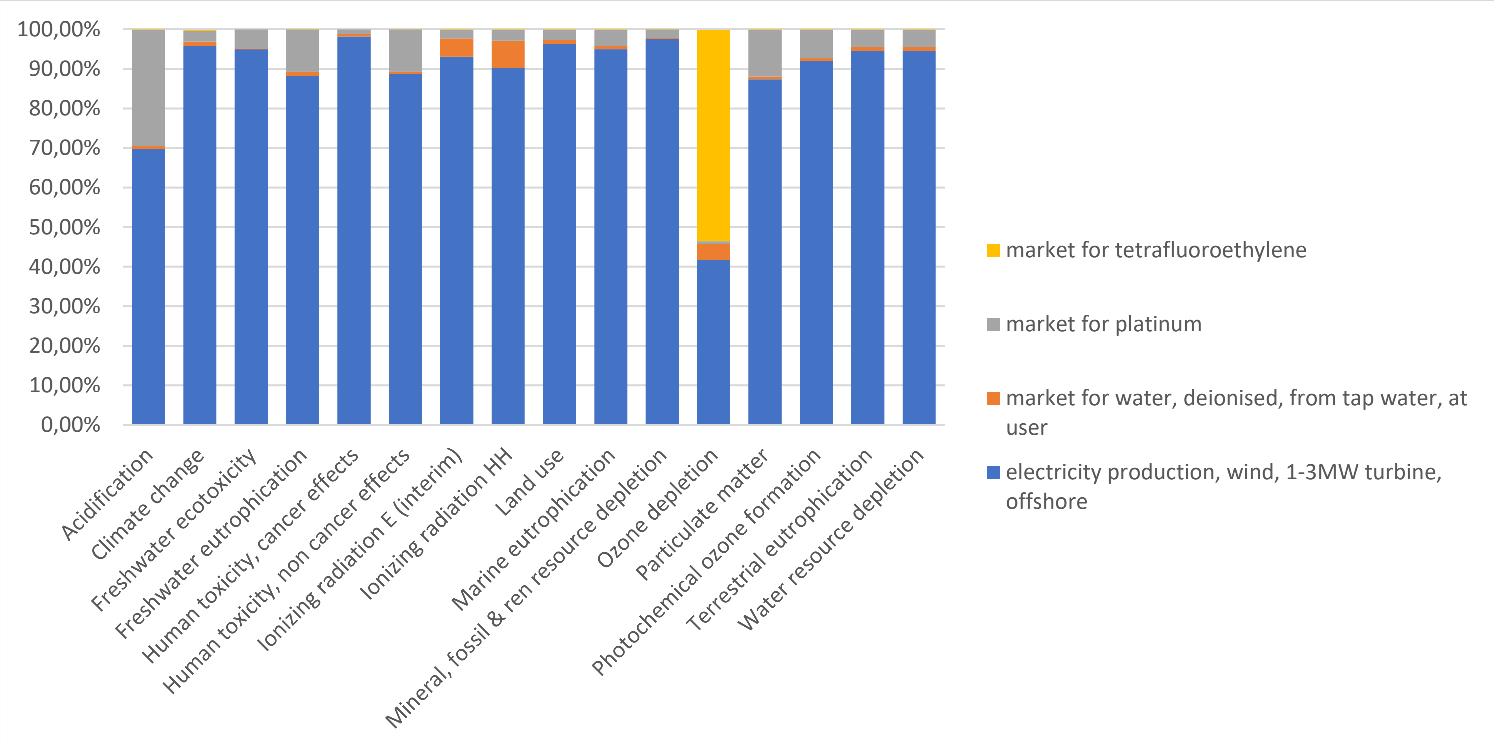


Figure 17. Contribution analysis for PEM NL 2018b (based on Schmidt et al., 2018) for the different impact categories from ILCD 2011 baseline.

Again, the electricity production is the biggest process contributor to all impact categories, as shown in **Figure 17** and **Table 35** (Appendix 3). The market for deionised water can be noticeable in some impact categories such as "Ionizing radiation HH" (7%) and "Ozone depletion" (8%). The cell components on the contrary account for negligible impacts, except in the "Ozone depletion" impact category with the tetrafluoroethylene market (7%). Again, the tetrafluoroethylene is linked to the Nafion membrane. Overall, similarly to the model PEM NL 2018a but to a lesser extent, the tetrafluoroethylene requirements and the water need for the PEM system should be considered for the upscaling process.

3.4.4.3) Comparison of the two models of PEM:

A comparison of 2 LCAs should be kept with perspective for many reasons. Nevertheless, a few considerations can be drawn from the previous results. Firstly, the electricity production is the highest process contributor for all the impact categories, as suggested as well by other LCA studies (Biswas et al., 2013). Secondly, the water market can become a non-negligible factor. Finally, the "constructing materials" (i.e. Nafion and steel) for the plant is relatively present in the PEM NL 2018a model, but not so much in PEM NL 2018b. In both cases, the tetrafluoroethylene (Nafion membrane) induces some contribution to the "ozone depletion" impact category. Therefore, better modelling for the Nafion membrane and the water needs could be elements to consider during upscaling processes. A final remark is that the influence of noble metals (Platinum, Iridium and Titanium) is shown to be negligible here. Nevertheless, some of these materials are Rare Earth elements and can become a sensitive parameter in a large-scale system.

3.4.5) Contribution analysis of the SMR model

The goal of this section is to conduct a quick contribution analysis of the SMR's model. By doing so, an overview is provided on the technology and the different constituents of it.

An SMR system has been modelled based on the work from Wulf & Kaltschmitt (2018). The SMR system includes a pressure swing adsorption system to purify the hydrogen. Detailed data tables for SMR were provided and were used as a base for the model. For the following results, the functional unit is 1 kg of H_2 and the electricity comes from the Dutch grid.

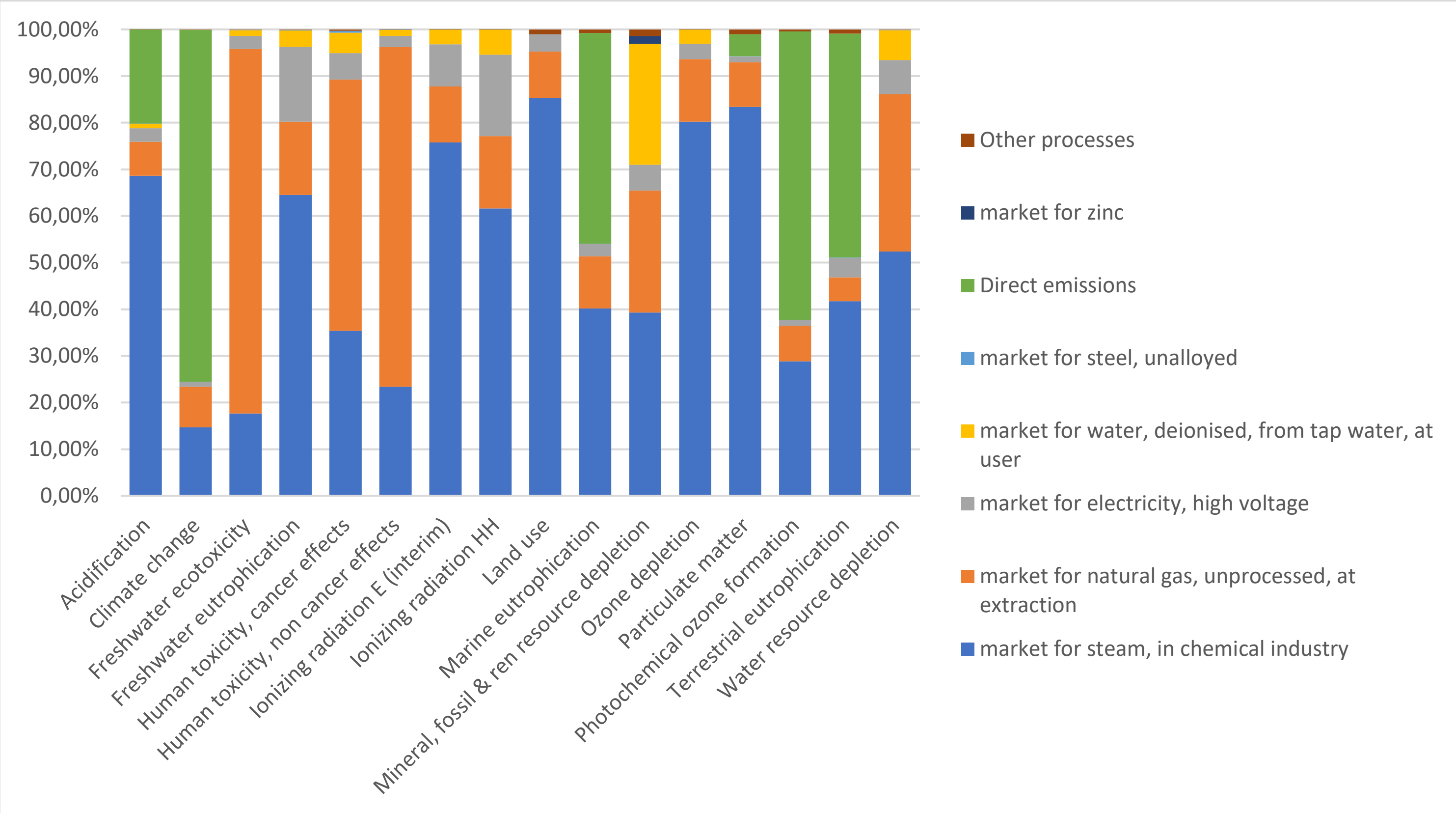


Figure 18. Contribution analysis for the SMR (based on Schmidt et al., 2018) for the different impact categories from ILCD 2011 baseline.

As shown in **Figure 18** and **Table 36** (in Appendix 3), the two main process contributors are the market for steam and for natural gas. The categories of "Climate change", "Photochemical ozone formation" and "Terrestrial eutrophication" show a large share of "Direct emissions". These emissions are due to the burning of the fuel itself (gas) (Wulf, personal communication, 2019). Otherwise, the market for electricity possesses a non-negligible share in impact categories such as "Ionizing radiation" or "Mineral, fossil & ren resource depletion".

3.5) Intermediary conclusions and answers to sub-questions 1 & 2

Based on all the results shown above, some conclusions can be made for the pilot-scale LCA model.

Firstly, no clear “most sustainable option” can be defined between PEM and AE. The models favour slightly the alkaline technology for now. Nevertheless, no strong conclusion can be drawn from it.

Secondly, when a complete comparison is being conducted (see Section 3.3.5), the SMR technology performs relatively well in different impact categories such as in “Freshwater ecotoxicity”, “Human toxicity”, “Mineral, fossil & ren resources depletion” and “Water resource depletion”. However, in some impact categories, SMR possesses the highest (or among the highest) impact, especially with the “climate change” impact category, but also in “Ionizing radiation E”, “Ionizing radiation HH”, “Land use”, “Marine eutrophication” and “Ozone depletion”.

Thirdly, a contribution analysis conducted on the alkaline electrolysis – based on AE NL 2917 and AE NL 2918 – showed that a focus should be made on the material components of the alkaline electrolyser, with nickel and tetrafluoroethylene. The water consumption can also be a factor to consider.

Fourthly, a contribution analysis conducted on the PEM electrolysis – based on PEM NL 2018a and PEM NL 2018b – showed that the tetrafluoroethylene consumption (linked to Nafion) could be an interesting parameter to consider for the upscaling process. The water consumption for the electrolyser can be a more sensitive parameter for PEM electrolysers than alkaline models. Otherwise, the performances remain mostly influenced by the electricity production. The results should still be considered with some perspective as PEM electrolyser is a less mature technology than alkaline and with the challenge to model the Nafion membrane.

Finally, the next steps will consist of tackling the different limits that appeared in the modelling’s development. One example is the modelling of the water feed. Electrolysers normally use demineralised water, which is slightly different than the “deionised water” available in ecoinvent. For the AE and PEM models developed at pilot-scale, the closest proxy (deionised water) has been chosen. The best option to improve the model is to develop a specific process for demineralised water’s production. The collaboration with ENGIE enabled to develop different models for the water resource. However, the results showed no significant change in the environmental profile and the assumption to consider “deionised water” from ecoinvent for hydrogen’s production was considered as consistent enough (see Appendix 8.1).

Some chemical components were also not available in ecoinvent, such as iridium dioxide or the membrane Nafion. The strategy chosen for the pilot-scale models was to use the stoichiometric approach and implement the chemicals separately (e.g. “Iridium” and “liquid oxygen” for “Iridium dioxide”). Similar approaches were used to model titanium, the carbon fibre and silicon (all details can be found in the electronic Excel file “Appendix, Life Cycle Inventories, Pilot-scale LCA files”). Most of the papers that were used to model the different chemicals came from Ullmann’s “Encyclopaedia of industrial chemistry” (Fitzer et al., 2012; Sibum et al., 2000; Zulehner, Neuer, & Rau, 2000).

Table 9 gives an overall review of the sensitive parameters to consider for the large-scale LCA.

Table 9. Parameters to consider for the upscaling of PEM and AE technologies, based from pilot-scale LCA models.

The Rare Earth elements for the PEM do not possess a significant environmental impact for now but this may increase in the system upscaling.

System AE	**System PEM**
Electricity production	
Water consumption	
Materials: Nickel and tetrafluoroethylene	Materials: membrane (Nafion)
	Rare Earth elements?

4) Development of the scenario

Now that some relevant parameters are found in **Table 9** for the upscaling process, there is a need to know in which context the ex-ante large-scale LCA should be modelled and with which quantified values. The goal of the chapter is to develop visions of the future with estimations on the different levels of implementation for hydrogen's technology.

To do so, the General Morphological Approach is used for the framework, as mentioned in section 2.5. However, the time and resources' limitations of this thesis disable conducting a full GMA with all the steps required, with organised workshops and continuous feedback from the stakeholders. Nevertheless, interviews and discussions with several actors provided a good basis for the thesis. All these meetings are described in more details in Appendices 6 & 8.

First, a morphological field was constructed and filled, based on desk research and interviews. Second, the same step was applied to construct a technological field. Finally, different field configurations were selected and described, corresponding to three different scenarios.

In total, three main scenarios were developed. The first scenario considers an optimistic development of the technology with positive inputs from the different stakeholders and the complete fulfilment of the goals announced by the Dutch projects. In this scenario, the electrolyser technology will be implemented on a large-scale, with centralised systems and the reuse of the gas network for distribution. The second scenario is constructed in the opposite way with only limited implementation of the technology in some regions and a slow technological improvement of the system. The third scenario describes an intermediary stage where the technology implementation is successful in some regions but non-existent in others, due to the stakeholders' decisions. Overall, the scenarios consider archetypal and cornerstones "What-if?" cases with, overall, high, low or medium values. All other intermediary levels were not considered due to time and resources constraints.

4.1) Morphological field construction

The different activities conducted for the technology's forecast provided inputs to construct the morphological field. The next sections summarise the different dimensions that were the most prevalent. A quantitative or qualitative value is provided for each dimension.

4.1.1) Market penetration

The first obvious aspect that should be considered for any emerging technology is the extent to which this technology will be applied or implemented. For this reason, a closer look at the green hydrogen technology's market penetration potential is discussed. This sub-section considers a narrowing approach, going from the largest consideration (hydrogen penetration in general, in the world) to a smaller scale (specific to technologies such as electrolysers).

Worldwide context:

Ball & Wietschel (2009) consider different projections for the hydrogen use and the implementation of electrolysers. The authors deliver the most optimistic scenarios, assuming that 70% of the worldwide car fleet by 2050 will be fed with hydrogen. However, according to Gielen & Simbolotti (IEA, 2005), the transport market penetration will reach only 30% for the most optimistic scenario in 2050. As the wind electricity source is considered in the thesis, an equivalence with wind power capacity is estimated. At a European scale, for a penetration of hydrogen cars at 30-70% of the fleet, the European wind capacity installed will have to increase 20-45-fold, respectively (Gielen & Simbolotti, 2005).

Ball & Wietschel (2009) note that if around 10-30% of all the existing fuelling stations in the world were able to provide hydrogen fuel, this should reach a sufficient coverage and facilitates the user's acceptance. This estimation indicates what minimum levels of implementation should be considered if hydrogen's technology is to be implemented successfully for transport's use. Naturally, Ball & Wietschel (2009) precise that the extent to which such an infrastructure and implementation will occur depends mainly on several factors specific to each country, requiring then individual assessments.

European context:

The ECN/TNO workshop on PEM technology presented some projections for the electrolyser technology, at a European scale. It is expected that by 2030, more than 65 billion € cumulative (2018-2030) will be invested in the PEM technology. On this amount of money, around 23% will be invested alone in the transportation sector (supplier + Original Equipment Manufacturer (OEM)) and ca. 70% will be invested in infrastructure (for distribution, storage and production). Again, the transportation sector is presented as a future hotspot for hydrogen's technologies.

With German and English case studies, Bertuccioli et al. (2014) claim that water electrolysis can compete with SMR or established alternatives by 2030 in the transport sector only. The competitivity of the electrolyser depends on the price of electricity, network service and gas (used as an alternative). The higher the electricity cost is, the more industries will look for cheaper electricity generation system, favouring hydrogen's production. According to Bertuccioli et al. (2014), the transport sector remains the most promising market for hydrogen. For other uses, the low prices of gas or other incumbent technologies make it hard for hydrogen's technologies to achieve a breakthrough. In this case, relatively strong political support or carbon taxes are the most evident tools to influence the situation.

In Germany, Smolinka et al. (2018) also estimate which market's sector would be the most favourable for hydrogen's technology penetration by 2050. The projections are shown in Appendix 7.1 and consider all the potential sectors for hydrogen's consumption, including industries and heat demand. Again, despite the variations induced by the authors' scenarios, a general trend can be observed. The biggest hydrogen penetration will most likely occur in the transport sector with penetration levels estimated between 40 and 80%. This value gives an order of magnitude of what could be expected from hydrogen technology's penetration in a European market.

Concerning the electrolysers' market itself, Bertuccioli et al. (2014) mention the fact that these technologies still face serious issues before being competitive with other alternatives. The electrolyser industry in Europe is rather mature but disperse for alkaline electrolysers and still emerging for PEM electrolysers. Important costs decrease through mass production is still achievable. Bertuccioli et al. claim that stakeholders expect a "wide deployment in hydrogen refuelling infrastructure around 2020" (Bertuccioli et al., 2014, p.4). Thousands of refuelling stations with a capacity ranging from 1 to 5 MW are expected to be installed across Europe in the 2020-2030 decade. Bertuccioli et al. (2014) indicate that electrolyser's sales for transport's demand are expected to operate the transition from small-scale production to larger-scale (Bertuccioli et al., 2014). These authors mention that the ability to respond dynamically to variable power generation will become a key requirement which could favour the PEM alternative.

Dutch context:

Gigler & Weeda (2018) claim in the TKI Gas report that the Netherlands (NL) possess currently over 100 hydrogen projects, proving the growing interest in this energy carrier. Several regions where some hydrogen activities are taking place are mentioned, such as Rotterdam, the North of the Netherlands (Eemshaven, Delfzijl), Goeree-Overflakkee, Zeeland and the South of the NL with a collaboration between Flanders and Arnhem/Gelderland. Amsterdam and its surroundings seem a bit lagging behind, even though this situation may change soon. Overall, a strong promotion of hydrogen technologies is present nowadays in the Northern regions (van Wijk, 2017).

For the Netherlands, Gasunie and TenneT have made some projections for the Dutch demand of hydrogen by 2050 with three types of scenarios (local, national and international initiatives), shown in **Figure 19**.

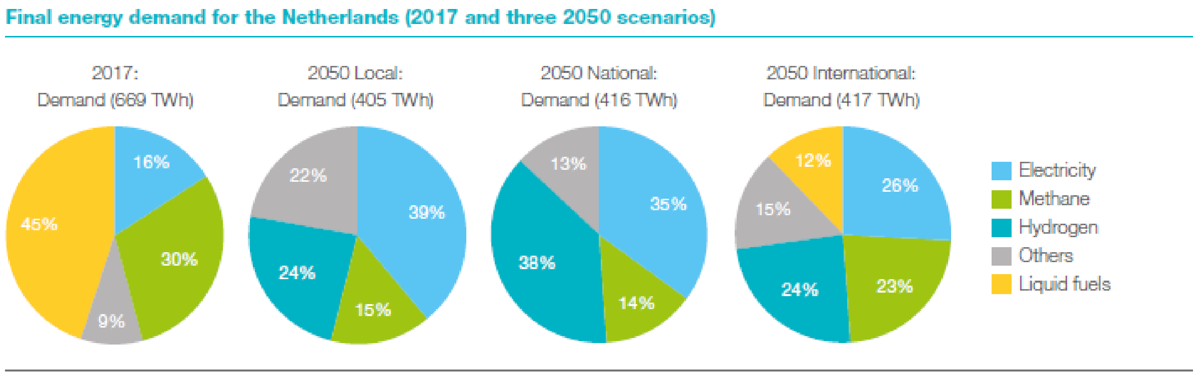


Figure 19. Projections for the Dutch demand of hydrogen (situation in 2017 and scenarios for 2050) (extracted from TenneT & Gasunie (2019))

As shown in **Figure 19**, hydrogen's demand will increase significantly from non-existent in 2017 to 24-38% of the final Dutch energy demand in 2050.
In the NL, the vehicle market seems to offer the largest market's penetration potential for hydrogen's technologies, even though this will depend on stakeholder's decisions. The electrolyser's industry has potentials to increase and ambitious target goals can be set.

Concerning the production of hydrogen from wind energy, some existing Dutch projects show potentials. For example, TenneT, Gasunie and the Port of Rotterdam Authority proposed the "Dogger Bank" project where the stakeholders seek to create an artificial island which would collect the electricity from numerous wind turbines in the neighbourhood. The total capacity of wind turbines connected to this project is evaluated at 100 GW (TenneT, 2017). This value is higher than the 80 GW potential from Dutch offshore wind turbine (see Section 5.1.1) since different countries are involved in the project, such as Denmark. This artificial island could be used to produce hydrogen on large-scale and then sent the product via pipelines to the continent. If uncertainties imply that another 10-15 years from 2019 on may have to pass before the island is built, this option may be reasonably available by 2050.

In summary, the green hydrogen technology can be massively implemented in the NL by 2050 or show a limited development, with a whole range of intermediary levels. The transport's market penetration by hydrogen cars is expected to be valued at between 10 and 70%. The 10% penetration would occur in the case where hydrogen's technology is not pushed but still promoted in some specific places or projects. The 70% penetration is expected in a scenario where hydrogen is highly promoted at a national scale. The 30% left would be shared with other technologies such as fossil fuels-based cars or battery-based electric cars.

Two dimensions for the morphological field (Section 4.2) can be extracted from this sub-section: "Level of electrolysis implementation" and "Transport market penetration by H_2 cars", both considering the Dutch national scale.

4.1.2) Stakeholders' landscape

A second aspect that should be considered is the actor's landscapes, with the identification of stakeholders and the potential interactions between them.

The different interviews conducted for the thesis provided a list of some actors who can be influential in the Dutch landscape (see Appendix 6; Personal communication, van Hulst, 2019). Among the actors, Shell, Siemens and ENGIE are expected to play significant roles in energy production. Gasunie, TenneT and Stedin are more relevant for transport and distribution. The Dutch government (Ministry of Economic Affairs and Climate) plays also an important role to promote the technology and to communicate it to the public in a transparent way. Moreover, policies can have an impact on the electricity price or CO_2 taxes which can facilitate the hydrogen technology 's implementation.

As recalled by Gigler & Weeda, (2018), legislative aspects can also play a significant role in a technology development's pace. These aspects can delay or halt technological development since no existing legislation framework takes clearly hydrogen's production into consideration. The same goes for all the safety regulations: the existing ones are based on hydrogen use for the industries and not in public systems (gas network, transports…).

Financial helps, such as subsidies, are already present in different scales (companies clusters, European institutions…) but they are rather fragmented and concern mostly early research phases or temporary pilot installations. There are no strong subsidies yet available for large-scale installations.

Gigler & Weeda (2018) recall that the public opinion is also particularly important if hydrogen has to be developed massively. Better knowledge on hydrogen, its properties, risks, limitations should be more known by the public. For example, the "blue hydrogen" (where the harmful emissions are captured) alternative may be a sensitive topic as previous experiences showed that the public can be really critical about the use of Carbon Capture Systems. For this perspective, political actors can play an influential role.

An indirect consequence from political subsidies or supports would likely be an improvement in electrolysers. When more scientific projects are supported on electrolysers, the technical parameters can be improved and the knowledge level increased. Therefore, it is assumed that strong political support would be correlated with a better scientific knowledge of electrolysers. The technological field provides more details on the potential scientific developments expected for electrolysers (see Section 4.3).

Collaboration between stakeholders is a strong driver to construct hydrogen production and distribution systems. The first pilot installations seek to provide compelling results to encourage larger development. These first results may be the trigger to promote long-term perspectives with the hydrogen economy. Coordination between the projects, stakeholders and cities are important at this stage (Gigler & Weeda, 2018). A combined effort from most stakeholders would result in consistent results (see Appendix 6.3; Personal communication, van Hulst, 2019). On the contrary, isolated efforts between the stakeholders would result in scattered improvements of green hydrogen technologies.

In summary, a list of different stakeholders is provided in the section, with technical and non-technical perspectives. To ensure a steady development of green hydrogen technology, a close collaboration between stakeholders is necessary with combined efforts. Scattered efforts will hinder the implementation of a hydrogen economy.

Three dimensions for the morphological field (Section 4.2) can be extracted from the subsection: "Policy support", "Scientific knowledge of the electrolyser" and "Stakeholders' involvement".

4.1.3) Centralised vs decentralised system

A third aspect to discuss is the approach that should be adopted for large-scale implementation of green hydrogen technologies. A comparison can be made between centralised and decentralised approaches, for production and distribution.

The different Dutch projects seem to promote slightly more the centralised system with massive capacities systems, among other reasons for costs reductions. Nevertheless, the Northern NL project still considers some decentralised aspects with solar or biomass-based systems (van Wijk, 2017).

According to Bertuccioli et al. (2014), large-scale (≥1MW) and centralised production are not deemed to possess any particular advantage by 2030 regarding the cost's perspective. However, the interviews conducted indicate that a parallel evolution will most likely occur between centralised and decentralised production/distribution system. The decentralised approach would be first used for pilot or small-scale systems (see Appendix 6; Personal communication, van Hulst, 2019). The centralised approach would become more prominent with the emergence of a backbone infrastructure or large-scale installations.

Gigler & Weeda (2018) indicate that buffering and storage systems will enable to implement hydrogen as an energy carrier in the Dutch grid where the gas potential is much stronger than electric potential. The TKI Gas report indicates that large sections of the current natural gas network can be reused for hydrogen transportation, in coherence with some interviews conducted (see Appendix 6). The reuse of the gas network could help to develop a backbone structure, going in the sense of a centralised system.

In the case where green hydrogen technology is not strongly promoted, a decentralised approach for production would take place with many different low or medium-scale plants and no large coherence in the transportation's framework.

In summary, in an optimistic development pathway for hydrogen's technology, a parallel evolution of centralised and decentralised production and distribution frameworks can be expected. In a pessimistic development pathway for hydrogen's technology, a centralised system will unlikely be implemented, due to the scattered efforts implemented.

One dimension can be extracted from the subsection for the morphological field (Section 4.2): "Production/distribution framework".

4.1.4) Competing technology

Finally, a relevant aspect to study is the potential alternatives for (green) hydrogen production. Possessing a clear overview of what are the potential competing technologies for electrolysers is important to understand the potential threats or opportunities to seize for technological developments. Two levels are considered in this section. Firstly, the hydrogen production technologies in general (not only electrolysis) will be discussed. Secondly, a focus will be put on electrolysers themselves (with differences in electrolysers' type or electricity's origin).

Steam methane reforming and coal gasification are the most used technologies nowadays to produce hydrogen and these alternatives remain the most cost-effective in 2019. If the status quo is maintained, these two options will remain the most used alternatives.

Other options for producing hydrogen exist as well such as plasma physics, or hydrogen-based on biomass. However, different reasons (scope definition, practical limitations or state-of-the-art) justify that they were not further considered in the thesis. In the NL, the most competitive alternative technologies mentioned by Gigler & Weeda (2018) were based on biomass. However, the authors consider that biomass may face fierce competitions for other usages and is more relevant for syngas production rather than hydrogen.

In general, most of the studies seem to indicate that electrolysis will most likely remain the preferred option to produce hydrogen. Some change may occur in the electricity's source or other, but the electrolysis' concept should remain the most promoted technology for producing sustainable hydrogen. For example, Smolinka et al. (2018) compared in Germany the relative shares of the different hydrogen production alternatives by 2030 (considering the total hydrogen production). The results are shown in **Figure 20**.

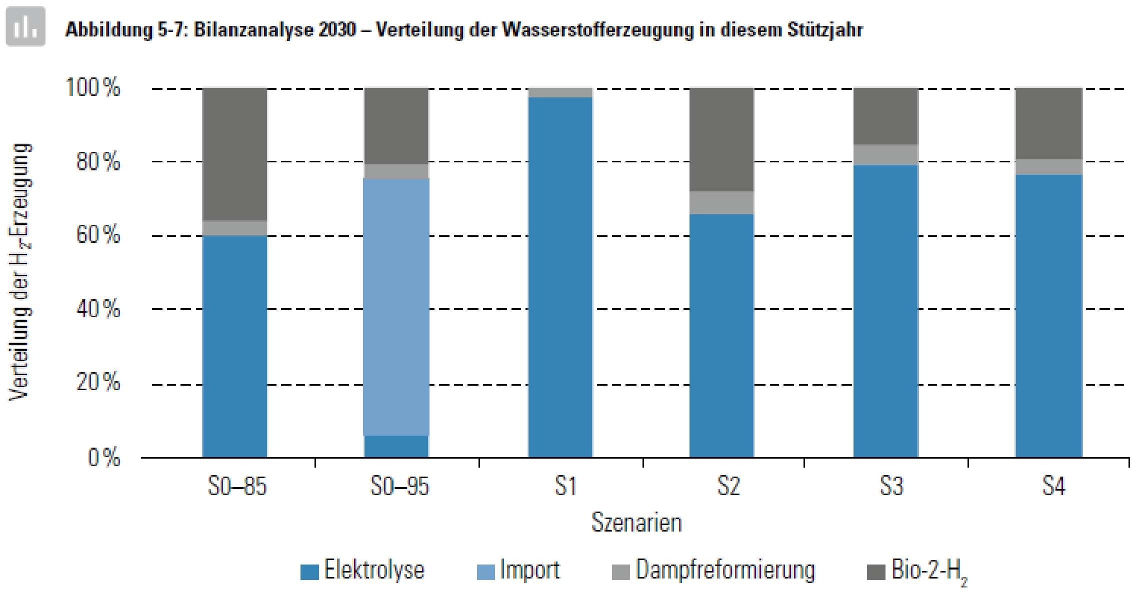


Figure 20. Projections for the relative shares of the different hydrogen production technologies in Germany. Each "S" represents a specific scenario developed by the study (extracted from Smolinka et al. (2018, p.71)). ("Dampfreformieurung" = SMR, Bio-2-H_2 = biomass-based)

Different scenarios are considered in **Figure 20**. However, the trend shows that electrolysis is likely to become the most used technology to produce hydrogen by 2030 in Germany. A similar situation can be expected to occur in the Netherlands.

Within the electrolyser's field, different alternatives are available: AEM, solid oxide electrolysers, wind-based, solar-based, biomass-based, etc.

AEM is still at an early stage of development, which makes it harder to study and compare with the PEM and alkaline electrolysers. The main R&D trends to improve this alternative focus on lifetime and durability (Vincent & Bessarabov, 2018).

Solid oxide electrolysis requires further research and understanding of the fundamental characteristics of the materials used for a fair comparison with alkaline or PEM alternatives.

In general, PEM and alkaline electrolysers are considered as the main options to be implemented in the NL by 2050 (Gigler & Weeda, 2018). Dutch projects usually consider electrolysers (without a clear distinction between PEM and alkaline) with different electricity resources (van Wijk, 2017). The two biggest renewable energy sources potentials in the NL are the solar and wind. Solar-based electrolysis can be considered as a competing technology with wind-based electrolysis. However, as mentioned in Section 2.1.2, the wind potential is deemed stronger than solar in the Netherlands. Furthermore, there is a stop on large-scale solar installations in some areas due to the limited capacity of the electricity network (and hence its potential) (ECN workshop, see Appendix 6.1).

An option that has been mentioned several times in interviews is the production of hydrogen-based on nuclear energy (see Appendix 6; Personal communication, van Hulst, 2019). Some projects are being conducted in the USA for small-scale nuclear reactors. If those projects work successfully, nuclear-based electrolysis could be a serious alternative to wind-based or solar-based alternative.

In summary, two levels can be defined. Firstly, different technologies exist for hydrogen's production. From the thesis' perspective, the most relevant technology to promote an optimistic development of green hydrogen production is the electrolyser. In more pessimistic or nuanced development of green hydrogen production, the incumbent technologies in 2019 would still be used in 2050, i.e. steam methane reforming and coal gasification. Secondly, on an electrolyser's level, there are different options for achieving the electrolysis (electricity from the wind, solar or nuclear). The nuclear-based electrolysis is considered as the most plausible alternative in case green hydrogen from wind or solar is not developed.

Two dimensions, corresponding to the two levels defined above, can be extracted from the subsection for the morphological field (Section 4.2): "Technology for H_2 production" and "Main origin for electricity (for electrolysis)".

4.2) Morphological field populated

Below is presented the morphological field populated (**Table 10**), based on the previous sections' inputs. **Table 10** considers some societal perspectives with the stakeholders' influence and positions, political supports, etc.

Remark about "Technology promoted for H2 production" and "Main origin of electricity (for electrolysis)"

The dimension "Technology promoted for H2 production" considers the main technology used to produce the total hydrogen in the Netherlands, so it does not consider only sustainable pathways such as electrolysis. The dimension "Main origin of electricity (for electrolysis)" considers the electricity's origin for the electrolysers used in the NL. So, there can be a scenario where electrolysis concerns only 10% of the Dutch hydrogen's production (with SMR being the most used technology) and where the electricity for the electrolysers comes from wind energy.

Table 10. Final hydrogen implementation morphological field

Level of electrolysis implementation	**Transport market penetration by H2 (in % of car fleet)**	**Policy support**	**Scientific knowledge of the electrolyser**	**Stakeholders involvement**	**Production/distribution framework**	**Technology promoted for H2 production**	**Main origin of electricity (for electrolysis)**
Implemented in all potential regions	70%	Strong policy support	Strong development	Strong collaboration (clusters, supply chain construction)	Mostly centralised	Electrolysis	Wind
Implemented in limited regions (mostly North)	50%	Limited policy support (electrification, blue/grey hydrogen)	Limited development	Limited collaboration (specific on locations)	Mostly decentralised	Anion Exchange Membrane electrolyser	Solar
Not significantly implemented	30%	No support (electrification, blue/grey hydrogen)	No significative change	Dispersed efforts	Parallel evolution	SMR (Grey or blue hydrogen)	Nuclear
	10%					Coal gasification	

4.3) Technological field construction

In this section, the forecasts for some technical parameters are discussed, based on different reports and stakeholders' opinions. A narrowing is made from large consideration to smaller elements, ending with the parameters from **Table 9**. All the next sub-sections are building bricks for the final technological field (Section 4.4).

4.3.1) Lifespan of the plant and the electrolyser:

One of the broader and most relevant parameters to consider for large implementation is the lifespan of the electrolyser and the plant.

Nowadays, the majority of the literature considers an electrolysis plant's lifespan of 20 years, with sometimes lower lifespans for the electrolysers themselves, usually around 10-15 years (Koj et al., 2017; Schmidt et al., 2018; Wulf & Kaltschmitt, 2018). However, a large implementation of the technology added to improvement in the design aspects will enable to extend this factor. Some extrapolations are conducted by Bertuccioli et al. (2014) and Smolinka et al. (2018) as shown in **Table 11** and **Figure 21**.

Table 11. Projections by 2030 for the system's lifespan (adapted from Bertuccioli et al. (2014, p.65))

Year	*2019*	*2030*	**Unit**
Alkaline electrolyser	20 - 30	30	years
PEM electrolyser	10 - 30	30	years

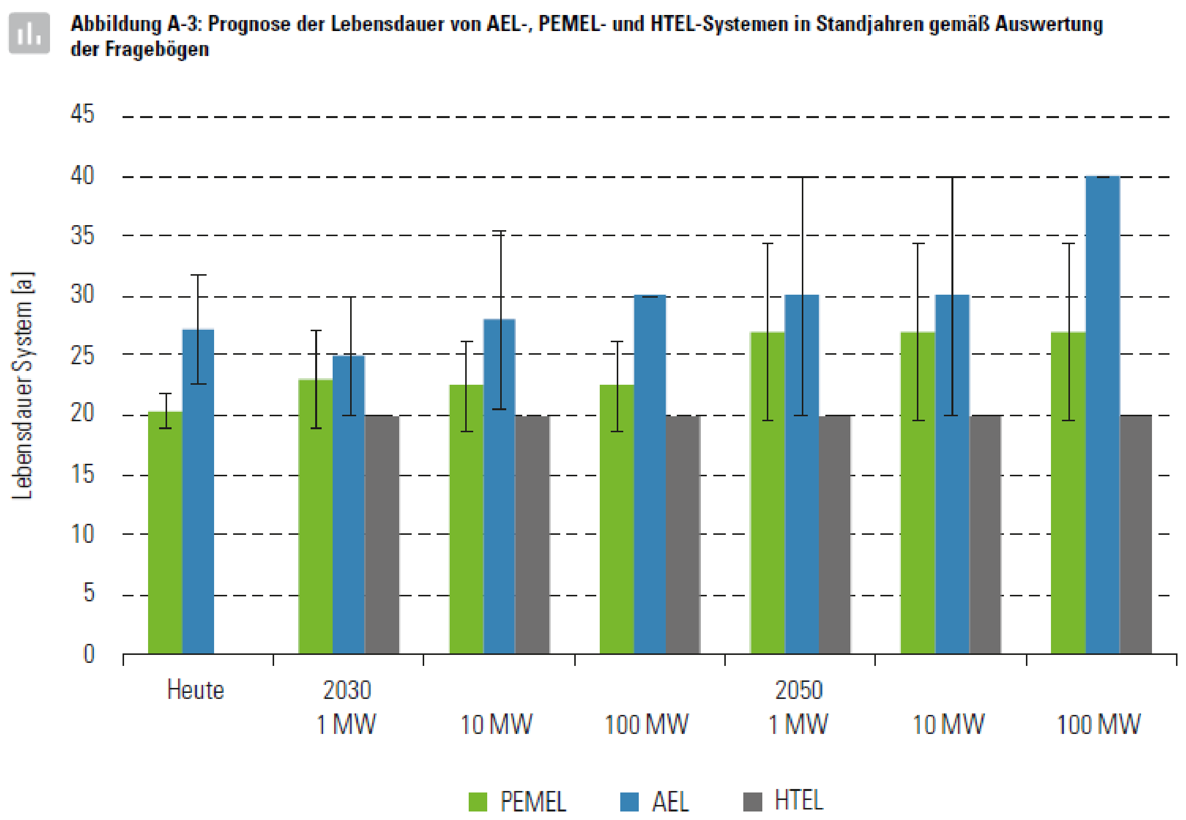


Figure 21. Projections by 2050 for the electrolysis plant's lifespan (extracted from Smolinka et al. (2018, p.174)) ("HTEL" = solid oxide cells at high temperatures)

Alkaline and PEM technologies are expected to possess identical system's lifespan – 30 years in 2030 – according to Bertuccioli et al. (2014).

Smolinka et al. (2018) operate projections until 2050 and favour then the alkaline technology with a value of 40 years. A PEM electrolyser would reach "only" 26-27 years, even though its errors bar is much larger than for alkaline systems.

Some studies were conducted to consider the lifespan at the stack's level. As shown in **Table 12**, Bertuccioli et al. (2014) claim that the lifespan for an alkaline stack will reach 100,000 h and 90,000 h for PEM's stack by 2030, considered as a best-case situation (see **Table 12** and Appendix 7.2 for more details). Usually, lifetimes improvements induce more costs or lower efficiencies. The recommendation from Bertuccioli et al. (2014) is to reach long lifetimes at low cost, without reducing significantly the efficiency.

Table 12. Projections for the stack's lifetime (adapted from Bertuccioli et al. (2014, p.65)

Year	*2019*	*2030*	**Unit**
Alkaline stack lifetime	60,000 - 90,000	90,000 - 100,000	hours
PEM stack lifetime	20,000 - 90,000	60,000 - 90,000	hours

Smolinka et al. (2018) also make some projections for the lifetime of the electrolyser stack by 2050, as presented in **Figure 22**.

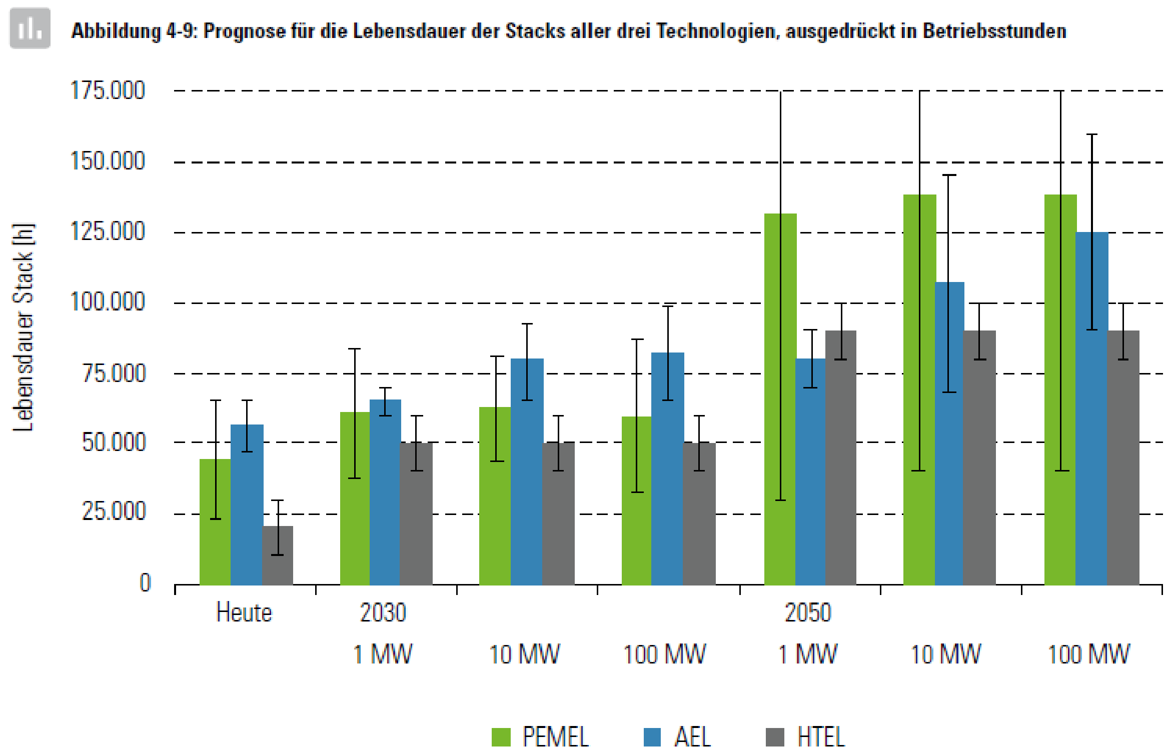


Figure 22. Projections for the stack lifetime through the years (extracted from Smolinka et al. (2018, p.41)) ("HTEL" = solid oxide cells at high temperatures).

Figure 22 shows that by 2050, the PEM's stack may possess the highest lifespan value (ca. 135,000h) but it also possesses the largest error bar. Projections for alkaline are less uncertain and state a value in the range 80,000 – 125,000h.

Moreover, Bareiß et al. (2019) assume that the current stack lifetime is worth 7 years but would reach 90,000h in the near future (equivalent to more than 10 years). These values are coherent with the previous studies mentioned.

Based on the pilot-scale LCA models and on the reports, an average value for the system's lifespan is chosen at 20-25 years for an AE installation and at 20 years for PEM in 2019. By 2050, this value is expected to increase to 30-40 years for AE and 30 years for PEM. The stack's lifespan is assumed to be around 80,000 h for alkaline and 45,000 h for PEM, for current systems. By 2050, the stack lifespan is expected to increase to 120,000h for AE and 130,000h for PEM.

In summary, based on different resources, the lifespan of the electrolyser can reasonably reach 30 years by 2050 for alkaline and PEM electrolysers. The alkaline's stack lifespan can reasonably reach 120,000 h and the PEM's stack lifespan can reach 130,000 h.

Two dimensions for the technological field (Section 4.4) can be extracted from the subs-section: "Lifespan of the electrolysis plant" and "Lifespan of the stack".

4.3.2) System and stack capacities

After the lifetime, sizing the system's capacity for the future scenario is another important aspect. With equivalent capacities, a more relevant comparison between the alkaline and PEM technologies can be achieved. This was one of the limitations for the direct comparison in the pilot-scale LCA models as described in Section 3.2.3.

Bertuccioli et al. (2014) claim that PEM systems with a capacity of several MWs exist nowadays but are made of several stacks. For the alkaline technology, individual stacks with a capacity of several MWs are already available. Bertuccioli et al. (2014) state that "developing large cell [and therefore stack] areas is expected to […] reduce the amount of expensive materials used" and "using larger single cell areas may result in ~30-50% less material than small ones at equivalent current densities" (Bertuccioli et al., 2014, p.14). The authors make projections for the system size for the different technologies, shown in **Figure 23** and **Table 13**.

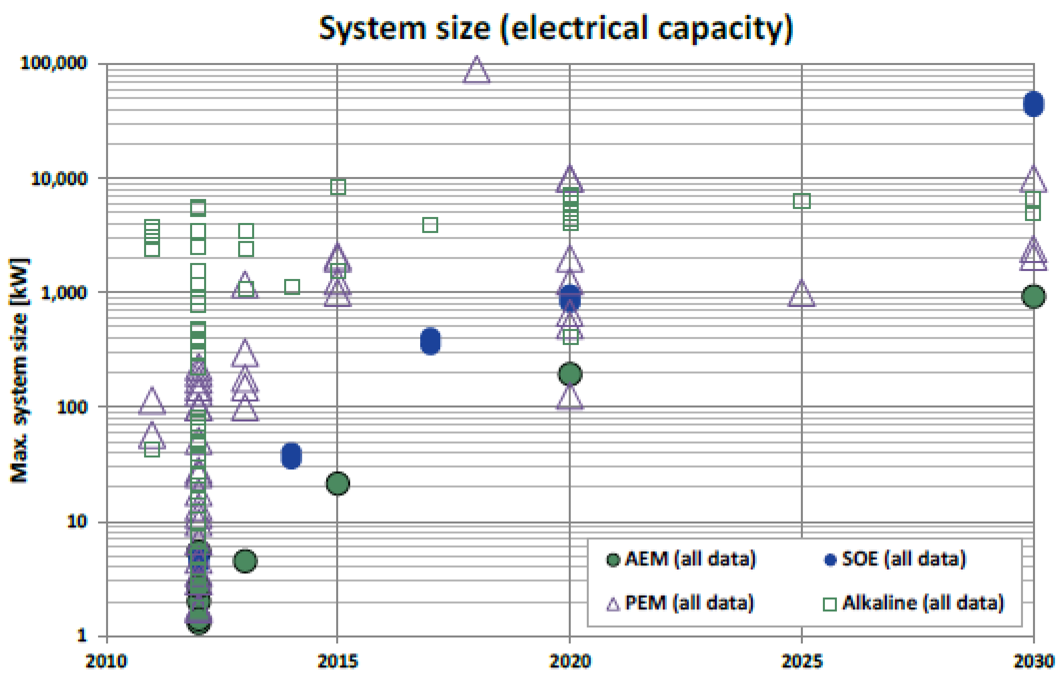


Figure 23. Expectations for the system's size, by 2030 (extracted from Bertuccioli et al. (2014, p.60)). SOE = Solid Oxide Electrolyser (an alternative not developed in the thesis).

Table 13. Expectations for the system size by 2030 (adapted from Bertuccioli et al. (2014, p.61))

Year	*2019*	*2030*	**Unit**
Alkaline system size	1,100 - 5,300	4,900 - 8,600	kW
PEM system size	100 - 1,200	2,100 - 90,000	kW

Figure 22 and **Table 13** show an increase in the plant's size up 8.6 MW for the AE and up to 90 MW for PEM in 2030 (see Appendix 7.3 for more details). The technological potential seems to be much larger and flexible for PEM than alkaline electrolysers. Nevertheless, the two technologies are expected to be at a power capacity of around 6 MW by 2030, according to Bertuccioli et al. (2014). These elements can be related to the Dutch goals. As indicated by Nouryon (cf. Appendix 6.3), the Netherlands plans to install 1-4 GW of electrolyser capacity by 2030 and 20 GW by 2050. The goal of possessing a GW-scale electrolyser plant by 2030 was also indicated by the ECN/TNO workshop on PEM electrolysers (see Appendix 6.1). The projections from Gigler & Weeda (2018) confirm that the GW-scale for the electrolyser is reachable by 2030 and is coherent with the Dutch projects. The evolution of the system size presented by Bertuccioli et al. (2014) shows that some improvements will be necessary between 2030 and 2050 to reach the Dutch goals for the electrolyser's plant (several GW). As a matter of fact, the electrolyser's system size will have to increase ten-fold for PEM's technology and even more for the alkaline's one.

In a pessimistic development path for green hydrogen technology, some relatively large-scale systems could still be reached. Some projects in 2019 in Europe already reach several MW (like the case studies used for the pilot-scale LCA models AE NL 2017 or PEM NL 2018b). Considering a plant's capacity of 100 MW by 2050 in a pessimistic development path is still ambitious but is assumed reasonable as being 10 times lower than the optimistic scenario (1 GW).

After defining the plant's capacity, a closer look can also be made at the stack level with **Table 14**, based on the report from Bertuccioli et al. (2014).

Table 14. Projections for the stack's size by 2030 (adapted from Bertuccioli et al. (2014, p.61)).

Year	*2019*	*2030*	**Unit**
Alkaline stack size	200 - 4,500	400 - 7,800	kW
PEM stack size	40 - 100	1,000 - 10,000	kW

At the stack level, the PEM technology possesses a wider range of potential, up to 10 MW whereas the AE reaches a maximum of 7.8 MW. Nouryon (see Appendix 6.3) indicated that a stack could reach theoretically a maximum capacity of 20 MW.

In summary, based on previous results, a large centralised system plant can be expected to reach 1 GW of capacity (optimistic development path) and 100 MW of capacity (pessimistic development path) by 2050. A stack could reach 20 MW for both technologies by 2050 (optimistic development path) or remain at the same level than nowadays, averaged at 5 MW for both electrolysers (pessimistic development path).

Two dimensions for the technological field (Section 4.4) can be extracted from the subsection: "Plant's capacity" and "Stack capacity".

4.3.3) Efficiency of the electrolyser:

The efficiency is another important parameter to consider for the electrolyser's development. This parameter is one of the most common that is studied in technology assessments and is one of the most interesting ones for stakeholders.

To the knowledge of the author, there is not yet a clear definition accepted by all stakeholders concerning an "electrolyser's efficiency" since there can be chemical differences for example between Higher Heating Value (HHV) and Lower Heating Value (LHV). Bertuccioli et al. chose the definition of "energy input in kWh per kg of hydrogen output" (Bertuccioli et al., 2014, p.10) which is the same that is applied in the thesis. These authors confirm that the "state of the art systems can reach electrical energy inputs close to 50 kWh/kg H_2" (Bertuccioli et al., 2014, p.10). These results are confirmed by the literature review conducted previously.

As explained by Bertuccioli et al. (2014), a low current density within an electrolyser's cell enables to reach high efficiency. However, a lower current density increases the surface area required, the material needs and thus raises the costs. As the majority of the technological improvements are cost-driven, higher energy input is accepted, as long as it leads to reduced needs for materials. In all cases, the report explains that the theoretical minimum electrical energy input is worth 39.4 kWh/kg H_2 (HHV of H_2 at ambient pressure and temperature). **Figure 24** and **Table 15** present the expected trend for the energy input requirement.

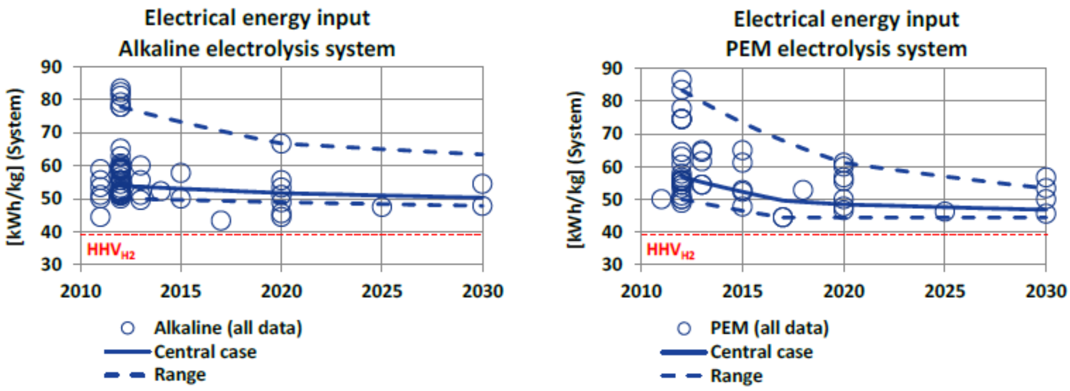


Figure 24. Projections for the electrical input (extracted from Bertuccioli et al. (2014, p.11)).

Table 15. Projections for the electrical input (adapted from Bertuccioli et al. (2014, p.11)).

Year	*2019*	*2030*	**Unit**
Alkaline electrolyser's energy input	50 - 78	48 - 63	kWh/kg of H_2
PEM electrolyser's energy input	50 - 83	44 - 53	kWh/kg of H_2

As seen in **Figure 24** and **Table 15**, the PEM technology possesses a lower range of electrical input than alkaline by 2030, even though the differences are not significant ([44-53] vs [48-63], see Appendix 7.4) for more details).

As mentioned by Bertuccioli et al. (2014), as the energy need is already close to the theoretical minimum, further improvement is expected to be marginal and no breakthrough will likely occur. The focus should be more on the design aspect rather than purely technical. Research aiming at reducing the costs of high-efficiency electrolysis would be valuable.

The electricity consumption is also a factor considered by Smolinka et al. (2018). In their report, the authors make a specific comparison between alkaline, PEM and solid oxide electrolysis technologies.

Their projections go as far as 2050. **Figure 25** shows what they expect for the electricity consumption for the 3 technologies

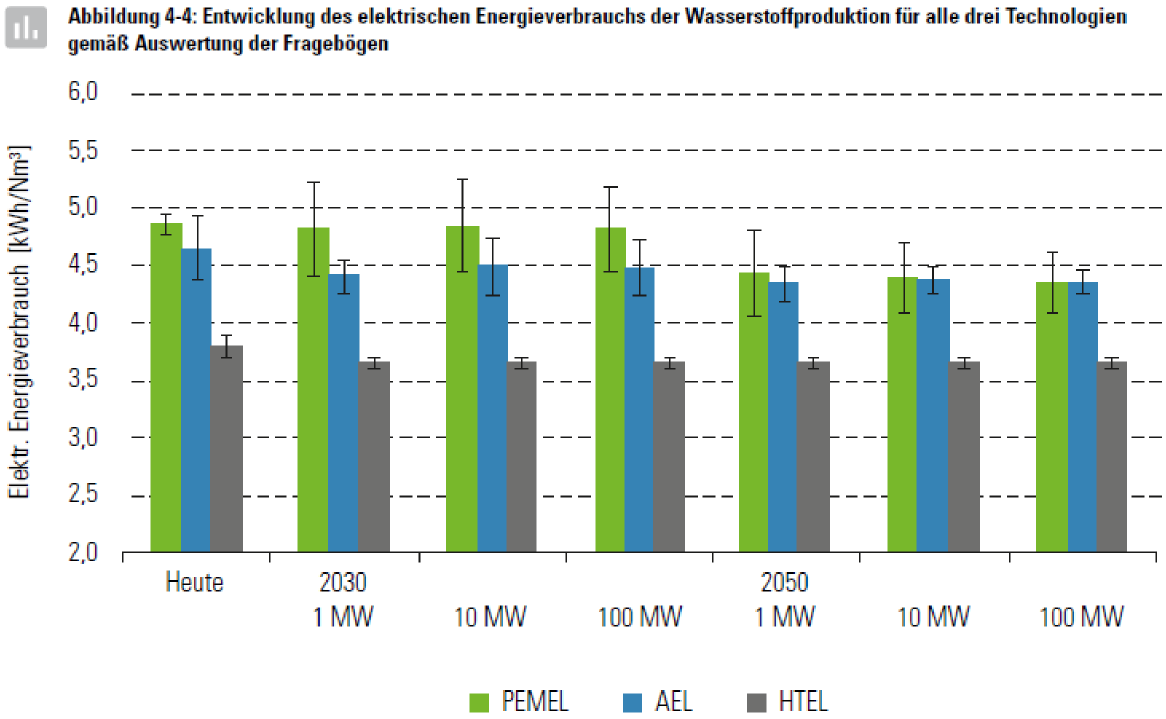


Figure 25. Projections for the electricity need input for 3 electrolysers technologies (extracted from Smolinka et al. (2018, p.36)). ("HTEL" = solid oxide cells at high temperatures).

The values are given in kWh/Nm^3. However, when the equivalence 1 Nm^3 of H_2 ⇔ 0.09 kg of H_2 is considered (see Appendix 1), PEM and alkaline would require ca. 49 kWh$_e$/kg of H_2 in 2050. Therefore, the results are consistent with the previous graphs.

In summary and based on feedback from experts, the electricity consumption is expected to be reduced by a few kWh for alkaline electrolyser (47-50 kWh/kg of H_2) and to be kept constant for PEM (50-55 kWh/kg of H_2).

One dimension for the technological field (Section 4.4) can be extracted from the subsection: "Electrical consumption" (of the electrolyser).

4.3.4) Material use

Finally, most of the parameters described in **Table 9** are discussed in the next section, considering different material or chemical consumption in electrolysers.

Concerning the water consumption of the electrolyser, all the pilot-scale LCA models consider the value's range 10-19 kg of H_2O/kg of H_2. The mass balanced applied to (Eq. 1) (Section 2.1.5) shows that to produce 1 kg of H_2O, there is a minimum chemical need of 9 kg of H_2O. Hence, it is chemically impossible to reduce the water consumption below 9 kg of H_2O/kg of H_2. Noack et al. (2015) project that water consumption for the electrolyser will decrease to 9 kg of H_2O/kg of H_2 for PEM and alkaline electrolysers. Therefore, a water consumption range of 9-10 kg of H_2O/kg of H_2 is expected by 2050 for both electrolysers.

The steel consumption for the electrolyser's framework is a parameter that was defined in different electrolysers' models and that can vary (Koj et al., 2017; Mori, Jensterle, Mržljak, & Drobnič, 2014;

Schmidt et al., 2018; Wulf & Kaltschmitt, 2018). Furthermore, as the steel process can be energy-intensive and as some projections for the steel consumption were made for PEM electrolysers (Bareiß et al., 2019), it was deemed relevant to consider it as an added parameter to **Table 9**. Based on the papers previously mentioned, the steel consumption is estimated to be in the range 10-30 kg/kW for alkaline electrolysers and in the range 7-10 kg/kW for PEM electrolysers by 2050.

The potassium hydroxide consumption for alkaline electrolysers is a relevant parameter since it is the electrolyte used and one of the main differences with PEM systems. Some projections are available from Noack et al. (2015). Based on this, the potassium hydroxide consumption is projected to be in the range 1-2 g/kg of H_2, which is the same level than current systems available. Thus, no evolution is expected for this parameter.

The nickel consumption for the cathodes in alkaline electrolysers possesses a rather broad range of values (0.2-2 kg/kW) based on pilot-scale LCA models. No projections were found for the evolution of its consumption. So, the nickel consumption has been considered with the same range for alkaline electrolysers by 2050 and this parameter has been adjusted depending on the scenarios.

The next paragraphs will describe the different sensitive materials involved in the PEM electrolyser. To begin with, more detailed descriptions of the PEM electrolyser are required to understand which parts of the cell an improvement may be expected.

The PEM electrolyser possesses a catalyst-coated membrane (CCM) in its centre which conducts protons and separates the gas flows. The CCM is compressed between two porous transport layers (PTL). The latter are pathways for mass transport for water and gas flows. Finally, the PTLs themselves are coated with bipolar plates (BPP) which ensure an even flow of the water over the PTL and easy removal of gas products (H_2 and O_2). **Figure 26** gives a visual representation of the different parts from a PEM electrolyser.

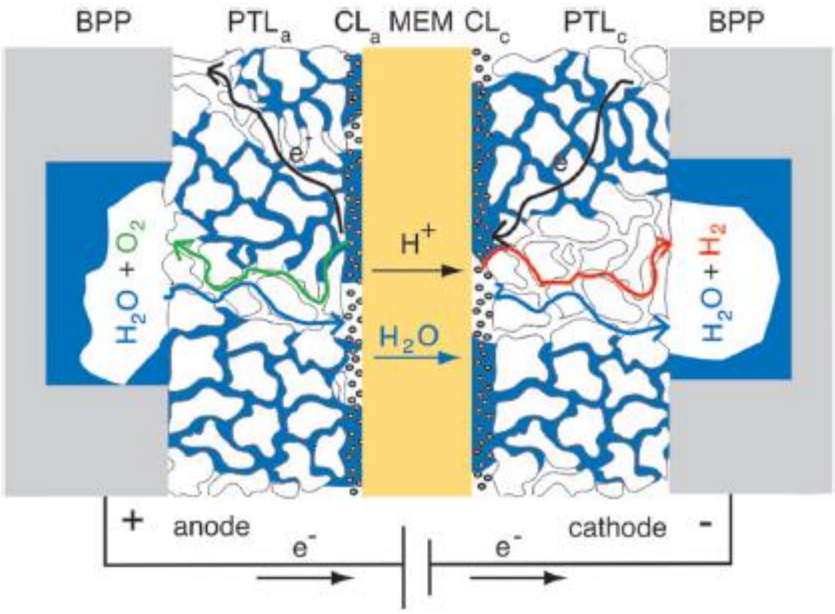


Figure 26. Visual representation of a PEM electrolyser. The membrane (MEM on the figure) is coated with anodic and cathodic catalyst layer (CL_a and CL_c), sandwiched between two porous transport layers (PTL_a and PTL_c) and bipolar plates (BPP) (extracted from Babic, Suermann, Büchi, Gubler, & Schmidt (2017))

The noble metal iridium is used in the PEM's anode and cathode. According to Smolinka et al. (2018), the load of iridium could decrease from 0.667 g/kW nowadays to 0.05 g/kW by 2050, resulting in a reduction of more than 90% (see Appendix 7.5 for more details). However, this value would hardly decrease further on since no relevant alternative has been found now. The LCA from Bareiß et al. (2019) considered that the Iridium load value could decrease from 2 g/cm² (or 7.5×10^{-4} g/kW) to 0.2 g/cm² (or 3.7×10^{-5} g/kW) with an increased current density in the PEM electrolyser (reaching 3 A/cm²). The iridium's use reduction would be highly valuable since iridium is considered as a critical material. The iridium global production value is estimated at between 3.5 and 7 t/year on average, for the last years (Bareiß et al., 2019). To limit this criticality aspect, improved recycling aspects may be used. Some literature suggests that a recycling rate of 95% could be reached with this metal (Smolinka et al., 2018).

Concerning the platinum's need for the anode and cathode, Smolinka et al. (2018) estimate that current electrolysers' technologies possess a platinum load of 0.333 g/kW. This load could be reduced to 0.0375 g/kW for the optimistic scenario, resulting in a decrease of around 88%. With the conservative scenario, the load's value remains at 0.333 g/kW (see Appendix 7.5 for more details). The LCA from Bareiß et al. (2019) estimated that the platinum loading value can decrease from 0.2 mg/cm² (7.5×10^{-5} g/kW) to 0.025 mg/cm² (or 1×10^{-5} g/kW) without significant influence on the cell's performance. The annual production of titanium is estimated at 190 t/year. Again, improved recycling systems would be valuable for this metal.

PEM electrolysers possess bipolar plates made of titanium. The latter is also used for the PTL on the anode side. Smolinka et al. (2018) mention the fact that very few data or literature is available on the titanium's needs. However, by considering similar systems, the authors used proxies and evaluated the need at 414 g/kW for conservative scenarios and 32 g/kW for innovative scenarios, resulting in a reduction of more than 90%. The LCA from Bareiß et al. (2019) estimates that the titanium loading value can decrease from 0.2 mg/cm² (0.528 g/kW) to 0.025 mg/cm² (or 0.037 g/kW) without significant influence on the cell's performance. The production rate of titanium varies noticeably through the years, with a production of 290,000 t in 2016 but only 171,000 t in 2015. Smolinka et al. (2018) consider that even though the titanium price is high, the material is not considered as a "critical material", or at least to a much lesser extent than iridium and platinum.

No significant change or breakthrough in the PEM's membrane composition is expected in the years to come. The Nafion (membrane) consumption for PEM electrolysers was clearly defined by (Schmidt et al., 2018). Bareiß et al. (2019) make some projections for its consumption. Based on these resources, the Nafion consumption is expected to be in the range 0.002-0.016 kg/kW.

Based on the previous paragraphs, **Table 16** summarises the different flows consumption's values. Each flow represents a dimension for the technological field (Section 4.4). In total, 8 dimensions for the technological field can be extracted from the sub-section.

Table 16. Summary of the load values for noble metals in PEM electrolysers, between 2019 and 2050.

Year	*2019*	*2050*	**Unit**
Water (AE & PEM)	10-20	9-10	kg/kg H_2
Steel (AE)	10-30	10-30	kg/kW
Steel (PEM)	7-10	7-10	kg/kW
Potassium hydroxide (AE)	1-2	1-2	g/kg H_2
Nickel (AE)	0.2-2	0.2-2	kg/kW
Iridium load	0.7	0.01 - 0.05	g/kW
Platinum load	0.1 - 0.3	0.01 - 0.03	g/kW

Titanium load	450 - 500	35	g/kW
Nafion consumption	0.016	0.002-0.016	Kg/kW

4.4) Technological field populated

The second table (**Table 17**) is named the "technological field" for clear distinction with the morphological field and provides more technical perspectives and quantified values. This table is deduced from the previous section's inputs.

Table 17. Electrolyser's technological field

Lifespan of the electrolysis plant	AE	*2019*	20-25 years
		2050	30 years
	PEM	*2019*	20 years
		2050	30 years
Lifespan of the stack	AE	*2019*	80,000h
		2050	120,000h
	PEM	*2019*	60,000-80,000h
		2050	130,000h
Plant's capacity	AE	*2019*	A few MW
	AE	*2050*	100 MW - 1 GW
	PEM	*2019*	A few MW
	PEM	*2050*	100 MW - 1 GW
Stack capacity (power)	AE	*2019*	2-4.5 MW
		2050	20 MW
	PEM	*2019*	1 MW
		2050	20 MW
Electrical consumption	AE	*2019*	50 kWh_e/kg H2
		2050	47-50 kWh_e/kg of H2
	PEM	*2019*	50 kWh_e/kg H2
		2050	50-55 kWh_e/kg of H2
Water consumption	AE	*2019*	10 kg/kg h2
		2050	9-10 kg/kg H2
	PEM	*2019*	10 kg/kg h2
		2050	9-10 kg/kg H2
Steel consumption	AE	*2019*	10-30 kg/kW
		2050	10-30 kg/kW
	PEM	*2019*	7-10 kg/kW
		2050	7-10 kg/kW
KOH (electrolyte) consumption (AE)	AE	*2019*	1-2 g/kg H2
		2050	1-2 g/kg H2
Nickel consumption (AE)	AE	*2019*	0.2-2 kg/kW
		2050	0.2-2 kg/kW
Iridium load (PEM)	PEM	*2019*	0.7 g/kW
		2050	0.01-0.05 g/kW
Platinum load (PEM)	PEM	*2019*	0.1-0.3 g/kW
		2050	0.01-0.03 g/kW

Titanium load (PEM)	PEM	*2019*	450-500 g/kW
		2050	35 g/kW
Nafion consumption (PEM)	PEM	*2019*	0.016 kg/kW
		2050	0.002 kg/kW

Table 17 is not part of the morphological field developed within the GMA framework. The table is more technological and results from the interviews and the desk research conducted (see Appendix 6 and 7). **Table 17** will serve as a basis to implement quantitatively the scenarios for the ex-ante large-scale LCA models, in combination with the morphological field (see Section 5).

4.5) Selection and description of scenarios

When all ranges for the morphological field's dimensions are considered, the total number of possibilities equals 11,664. Naturally, it would be impossible to study all the possible alternatives and drastic selections must be made. The next section aims to reduce the alternatives' number by eliminating all the mutually contradictory paths. Finally, the most diverse scenarios for the thesis will be considered to explore the most "extreme" cases.

4.5.1) Cross-consistency check:

To reduce the number of scenarios to consider, a cross-consistency assessment (CCA) is achieved, as described by Ritchey (2011b).

At this stage, all the dimensions' values from the morphological field are compared with one another, pair-wise. Usually, this is achieved via a cross-impact matrix. For each pair, a judgment is made on whether the combination is internally consistent or not. Two kinds of inconsistencies are often used: the *logical contradiction* (based on the concept's natures themselves) and the *empirical constraints* (combinations judged as highly improbable). Due to the practical constraints of the thesis, a simplified CCA has been applied and no cross-impact matrix has been developed. Nevertheless, all scenarios that are internally consistent but are highly improbable are taken out. For example, a scenario where 100% of the Dutch car fleet would consume hydrogen by 2050 seems highly unlikely. Oil-based cars or battery-based electric cars are still expected to be present by 2050, preventing hydrogen-based cars to reach full coverage of the fleet. The resilience of the oil-based system is also expected to hinder full coverage of the vehicle fleet by hydrogen cars.

Another criterion that has been used in the selection of the paths of the scenarios is the alternative's relevance. Due to intrinsic uncertainties linked to the future, an interesting perspective would be to consider a "positive" scenario – where hydrogen is strongly promoted – and a "negative" scenario – where hydrogen technology has been neglected in favour of other options. Then, an "intermediary" scenario would be considered with mixed outputs. The last option may actually be considered as the most realistic one, due to the high number of technological possibilities available currently. As there is no "ultimate answer", it is likely that several technologies (solar, wind, hydrogen and others) will be developed in the Netherlands in the future, ending in "mixed" evolutions with some successes and failures. The approach described for the three scenarios can be related to "high", "low" or "medium" values. This approach obviously possesses some limitations in its "radical" perspectives whereas reality is much more likely to be more toned in outputs. However, these "radical" cornerstones scenarios are useful as a basis to cover a large spectrum for potential evolution of hydrogen, in a similar way with the "worst-case (or best-case) scenario" approach.

Furthermore, some simple relationships between dimensions in the morphological field were implemented to reduce even more the number of possible alternatives. These are described below:

- As mentioned before, some dimensions are correlated to simplified values corresponding to “high”, “low” or “medium” cases. Three main scenarios were developed and constructed with considering a positive, negative and mixed development paths of hydrogen’s technology. More subtle combinations can be found and explored in further works and were not considered due to thesis’ constraints.
- The dimensions of “Level of electrolysis implementation”, “Policy support” and “Stakeholders involvement” are deemed as correlated. In an ideal scenario, all options and combinations would be considered, yet for practical and simplicity purposes, it is considered that when one of these dimensions have a high value, the others have one as well (and vice-versa). Strong political support for hydrogen would enable a high level of implementation, based on relatively strong collaboration between stakeholders. As a matter of fact, a high-level of implementation is unlikely to occur without some political support. On the contrary, low political support would induce a limited/low implementation of electrolysis and collaboration between stakeholders may be hard to achieve. Naturally, a group of companies may want to promote hydrogen’s technologies without governmental support. However, it is unlikely then that after a clear will showed by companies, the political actors will not adjust the situation to favour sustainable hydrogen’s technologies. So, this alternative was not considered. An inflexible position from the government to not implement elements favouring hydrogen’s production and use in general may hinder the initial push from companies who will most likely need some helps, at least in the initial phases. Again, the collaboration perspective is evaluated, and a correlation is found between “Level of electrolysis implementation”, “Stakeholders involvement” and “Policy support”.
- The “Scientific knowledge of the electrolyser” dimension is also deemed correlated to the dimensions of the previous paragraph. Strong political support will most likely induce more R&D projects with outputs and improve the state-of-the-art of the technology. However, the “Scientific knowledge of the electrolyser” may remain unchanged despite strong policy support or large-scale implementation in some scenarios. Due to practical constraints from the thesis, this alternative has not been considered further.
- The “Production/distribution network” dimension needs to consider the geographical perspective. For example, for a successful green hydrogen development mostly in the Northern Netherlands (“mixed” results case), a centralised network is more likely. A decentralised pattern is not deemed as supportive enough to enable a successful green hydrogen implementation in a region. In short, a green hydrogen development at a regional scale is more likely to be successful with a dense/centralised view rather than decentralised.
- The “Anion exchange membrane electrolyser” option has not been considered in the scenarios described below. Different Dutch projects for developing the green hydrogen economy have already started (even though they may just be at the development phase) and the two options that could be selected nowadays (in 2019) are PEM and alkaline electrolysers. Considering the anion exchange membrane would add another level of uncertainty that requires further research and understanding.
- No clear consideration of the refuelling stations for hydrogen cars has been made. The refuelling stations are outside the scope of the study. Only indications on the distribution (connected among others to refuelling stations) are made. It is judged that the production’s and distribution’s frameworks should be the same (centralised or decentralised). Other combinations are deemed more delicate to handle due to a lack of coherence.

The other dimensions showed fewer correlations with each other based on empirical grounds. The final selection of dimensions depended mostly on the interviews' inputs (see Appendix 6).

Final field configurations selected:

The selection of the field configuration from the morphological field resulted in the three scenarios described in sections below. A visual field configuration and a short narrative are provided for each scenario. The temporal indications and other numbers were extrapolated based on the interviews conducted (see Appendix 6). Naturally, all scenarios take place only within the Netherlands, unless otherwise specified. Each scenario is described with a prospective point of view placed in 2050.

4.5.2) *Scenario A:* "Full hydrogen power"

Table 18. Configuration field selected (in yellow) for scenario A "Full hydrogen power"

Level of electrolysis implementation	**Transport market penetration by H2 (in % of car fleet)**	**Policy support**	**Scientific knowledge of the electrolyser**	**Stakeholders involvement**	**Production/distribution framework**	**Technology promoted for H_2 production**	**Main origin of electricity (for electrolysis)**
Implemented in all potential 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 limited regions (mostly North)	50%	Limited policy support (electrification, blue/grey hydrogen)	Limited development	Limited collaboration	Mostly decentralised	Anion Exchange Membrane electrolyser	Solar
Not significantly implemented	30%	No support (electrification, blue/grey hydrogen)	No significative change	Dispersed efforts	Parallel evolution • Backbone and decentralised frameworks	SMR (Grey or blue hydrogen)	Nuclear
	10%					Coal gasification	

In “Scenario A”, the most optimistic development path is selected for hydrogen’s technology. The different goals presented by Dutch projects were reached and the electrolyser’s technology has been implemented in all potential regions. In this sense, GW-scales plants for hydrogen production were constructed in different regions. The ex-ante large-scale LCA model for “Scenario A” will consider the production of 1 kg oh H_2 from a 1 GW-scale plant.

The first hydrogen-related projects were implemented at pilot-scales in the period 2020-2030. Some experiments on an urban-size were conducted with hydrogen-based transports. After the compelling first results of these experiments, different hydrogen coalitions and clusters presented several business plans to the Dutch government, asking for financial and political support. Convinced by the different projects and the potentials from them, the Dutch government implemented a series of measures promoting green hydrogen development. Strong policy supports helped to communicate about the hydrogen’s technology and subsidized R&D. Therefore, the different electrolyser’s technologies reached their expected performances for their efficiencies and other parameters and the scientific knowledge on electrolysers improved. The public became aware of the strong potentials from hydrogen and asked for transparent communication about the safety issue. Significant research programs were conducted in order to define clear regulations on the technology’s use. An online public platform was created, summarising all the potential incidents and progress made with hydrogen’s technology in general.

An ambitious program was applied within a few years to make a shift towards 100% hydrogen transport in the gas network. In this perspective, the Dutch law has been adjusted to allow the transport of hydrogen in the national pipelines system. The construction of the large offshore wind parks enabled to increase the capacity of green hydrogen production with electrolysers. At the same time, a carbon tax implemented by the Dutch government was one of the most efficient measures to operate a shift towards more sustainable ways of energy production, including the use of hydrogen. Therefore, electrolysis became the most used technology for hydrogen’s production in the NL and many large companies (Shell, Nouryon, Hydron energy…) constructed larger and larger electrolysis plants. Quite rapidly, a backbone structure appeared with several large-scale (GW capacity) plants being constructed in the 2030-2040 interval. In parallel, decentralised and smaller scale of hydrogen production and transportation are deployed. The latter is implemented in more isolated regions such as countryside or islands. A parallel implementation of the two modes of production/distribution occurred, depending on the local conditions to optimise the potentials. Large flows of hydrogen are transported between the different regions of the Netherlands and neighbour countries (Belgium, Germany, Denmark…). Strong collaborations between different European countries have been implemented (Benelux, Germany, Denmark and Sweden). These relationships settled clear frameworks for export/imports of hydrogen, avoiding any mismatch problem between green electricity supply and demand. This successful evolution inspired other countries around the world to adopt similar approaches.

All these successful developments enabled a transport market’s penetration by hydrogen cars at 70%, one of the highest values in the world. Strong collaborations between key electrolysis’ stakeholders have appeared through time and consistent supply chains have been established. The remaining 30% of the Dutch transport’s fleet is mostly composed of oil-based cars or battery-based electric cars which were particularly common at the beginning of the 21st century. These two options remain relatively the biggest competitors against hydrogen cars.

For hydrogen’s production, the most important competitor to the wind-based electrolysis is the solar-based electrolysis, used on a lower scale. Nonetheless, the wind-based electrolysis keeps the first position and provides 100% of the total hydrogen cars’ demand. Solar-based and wind-based electrolysis are used to supply energy in industry, built environment (households and offices), agriculture, etc.

Overall, these factors led to the implementation of an extended green hydrogen economy in the Netherlands, at a national scale.

4.5.3) *Scenario B*: "No to wind-based Hydro"

Table 19. Configuration field selected No to wind-based Hydro (in yellow) for scenario B "No to wind-based Hydro"

Level of electrolysis implementation	**Transport market penetration by H2 (in % of car fleet)**	**Policy support**	**Scientific knowledge of the electrolyser**	**Stakeholders involvement**	**Production/distribution framework**	**Technology promoted for H2 production**	**Main origin of electricity (for electrolysis)**
Implemented in all potential regions	70%	Strong policy support	Strong development	Strong collaboration (clusters, supply chain construction)	Mostly decentralised • No strong trend of evolution	Electrolysis	Wind
Implemented in limited regions (mostly North)	50%	Limited policy support (electrification, blue/grey 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/grey hydrogen • Support for other alternatives	No significative change • Status quo on the performance	Dispersed efforts • Few coalitions exist but no main leader or trend	Parallel evolution	SMR (grey or blue hydrogen)	Nuclear • Nuclear-based electrolysis = the alternative chosen
	10%					Coal gasification (grey or blue hydrogen)	

In “Scenario B”, the most pessimistic path for green hydrogen development has been considered. None of the massive Dutch projects for hydrogen was achieved to their ends and other technologies were promoted instead. Nevertheless, a few electrolysis plants were built, and the largest capacity reached is worth 100 MW, which is ten times smaller than in “Scenario A” or C. From the methodological point of view, a lower plant’s capacity could have been considered but would have diminished the relevance of the “large-scale” concept and the comparability in the LCA models. Moreover, different projects will likely occur in any case in the NL, based on the trends observed from the 2010s. Several pilot-scale projects in Europe already reach some MW (Koj et al., 2017; Wulf & Kaltschmitt, 2018) and 2050 is deemed as distant enough to reach a 100 MW plant’s scale even with low development of hydrogen’s technologies. The ex-ante large-scale LCA model for “Scenario B” will consider the production of 1 kg oh H_2 from a 100 MW-scale plant, fed by electricity from wind turbines.

In the decade 2020-2030, different failures from the small-scale installations and other pilot plants promoted the use of other technologies. The Dutch government was not convinced by hydrogen’s perspectives and supported other alternatives. Massive electrification occurred in different consumption’s sectors with large renewable energy systems installed (wind turbines and solar panels). A large implementation of battery-based electric cars occurred in the vehicle sector. A lack of efficient communication led to disinterest from the public opinion on hydrogen. The electrification of different sectors (heating, transport…) was deemed as enough sustainable by the general opinion, not requiring further research in other alternatives. No strong public (and to some extent, political) support was present for the development of green hydrogen technologies. The hydrogen economy has consequently not been implemented.

The different offshore wind parks were actually constructed but are used to feed the electricity grid. The latter has been expanded and adjusted to increase its potential. The Dutch government has stopped the use from domestic natural gas (from the North of the Netherlands) but is importing gas from foreign countries, such as Russia. This situation has led to the construction of one relatively large plant (100 MW) in the North of the Netherlands in the decade 2020-2030, fed with electricity from wind turbines. Only a small proportion of wind parks’ electricity production is used to feed the 100-MW electrolysis plant (hundreds of MW on several GW). After the other electrolysis installations’ failures in the NL, no large program for electrolysis has been implemented before the 2040s.

From the 2040s, some small-scale nuclear reactors have been built in several regions of the NL and were partly used for electrolysis, after the success of the first models tested in the USA. Nuclear-based electrolysis avoids the intermittency’s problem, is especially useful as a backup system in case of a mismatch between supply and demand and obtained good results. The few projects that sought to promote hydrogen in the decades following the 2040s promoted nuclear-based electrolysis. In this sense, the nuclear-based electrolysis is the biggest competitor to the wind-based electrolysis and the alternative that has been finally chosen. The nuclear-based electrolysis is used to provide mostly electricity or heat at a district or city-scale. Apart from this, when hydrogen is necessary for industrial processes, the Steam Methane Reforming technology and coal gasification remain the most used option with Carbon Capture System to decrease the environmental impact (blue hydrogen). Overall, on a national level, SMR and coal gasification remain the most used technologies for hydrogen’s production. For the electrolysers implemented, apart from the exception of the 100-MW plant based on wind energy, the other installations (with MW’s capacities, never higher) are based on nuclear.

Due to the lack of political and industrial support, no significant technological improvement has been achieved in electrolysis technology. The several green hydrogen projects were implemented in a dispersed and decentralised way and some of them were abandoned after some time. As there are only some physical “hotspots” of green hydrogen in different places, without connection between them, the hydrogen cars made a market penetration estimated at ca. 10%.

Some hydrogen coalitions still exist and try to promote the green hydrogen technology, but the actions are mostly taken from the laboratory side and no strong collaboration has been established with leading stakeholders or between countries.

Overall, a combination of different failures (from the tests, change in legislation, communication) has led to the situation where the hydrogen option has been neglected in favour for electrification of consumption’s sectors and nuclear energy use for electrolysers from the 2040s.

4.5.4) *Scenario C:* "Mixed results"

Table 20. Configuration field selected (in yellow) for scenario C "Mixed results"

Level of electrolysis implementation	**Transport market penetration by H2 (in % of car fleet)**	**Policy support**	**Scientific knowledge of the electrolyser**	**Stakeholders involvement**	**Production/distribution framework**	**Technology promoted for H2 production**	**Main origin of electricity (for electrolysis)**
Implemented in all potential regions	70%	Strong policy support	Strong development	Strong collaboration (clusters, supply chain construction)	Mostly centralised	Electrolysis	Wind • Green hydrogen mostly produced in the North
Implemented in limited regions • mostly North	50%	Limited policy support • Strong support in the North • Diverse and scattered support in the rest of the NL	Limited development • Reduced noble metals consumption • Large-scale systems	Limited collaboration • Coalitions in the North • Attempts to make a breakthrough in the rest of the NL	Mostly centralised • Backbone system in the North with some adjustments (law, infrastructure…)	Anion Exchange Membrane electrolyser	Solar
Not significantly implemented	30%	No support (electrification, blue/grey hydrogen)	No significative change	Dispersed efforts	Parallel evolution	SMR (Grey or blue hydrogen)	Nuclear
	10%					Coal gasification (grey or blue hydrogen)	

In “Scenario C”, the green hydrogen technology’s development has resulted in mixed outcomes with strong spatial disparities. A more balanced situation has taken place with some successes but some failures as well. The ex-ante large-scale LCA model for “Scenario C” will consider the production of 1 kg oh H_2 from a 1 GW-scale plant, fed by wind electricity, installed in the North of the NL.

The Northern Netherlands, because of its strong need for an alternative to natural gas, has made a shift towards hydrogen economy and embraced its potential. Consequently, a few 1-GW’s plant-scale was built in the Northern regions. Other regions in the NL which possessed potentials (Zeeland, Rotterdam, Arnhem) have seen much slower implementations of hydrogen’s systems. Limited political and public support has occurred, depending on the location’s context. Again, the Northern Netherlands has become a key player in green hydrogen’s production and most of the support took place there. In other regions, the presence of too many diverse potentials and actors hindered the selection of a single solution and a strong focus put on it. Instead, several different technologies were implemented with a growing trend in electrification.

Nevertheless, due to the large hydrogen use in the Northern Netherlands, some scientific and technological improvements have been achieved by research institutes for the electrolysers and they could have been applied on a large scale. Thanks to this, hydrogen cars have managed to make a market breakthrough evaluated at 30% of the Dutch vehicle fleet, mostly in the North (for more details on the value 30%, see Appendix 7.1). The presence of large green hydrogen installations added to the presence of important wind parks in the North Sea triggered the hydrogen economy but limited in the Northern regions. Some specific adjustments have been achieved by political parties concerning the organizational structure and the legislation. In this way, the hydrogen economy could have been implemented in a coherent and consistent way in the Northern region.

In the Northern Netherlands, mostly for economic reasons, a backbone system has been implemented and this region has become a privileged zone for exchange with the Northern countries who also promoted the hydrogen technology (Denmark, Sweden…). The approach is therefore mostly a centralised production and distribution process.

In the regions of the NL where green hydrogen technology’s development has not been pushed but where the product is still required by industries, the main production technologies used are steam methane reforming and coal gasification, in a business-as-usual situation. In this side, a growing number of Carbon Capture System (CCS) have been installed, in order to produce “blue hydrogen” with no net-CO_2 emissions. That is why that SMR and coal gasification are still the most competing technology towards sustainable electrolysis. Overall, SMR and coal gasification possess the largest share for hydrogen’s production, but the electrolysis plants installed (especially in the North) use electricity from wind turbines for operation.

Strong collaborations and coalitions between stakeholders have been established in the Northern regions but are lacking in others. In the second case, the hydrogen coalitions are trying to promote more the communication on hydrogen technologies by presenting the success in the North of the NL. Some pilot-scale installations are still present and seek to enable a larger breakthrough of hydrogen in the market.

Finally, the results are “mixed”. In the Northern regions, the green hydrogen economy has been a significant success, but the improvements are lagging and dispersed in other places.

5) Implementation of the scenario

The scenarios have been developed and described, mostly based on the morphological field. In this section, these scenarios are quantified and translated into LCA inputs, based on the technological field ("Phase 3" from the Methodology overview). First, quantifications of the Dutch offshore wind capacities, hydrogen production and electrolysis potentials in the NL are calculated. These quantifications enable to check whether the three scenarios could be applied in the NL in practice or are completely unrealistic. Then, some reflections are made about the boundaries of the ex-ante large-scale LCA model to develop (transport and recycling). Finally, with the help of the technological field, quantified numbers are given in **Table 23** for an LCA implementation.

5.1) Quantification of the scenarios

This sub-section quantifies the three scenarios A, B and C on a national scale. If one of the scenarios is found to be completely unrealistic in the NL, it would be irrelevant to consider it further.

5.1.1) Offshore wind capacity

The wind energy capacity in the NL and its supply's potential for hydrogen demand is estimated.

Nowadays, the total offshore installed capacity of wind energy in the NL is evaluated at ca. 1,118 MW (Global Wind Energy Council, 2018). For example, the wind park Borssele 1&2 (owned by Ørsted) has a power capacity of 752 MW. Ørsted plans to install a new wind park "Holland Coast South 3&4" with a 700-MW capacity (Ørsted, 2018). The Dutch government settled a target to reach a capacity of 11.5 GW offshore wind installed by 2030 (Ørsted, 2019).

In the "Green hydrogen economy in the Northern Netherlands" project, some possibilities are indicated concerning the offshore wind energy capacity (van Wijk, 2017). One offshore wind park to be built between 2018 and 2030 is expected to possess a capacity of 4,000 MW and the existing Gemini park already has a capacity of 600 MW (Gemini Wind park, 2018). In the project, some electricity will be imported from the NorNed and Cobra cable. The former is a connection with Norway and the latter with Denmark. Both have a capacity of 700 MW each and are intended to transport renewable electricity in the first place (hydropower and wind-power) (energinet & TenneT, 2018; TenneT, 2019). As there is no clarity on the origin of the electricity imported from these foreign countries and the imports are not intended to be modelled, the energetical flows imported from foreign lands will not be considered further on in the thesis.

TenneT & Gasunie (2019) and the presentation by ECN (see Appendix 6.1) estimate the total offshore wind capacity installed in the NL by 2050 between 6 and 53 GW. This capacity could be used for hydrogen production.

Gigler & Weeda (2018) conduct some quantifications as well for the future energy system. In 2016, the installed offshore wind capacity in the NL is worth 957 MW. To fulfil the visions from the authors for future scenarios, the wind capacity would have to be expanded more than 160 times (see tables in Appendix 7.6). However, the total offshore wind energy potential for the NL is estimated at 40-80 GW. Hence, other production's origins or imports will be necessary. Gigler & Weeda (2018) predict that large production unit capacities will be available by 2030 (10-100 MW of wind, equivalent to a production of 4-40 t H_2/day) (Gigler & Weeda, 2018, p.49).

Finally, as a precaution, the Dutch offshore wind capacity is estimated at 6-53 GW.

5.1.2) Hydrogen demand

The hydrogen demand in the NL by 2050 is evaluated, based on different projections.

TenneT & Gasunie (2019) considered different scenarios for the hydrogen demand in the NL by 2050. Depending on the scenario, there is a hydrogen demand in the range of 24 to 38% of the national final energy demand. The latter is averaged at 415 TWh. Therefore, the total hydrogen demand in the NL by 2050 would be in the range 99.6 – 157.7 TWh (359 – 568 PJ or 2,564 – 4,057 kton of H_2). van Wijk, van Rhee, Reijerkerk, Hellinga, & Lucas (2019) estimate the production of hydrogen in the South-Holland region alone at 100-150 kton (14-21 PJ) from offshore wind energy by 2030. These resources provide orders of magnitude in the amount of hydrogen produced that can be expected in the Netherlands by 2050. However, the thesis focusses at hydrogen for transport's use, so the hydrogen demand for Dutch vehicles must be assessed.

The hydrogen demand for the Fuel Cell Electric Vehicle (FCEV) can be estimated with the Dutch car fleet value expected at 2050. Different resources indicate a value of ca. 8.2 million in the Dutch car fleet (personal and from the companies) in 2017 (CBS, 2019; Kennisinstituut voor Mobiliteitsbeleid, 2018). Some estimations indicate that there are 8.5 million vehicles in the NL at the beginning of 2019 (Blauwevinvis, 2019; TopGear Nederland, 2019).

Concerning the projections for the future Dutch fleet car, a thesis supported by Quist and Hemmes estimated the Dutch car fleet at 10 million cars in 2050 (Morales, 2009). A report from CPB and PBL estimated that the Dutch car fleet would be in the range of 8.2-10.2 million of cars (CPB & PBL, 2015). 10 million of cars may seem a bit excessive when we consider the projected population evolution, expected to reach 17.2 – 19.7 millions of individuals (CBS, 2017; CBS StatLine, 2017; PopulationPyramid.net, 2017; World population review, 2019; Worldometers, 2019). Nevertheless, a Dutch fleet's value of 10 million cars will be considered as a "worst-case" scenario with the largest evolution expected.

Now, the amount of hydrogen for 10 million cars must be assessed. van Wijk (2017) projects that, in the Northern Netherlands alone, 12,000 tons of hydrogen will be consumed by 100,000 cars, 10,000 tons for 1,300 buses and 3,000 tons for other mobility (trucks, etc…) in 2050. van Wijk et al. (2019) evaluate the demand for hydrogen for cars and buses in the Zuid-Holland region alone at 30-60 kton in 2030. In more details, van Wijk expects that between 60,000 and 120,000 cars, between 13,000 and 26,000 vans, between 340 and 680 buses will ride on hydrogen. These vehicles would lead to a hydrogen consumption of 25-50 kton (3.5-7 PJ). When the garbage trucks, fishing boats and others are also considered, the consumption is expected to reach 30-60 kton (4-8 PJ) (van Wijk et al., 2019). These projections are useful to convey an order of magnitude on hydrogen's consumption for vehicles in the Netherlands for the future.

To operate personal projections and calculations, several articles provide the same averaged value of hydrogen consumption by car: 1 kg of H_2/100 km (Biswas et al., 2013; Burkhardt et al., 2016; Singh et al., 2015). Different resources indicate that a Dutch car travels on average 13,000 km/year. This value has decreased from more than 14,000 km/year in 2000 to 13,000 km/year in 2015 (CBS, 2016; ODYSSEE-MURE, 2019). As a consequence, this value is kept constant for the projections in 2050, as a "worst-case" situation. For example, the "Northern Netherlands Hydrogen Economy" project estimates the annual distance driven by a car at 12,000 km, which is a bit lower (van Wijk, 2017). At the same time, the EAFO project considered an average annual distance travelled by a European car at 14,000 km/year (European Commission Directorate General Mobility & Transport, 2017).

Finally, 10 million cars are projected to be present in the NL by 2050, an average Dutch car is expected to drive 13,000 km annually in 2050 and its consumption to be worth 1 kg of H_2/100 km.

5.1.3) Electrolysis potential

Now that the wind potential has been evaluated in the Netherlands and the different elements are present to calculate the Dutch car's fleet consumption pf hydrogen, the electrolysis potential in the NL must be estimated.

The "Green hydrogen economy in the Northern Netherlands" project estimates that 1,000 MW of electrolysis capacity will be installed by 2050 only in this region (van Wijk, 2017). TenneT & Gasunie (2019) and the presentation by ECN (see Appendix 6.1) estimate the total electrolysis capacity installed in the NL by 2050 between 2 and 75 GW. This capacity would be used for hydrogen production.

Different resources give the following equivalence: a plant of 1 MW ⇔ a production of 18 kg of H_2/h ⇔ a volume 200 Nm^3 (Koj et al., 2017; Mori et al., 2014; Schmidt et al., 2018; Denis Thomas, 2016).

Finally, the main outputs from the three previous sections are summarised in **Table 21**.

Table 21. Information for the scenarios' quantification.

Dutch car fleet in the NL (2050)	Hydrogen use in a car	Distance travelled by a car annually (NL, 2050)	Offshore wind turbine potential (NL, 2050)	Electrolysis potential (NL, 2050)
10 million cars	1 kg of H_2/100 km	13,000 km/year	6-53 GW	2-75 GW

All the elements are provided to calculate the hydrogen's demand for the Dutch car's fleet in 2050 and to compare the results with wind power and electrolysis potentials in the NL. This step is achieved in the next three sub-sections.

5.1.4) Quantification of scenario A "Full hydrogen power"

This scenario envisions the most optimistic development of green hydrogen in 2050. Based on the configuration field selected (see **Table 18**), 70% of the Dutch car fleet will consume hydrogen. This leads to a total of 7 million hydrogen cars in the NL. The total distance travelled annually would equal:

$$7{,}000{,}000 \times 13{,}000 = 9.1 \times 10^{10}\ km\ (Eq. 6)$$

The total amount of hydrogen necessary per year would be then:

$$\frac{9.1 \times 10^{10}}{100} = 9.1 \times 10^{8}\ kg\ of\ H_2\ (Eq. 7)$$

The result is worth 910 kton which is in the range values from section 5.1.2.

Averaged on a year, we need a national production per hour of:

$$\frac{9.1 \times 10^{8}}{365.25 \times 24} = 103810.18\ {}^{kg\ H_2}/_{h}\ (Eq. 8)$$

With the equivalence 1 MW ⇔ 18 kg of H_2/h (cf. section 5.1.3), the power capacity needed can be evaluated in the NL:

$$\frac{103810.18}{18} = 5767.23\ MW\ or\ 5.77\ GW\ (Eq. 9)$$

However, the last result implies that the electrolyser's plant works in a continuous way all along the year, with no stop or pause. As we consider electricity from a wind turbine, a more realistic availability's value for the system would worth 30%. This factor implies a power capacity of:

$$\frac{5.77}{0.30} = 19.23\ GW\ (Eq. 10)$$

This value is obviously higher than the one from Equation 9 but takes more into account the intermittency factor due to wind energy resources. After the hydrogen is produced, it can be stored in different ways and can be further used for cars. Both power values are in the value range of the electrolysis and wind energy potential in the NL (cf. sections 5.1.1 and 5.1.3). "Scenario A" is deemed possible.

5.1.5) Quantification of scenario B "No to wind-based Hydro"

This scenario envisions the most pessimistic development of green hydrogen in 2050. Based on the configuration field selected (cf. **Table 19**), 10% of the Dutch car fleet will consume hydrogen. This leads to a total of 1 million hydrogen cars in the NL. The total distance travelled annually would equal:

$$1{,}000{,}000 \times 13{,}000 = 1.3 \times 10^{10}\ km\ (Eq. 11)$$

The total amount of hydrogen necessary per year would be then:

$$\frac{1.3 \times 10^{10}}{100} = 1.3 \times 10^{8}\ kg\ of\ H_2\ (Eq. 12)$$

The result is worth 130 kton which is in the range values from section 5.1.2.

Averaged on a year, we need a national production per hour of:

$$\frac{1.3 \times 10^{8}}{365.25 \times 24} = 14830.03\ {}^{kg\ H_2}/_{h}\ (Eq. 13)$$

With the equivalence 1 MW ⬄ 18 kg of H_2/h (cf. section 5.1.3), the power capacity needed can be evaluated in the NL:

$$\frac{14830.03}{18} = 823.89\ MW\ or\ 0.82\ GW\ (Eq. 14)$$

Again, as we consider electricity from a wind turbine, a more realistic availability's value for the system would worth 30%. This factor implies a power capacity of:

$$\frac{0.82}{0.30} = 2.75\ GW\ (Eq. 15)$$

The same remarks than in sub-section 5.1.5 apply here. Both power values from equations 14 and 15 are in the value range of the electrolysis and wind energy potential in the NL (cf. sections 5.1.1 and 5.1.3). "Scenario B" is deemed possible.

5.1.6) Quantification of scenario C "Mixed results"

This scenario envisions more nuanced development of hydrogen in 2050. Based on the configuration field selected (cf. **Table 20**), 30% of the Dutch car fleet will consume hydrogen. This leads to a total of 3 million hydrogen cars in the NL. The total distance travelled annually would equal:

$$3{,}000{,}000 \times 13{,}000 = 3.9 \times 10^{10}\ km\ (Eq. 16)$$

The total amount of hydrogen necessary per year would be then:

$$\frac{3.9 \times 10^{10}}{100} = 3.9 \times 10^{8}\ kg\ of\ H_2\ (Eq. 17)$$

The result is worth 390 kton which is in the range values from section 5.1.2.

Averaged on a year, we need a national production per hour of:

$$\frac{3.9 \times 10^{8}}{365.25 \times 24} = 44490.08\ {}^{kg\ H_2}/_{h}\ (Eq. 18)$$

With the equivalence 1 MW ⇔ 18 kg of H_2/h (cf. section 5.1.3), the power capacity needed can be evaluated in the NL:

$$\frac{44490.08}{18} = 2471.67\ MW\ or\ 2.47\ GW\ (Eq. 19)$$

Once more, as we consider electricity from a wind turbine, a more realistic availability's value would worth 30%. This factor implies a power capacity of:

$$\frac{2.47}{0.30} = 8.24\ GW\ (Eq. 20)$$

The same remarks than in sub-section 5.1.5 apply here. Both power values from equations 19 and 20 are in the value range of the electrolysis and wind energy potential in the NL (cf. sections 5.1.1 and 5.1.3). "Scenario C" is deemed possible.

Table 22 summarises the main parameters calculated for each scenario.

Table 22. Parameters calculated for scenario A, B and C

	Scenario A	Scenario B	Scenario C
Required hydrogen volume in a year	9.1×10^8 kg	1.3×10^8 kg	3.9×10^8 kg
Power capacity (continuous) (GW)	5.77	0.82	2.47
Power capacity (availability: 30%) (GW)	19.23	2.75	8.24
Plausible scenario?	Yes	Yes	Yes

When the power values calculated to fulfil the Dutch car's fleet demand in 2050 are considered, they may seem relatively low in comparison to the full electrolysis potential in the NL (2 – 75 GW). However, it must be recalled that these values consider the hydrogen demand for vehicles only and not for potential other uses. Overall, the three scenarios developed can be applied in concrete in the NL by 2050.

5.2) The boundaries of the ex-ante large-scale LCA model

The three scenarios developed are deemed plausible for the NL in 2050 and are to be implemented in an LCA model. However, some discussions can raise about the definition and the boundaries of the ex-ante large-scale LCA model, especially in comparison with the pilot-scale models. Along with the work for the thesis, two main topics were mentioned and are discussed now.

5.2.1) Reflection on hydrogen transport

This section discusses the reflections that raised along with the thesis' process about modelling hydrogen's transport.

A new step that can be added in the ex-ante large-scale LCA model is the hydrogen transportation. The latter raises some problems since, under common conditions, hydrogen possesses a low density (≈

0.085 kg/m^3). Several options for transporting hydrogen exist but the pipeline is the most likely one to be adopted on a large-scale. The literature review conducted shows that the pipeline distribution is the most environmentally friendly option and also a "decent economic way" at large-scale (Demir & Dincer, 2017, p.10428; Wulf & Kaltschmitt, 2018). Transport through pipelines requires high pressure, usually around 500-700 bars (Gahleitner, 2013). Since the Netherlands wants to get free of natural gas before 2050, a possibility is to adapt the existing gas infrastructure for hydrogen transportation. To do so, Ball & Wietschel indicate that "coating or lining the pipelines […] could solve the problems in using existing long-distance transmission pipelines made from steel" (Ball & Wietschel, 2009, p.629).

Gigler & Weeda (2018) mention the question of whether the Dutch gas network should be completely converted to hydrogen production or only gradually (called the "gas blending" option). According to the authors, the "100% hydrogen" path is slightly preferred. This solution seems was also mentioned in an interview (see Appendix 6.2).

For the transport sector, favourable taxes already exist in the NL to promote the use of hydrogen cars. The next relevant step would be the implementation of the basic network with refuelling points to serve as a strong basis for further development. Air Liquide is one of the key players in hydrogen's transport. The company possesses a hydrogen network, 1,000 km long, connecting Rotterdam, Zeeland, Belgium and the north of France. Studies from DNV GL and GTS23 indicated that the high-pressure natural gas pipes can cope with high percentages of hydrogen (up to 100%) and that the technical and economic costs for adjustments are relatively manageable. Nevertheless, the TKI Gas report claims that: "Specific components and elements such as compressors, monitoring stations and gas storage facilities will require modification and there are aspects […] that require further investigation." (Gigler & Weeda, 2018, p.55). Other actors such as Dow, ICL, Yara and Gasunie in Zeeland Flanders have conducted projects where they wanted to test the reuse of natural gas pipelines for hydrogen transport and the projects "aptly illustrate how the natural gas network can be used for hydrogen" (Gigler & Weeda, 2018, p.56). Further works are still necessary from the statutory and regulatory sides when the hydrogen use will increase in the years to come. Again, dual use of gas could be considered during a transitional period, but Gigler & Weeda (2018) specify that further studies will be required over the feasibility and practicality of this approach. Several other projects are under work from GERG, a European association of gas companies, or the "21 Leeds City Gate project" to explore the potential in transporting hydrogen through pipelines. Again, heavy vehicles or buses systems can be more easily implemented and adjusted to hydrogen technologies as their consumptions are much more predictable than individual vehicles.

One initial intention in the thesis was to model the hydrogen transport through pipelines in the ex-ante large-scale LCA model. This was mainly motivated by several papers claiming that hydrogen's transport in pipelines would require a change in the gas network's composition (Ball & Wietschel, 2009). However, the different interviews conducted (see Appendix 6) and the reading of other reports (TenneT & Gasunie, 2019) suggest that there will not be a need to make significant adjustments of the gas network for hydrogen transport. Naturally, some specific parts will need to be updated or changed and there would still be losses along the pipelines, as it is already the case nowadays. Therefore, some kind of "business as usual" scenario type is expected to apply for a hydrogen's transport through pipelines in the future. Furthermore, discussions with members from ENGIE France led to the assumption that the environmental impact of hydrogen transport would be most likely negligible in comparison to other factors. The use of compressors to reach the high pressures required would have some influence, but this element can be considered as a Balance of the Plant (BoP) element. Therefore, the impact of a compressor can be distributed along the whole lifecycle of the electrolysis plant. The

BoP elements are expected to see their environmental impacts decreased over time, due to the economy of scales (see Appendix 6; Möckl, personal contact, 2019).

Finally, reliable and relevant data about hydrogen transport are also delicate to find in the literature or even after some contacts with companies (such as Gasunie). The question of practical implementation of transport in an LCA model is also another factor to consider. One question that arises is the way to implement a pipeline transport in LCA. Should a functional unit be changed to "1 kg of H_2/km transported"? Or should an average distance travelled by hydrogen be considered? How to define this average distance then? All these practical questions were not mentioned in the literature reviewed.

As a consequence, even though the hydrogen's transport through pipelines is still mentioned in the scenarios (implementation, centralisation/decentralisation distribution), it will not be modelled in the ex-ante large-scale LCA model because of the lack of data on the topic and its potentially low environmental impact. Instead of hydrogen transport, another factor mentioned among others by ENGIE members will be discussed in the next section: the recycling aspects.

5.2.2) Recycling the electrolysers

When a technology is implemented at a large-scale, a topic that is commonly discussed is the end-of-life (EoL) phase. Concerning alkaline or PEM electrolysers, recycling technologies are currently under studies. This sub-section develops and considers optional recycling technologies that can be implemented in the ex-ante large-scale LCA models, particularly for noble metals recycling. These recycling processes are implemented in one ex-ante large-scale LCA model and is studied in a sensitivity analysis (see Section 6.4.5.1).

Recycling aspects were several times mentioned by members from ENGIE France, in the CRIGEN laboratory. Modelling electrolysers recycling would not have made a lot of sense in the pilot-scale LCA models. Nowadays, there are no deep studies conducted on the recycling perspective of electrolysers. No massive electrolysis plant exist currently (with alkaline or PEM technology) and only 4% of the hydrogen produced in the world is made by electrolysis (Ball & Weeda, 2015; Bhandari et al., 2014; Gielen & Simbolotti, 2005). However, if the technology is to be applied to large-scale, the state-of-the-art would change and a need for recycling systems would appear. The potential increase in PEM technology's use would raise several important issues, linked among others to the noble metals' use. Therefore, it is relevant to take into account as much as possible the recycling aspects. Different methods exist or are under study. Information is available to operate some basic modelling and given in the next paragraphs. However, due to the lack of detailed studies on the recycling systems for electrolysers, the modelling is sometimes estimated on averages and based on other similar technologies/processes. Nevertheless, these models would provide some orders of magnitude and indications.

The "common" elements from electrolysers such as steel, aluminium and others have been used in many different technologies and for years. Consequently, recycling infrastructures are already present and available in real-world and database. The (noble) metals (Iridium, Platinum, Titanium, Nickel) are more delicate to handle as no clear path has been implemented in large-scale or with consistent sustainability performances.

The HyTechCycling project, mentioned by members from ENGIE, is a European project that was conducted between May 2016 and May 2019. The project was funded by the Fuel Cells and Hydrogen 2 Joint Undertaking. Different industries and universities, mostly Spanish, were involved in this project (HyTechCycling, 2016). HyTechCycling's goal was to conduct a review of the different recycling technologies that are available or emerging for the recovery of valuable metals. The project also considered BoP elements' recovery of valuable metals for which mature recycling technologies already exist.

In general, the different reports published by HyTechCycling describe two main ways to recover valuable metals: hydrometallurgical and pyro-hydrometallurgical processes. As indicated by the name, the pyro-hydrometallurgical processes consider more drying/warming processes with high temperatures. The number of steps for the pyro-hydrometallurgical path may be lower in comparison to hydrometallurgical recovery, but the energy intensity is higher. Hydrometallurgical recovery is made under ambient (or similar) conditions and more detailed descriptions are given about this process. For these reasons, the hydrometallurgical process will be considered for the recovery of electrolyser's valuable metals. Lotrič A. et al. (2017) also describe some novel processes that could be used in the future. However, these processes are still on a research phase. Furthermore, not enough data was provided to potentially implement these processes in an LCA model.

The different recycling technologies (potentially) available for electrolysers are described below:

Recycling of the common elements:

Aluminium, copper and steel can be recycled at high rates with conventional techniques (Valente, Martin-Gamboa, Iribarren, & Dufour, 2017). The recycled elements can be reused as inputs. For example, "75% of all-copper based products are made of recycled copper" (Valente et al., 2017, p.25). The list of the treatment processes used to treat the common elements is to be found in Appendix 11.

Recycling of PTFE (for Nafion):

Despite the difference in composition with copper, polytetrafluoroethylene (PTFE) can be recycled in a similar way. First, PTFE scraps need to be heated to eliminate all the undesirable impurities. After, a grinding step reduces the scraps into a fine powder and blended with pure TFE. The mix is put into a long strand before being cut into small pieces. The latter is sent to the companies for reuse in new products.

Recycling for platinum (applicable also for iridium):

Duclos, Svecova, Laforest, Mandil, & Thivel (2016) and Laforest et al. (2016) considered recycling platinum from the MEA (Membrane Electrode assembly). A minimum of perspective must be taken with the work from Laforest et al. (2016) since the author considers the platinum recycling from the fuel cell and not from electrolysers. However, as an electrolyser performs the same operation than a fuel cell but in the opposite way (H_2's creation instead of H_2's consumption) with only some variations in the design and materials, it has been considered that the work from Laforest et al. (2016) can be used as a strong basis. The extraction and treatment of precious metals usually consider hydrometallurgical and pyrometallurgical processes (Valente et al., 2017). The same process can be applied to iridium and other platinum metals (Valente et al., 2017). The only difference in the flowchart and the processes described is that platinum is replaced by iridium. The final product outflow is then $(NH_4)_2IrCl_{6(s)}$, instead of $(NH_4)_2PtCl_{6(s)}$.

In the case of platinum extraction with the hydrometallurgical pathway, the first step is a leaching process carried out with hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2). The second step is separation, possible via solvent extraction, precipitation, cementation, ion exchange, filtration or distillation. In the platinum (or iridium) case, a liquid-liquid extraction process with Cyanex 923® and pentanol has been chosen since it enables to reach the highest efficiency of noble metal's recovery (Pt or Ir) at 76% (Duclos et al., 2016). After, a stripping step is applied with sodium hydroxide (NaOH).

Finally, precipitation and filtration steps enable to collect the final product $(NH_4)_2PtCl_{6(s)}$ and to eliminate the wastewaters. **Figure 27** is a flowchart for the extraction of platinum (the same flowchart for iridium is available in Appendix 9):

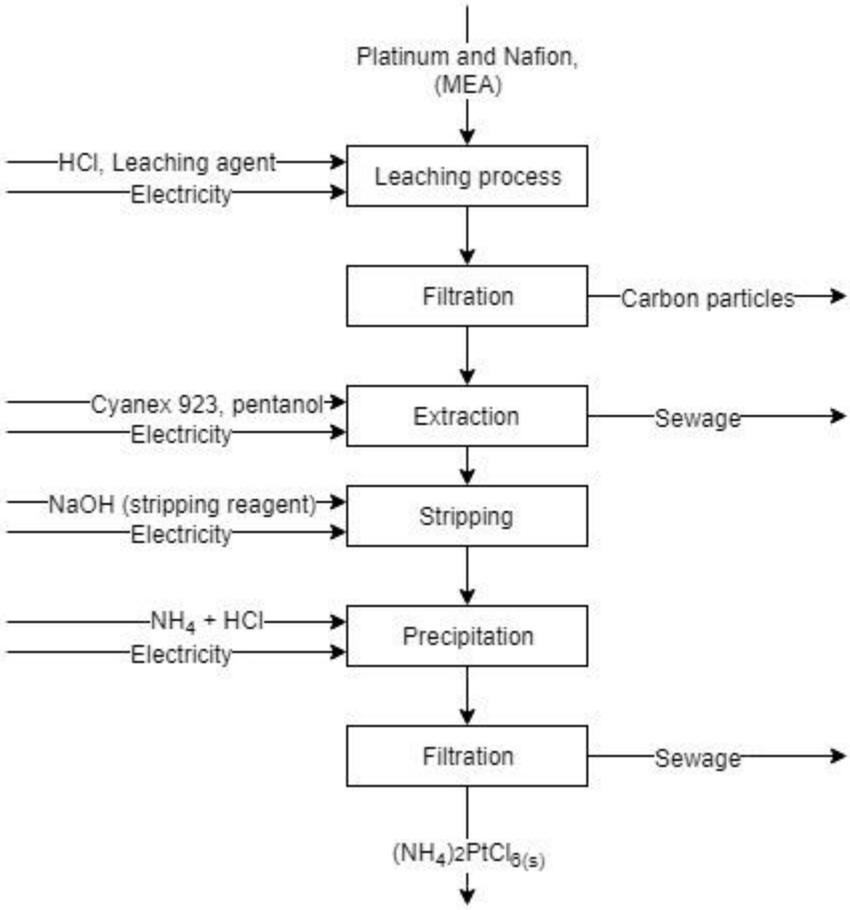


Figure 27. Platinum recovery process based on Duclos et al. (2016); Laforest et al. (2016) and Valente et al. (2017)

The quantification of the different flows for **Figure 27** was based on the work from Laforest et al. (2016) who considered only platinum's extraction. Adjustments have been made to consider the iridium and Nafion treatments. All the details can be found in Appendix 9).

Valente et al. (2017) indicate the different advantages of hydrometallurgical processes: "reduced risk of air pollution, higher selectivity of materials, lower energy consumption and the possibility to reuse the chemical agents" (Valente et al., 2017, p.26). Nevertheless, some drawbacks are still present, such as the need for mechanical pre-treatment and large volumes of solution and the generation of wastewaters which can be corrosive or toxic. The recovery of platinum from the initial content is evaluated at 76% (Valente et al., 2017).

Nickel recovery:

The catalyst (nickel) to be recycled is first washed with demineralised water. After, sulfuric acid is injected to operate leaching. Residues of nickel and aluminium are extracted from this stage. The output of the leaching process, the leach liquor is mixed with an alkali to remove all the aluminium still present. The aluminium is eliminated in the form of a precipitate. The purified leach liquor goes through a precipitation process with the injection of Na_2CO_3. The precipitate removes all the nickel element and is turned into $NiCO_3$ after drying. The filtrate is evaporated through heat and gives the final product sodium sulphate (H_2SO_4).

With this process, 99% of the Nickel and 39% of the aluminium can be recovered (Valente et al., 2017).

Figure 28 provides a flowchart for the nickel recovery process, based on J. Y. Lee, Rao, Kumar, Kang, & Reddy (2010). The numbers were adjusted based on the work from J. Y. Lee et al. (2010). For all the details about calculations and definitions of the flows, see Appendix 10.

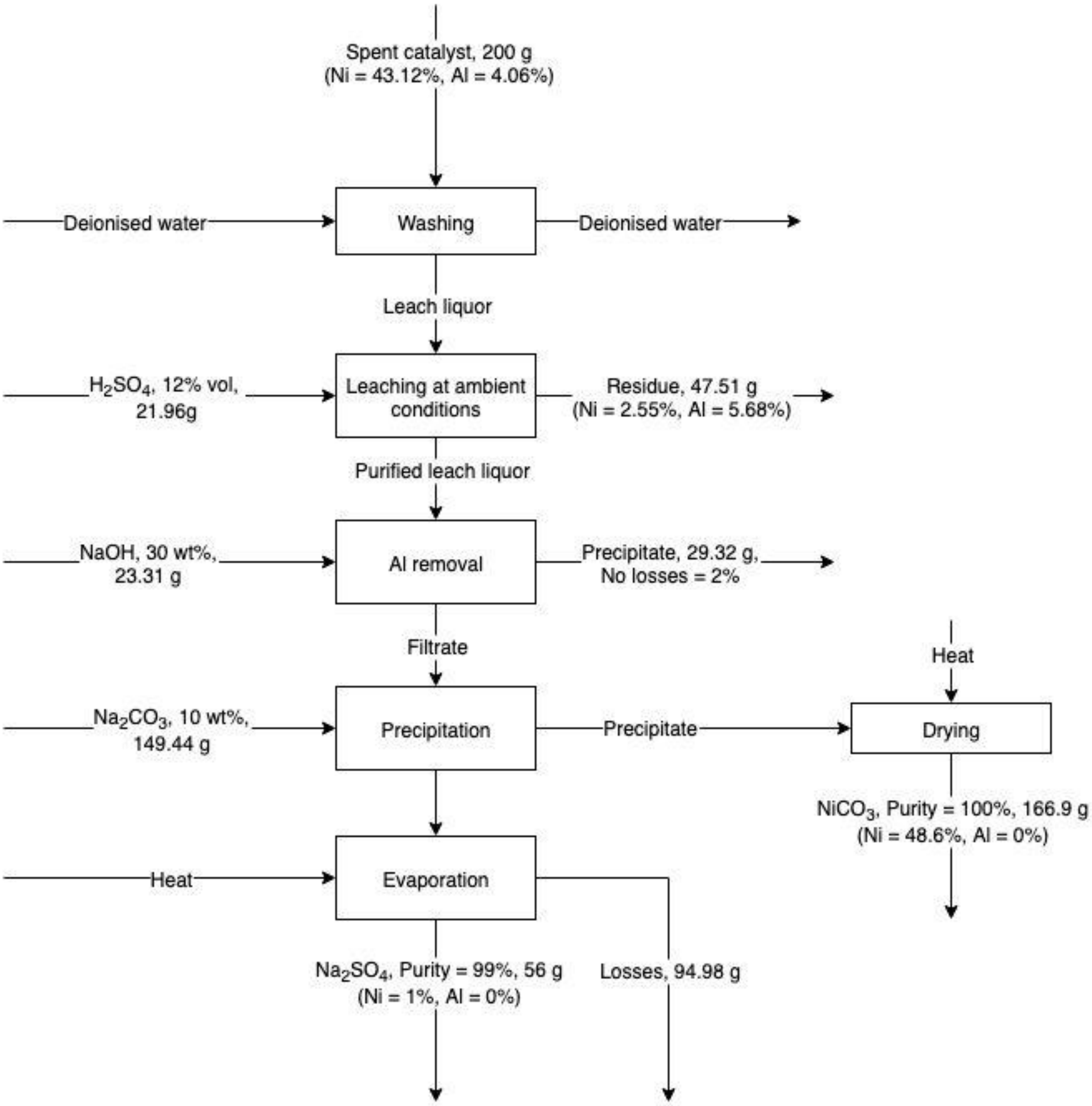


Figure 28. Nickel recovery process (based on Lee et al. (2010)).

Finally, the different potential recycling technologies for electrolysers have been succinctly described and information is available to implement some basic modelling in the ex-ante large-scale LCA model. However, as some of these recycling technologies are still under research and no clear evolution is present, the recycling technologies will only be applied for sensitivity analysis (Section 6.4.5.1). For this analysis, the boundaries of the ex-ante large-scale LCA model will be different than the ones from the pilot-scale LCA models.

5.3) Implementation in OpenLCA

Now that the boundaries of the ex-ante large-scale LCA models have been discussed, the electrolyser's technological field must be adapted to the three scenarios "A", "B" and "C". **Table 23** provides a general overview of the parameters and their values adopted. The choices of the parameters' values are then explained for each scenario. For a question of clarity, only the parameters that could have been implemented and adjusted in the LCA model are presented. The parameters that could not have been modelled or that kept the same value across the scenarios are absent.

Table 23. Electrolyser's parameters' values adapted from the technological field in relation to the scenarios.

			Scenario A	*Scenario B*	*Scenario B1*	*Scenario C*
Plant's capacity	AE	2050	1 GW	100 MW	1 GW	1 GW
	PEM	2050	1 GW	100 MW	1 GW	1 GW
Lifespan of the electrolyser plant	AE	2050	30 years	20 years	20 years	30 years
	PEM	2050	30 years	20 years	20 years	30 years
Lifespan of the stack	AE	2050	120,000h	80,000h	80,000h	120,000h
	PEM	2050	130,000h	80,000h	80,000h	130,000h
Electrical consumption	AE	2050	47 kWHe/kg H2	50 kWHe/kg H2	50 kWHe/kg H2	47 kWHe/kg H2
	PEM	2050	50 kWHe/kg H2	50 kWHe/kg H2	50 kWHe/kg H2	50 kWHe/kg H2
Stack capacity (power)	AE	2050	20 MW	5 MW	5 MW	20 MW
	PEM	2050	20 MW	5 MW	5 MW	20 MW
Water consumption	AE	2050	9 kg/kg H2	10 kg/kg H2	10 kg/kg H2	10 kg/kg H2
	PEM	2050	9 kg/kg H2	10 kg/kg H2	10 kg/kg H2	10 kg/kg H2
Steel consumption	AE	2050	10 kg/kW	30 kg/kW	30 kg/kW	20 kg/kW
	PEM	2050	7 kg/kW	10 kg/kW	10 kg/kW	8 kg/kW
KOH (electrolyte) consumption (AE)	AE	2050	1 g/kg H2	2 g/kg H2	2 g/kg H2	1 g/kg H2
Nickel consumption (AE)	PEM	2050	0.2 kg/kW	2 kg/kW	2 kg/kW	1 kg/kW
Nafion consumption (PEM)	AE	2050	0.002 kg/kW	0.016 kg/kW	0.016 kg/kW	0.005 kg/kW
Iridium load (PEM)	PEM	2050	0.01 g/kW	0.7 g/kW	0.7 g/kW	0.1 g/kW
Platinum load (PEM)	AE	2050	0.01 g/kW	0.3 g/kW	0.3 g/kW	0.05 g/kW
Titanium load (PEM)	PEM	2050	35 g/kW	500 g/kW	500 g/kW	100 g/kW

Scenario A: "Full hydrogen power"

In this scenario, the most optimistic path for the electrolyser's development is considered (see narratives in section 4.5). The strong subsidies from the government and a general trend from stakeholders to promote hydrogen's technologies enabled significant R&D improvements. With this perspective, all the parameters from **Table 23** reached their optimal values, based on the projections from **Table 17**. So, the electrolyser reached the best efficiency, with the lowest material's needs possible, the large-scale levels are reached without serious issues (stack's capacity, plant's capacity…) and the different lifespans were extended to the maximum envisioned. Naturally, more trade-offs would occur in reality. Increasing the efficiency of the electrolyser may require increasing some materials' needs. It is unlikely that an increase in electrolyser's efficiency while decreasing all materials' needs is technically possible. However, as the trade-off was not studied enough in this thesis, the assumption taken is to put all the parameters at their optimal values.

Scenario B: "No to wind-based Hydro"

This scenario sees a low development of hydrogen's technologies in the Netherlands (see narratives section 4.5). The first assumption in this sense is to consider that the maximum plant capacity reached in the NL is 100 MW (and not 1 GW as in scenarios A and C). Reaching a 100 MW-plant's capacity seems reasonable knowing that the current (i.e. in 2019) pilot-scale installations in the NL already reach several MW's capacity and different companies, such as Nel Hydrogen, plan to build plants with a several MW's capacities. The 100-MW plant would still remain an exceptional scale in the Dutch context of the hydrogen's development in "Scenario B", no other plant in the NL would reach such a high capacity.

With this perspective, all the parameters from **Table 23** are kept at the same values than the ones in 2019 (see **Table 17**). Only the stack capacity for both electrolysers' technologies (PEM and AE) is expected to reach 5 MW since these models are already reachable in 2019. When the technological parameters were defined with a range of values (for example, the steel consumption is projected to worth 10 to 30 kg/kW or the plant's lifespan is expected to increase from 20 to 30 years), the worst-case is considered as a consequence of the low R&D development (30 kg/kW in the case of steel's consumption or a plant's lifespan of 20 years "only").

Scenario B1: "No to wind-based Hydro"

This scenario is exactly the same than "Scenario B" but appears from a "conflict" between the LCA methodology and the scenario approach. Based on the scenarios, considering a 1-GW plant's scale makes sense in "Scenario A" and C (optimistic development of green hydrogen technology and mixed results with strong outcomes in the North of the NL). "Scenario B" (pessimistic development of green hydrogen technology) does not justify the construction of a 1-GW plant's scale. However, in the LCA methodology, when two (or more) systems are compared, the comparability must be the most relevant one. In the thesis' case, the scale of the plant *should* be the same between all alternatives (1 GW). Hence the conflict: the scenario justifies a plant with 100 MW's capacity whereas the LCA approach would promote a plant with 1 GW's capacity in all cases. As the 100 MW's plant is the one that would be actually built if "Scenario B" occurs, this alternative is considered more important. However, for quick analyses, an alternative to "Scenario B", called "B1", will consider a plant with 1 GW capacity, the other parameters remaining unchanged. Changing other parameters, such as lifespan of the plant could add interesting results or interpretations. However, due to practical constraints, only the plant's capacity parameter (100 MW ➔ 1 GW) will be changed. The idea is to quickly analyse how the environmental impacts may evolve if a large-scale installation is created based on the current performances of the electrolyser (no evolution, as in "Scenario B").

Scenario C: “Mixed results”

Because of the “mixed” evolution, “Scenario C” requires much more arbitrary assumptions and other values could be adopted with valid reasons. The logic used in the thesis is described below.

“Scenario C” considers good scientific development of electrolysers because of the North of the NL’s context (see narratives in section 4.5). However, as the electrolyser’s development is located to a specific region and not at national-scale, the resources invested for green hydrogen development are lower than in “Scenario A”. Consequently, some improvements are less significant than in “Scenario A”. The large-scale system could have been reached with a 1 GW-plant’s capacity and optimum lifespans. However, the water consumption remains at 10 kg H_2O/kg of H_2 since decreasing this value is particularly challenging for chemicals reasons. Different technological factors – such as the steel’s consumption, use of metals like nickel, iridium, platinum, etc. – have reached intermediary levels of improvements, shown in **Table 24**. It is assumed that upscaling processes added to some R&D would result in some progress in technological parameters without reaching the same optimal situation than in “Scenario A”.

Table 24. Technological parameters with their values for “Scenario C” and their assumptions

Parameter	Electrolyser's type	Value	Assumption
Water consumption	AE	10 kg/kg H_2	Value hard to decrease for chemical reasons
	PEM	10 kg/kg H_2	
Steel consumption	AE	20 kg/kW	Some progress was achieved with upscaling effects but not deemed as the main priority
	PEM	8 kg/kW	
KOH (electrolyte) consumption	AE	1 g/kg H_2	One of the priorities for technological improvement so good progress
Nafion consumption	PEM	0.005 kg/kW	Progresses achieved but not as optimistic as expected. This choice also reflects feedback from some contacts about the technological field.
Iridium load	PEM	0.1 g/kW	
Platinum load	PEM	0.05 g/kW	
Titanium load	PEM	100 g/kW	

Finally, all scenarios have been assessed for their likelihood, the boundaries of the ex-ante large-scale LCA models have been discussed and scenarios have been quantified for implementation in OpenLCA.

6) Ex-ante large scale LCA

The quantified scenarios from the last section can be implemented in the ex-ante large-scale LCA model (Phase 4 in the methodology overview). As a new LCA is conducted, the whole methodology described by Guinée (2001) is applied again. Naturally, due to the topic of the thesis, many similitudes can be found between the following sections and Chapter 3. For this reason, the definitions and purposes of each LCA phase are only shortly recalled.

6.1) Goal & scope definition

The first phase of an LCA is the “Goal and scope” definition. The assumptions that define the working plan for the LCA are stated.

6.1.1) Goal of the ex-ante large-scale LCA

The goals of the ex-ante large-scale LCA can be defined in several points:

- Firstly, the environmental impacts from the large-scale hydrogen’s production with alkaline or PEM electrolysers will be studied.
- Secondly, a comparison of the environmental performances will be made between the two electrolysers’ alternatives considered (PEM and alkaline), within a common scenario (PEM from “Scenario A” will not be compared to AE from “Scenario B”, since the two scenarios are different). The SMR is still treated as the incumbent technology and will be used as a gauge.
- Thirdly, the environmental performances from each electrolyser’s alternative (PEM and alkaline) will be compared with the results from the pilot-scale LCA models (see chapter 3).

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

The ex-ante large-scale LCA study is meant to be analysed and interpreted within this thesis context. The large-scale model has been developed with the help of different resources such as literature, desk research, interviews, one workshop and one collaboration with ENGIE (see Appendices 6 and 8). Clear communication on the assumptions adopted is made to avoid any misunderstanding. Therefore, the target audience concerns the different persons involved in this thesis and the ones who are interested in the study’s outcomes.

6.1.2) Scope of the ex-ante large-scale LCA

The ex-ante large-scale LCA considers two electrolysis’ technologies: PEM and alkaline. The LCA considers the environmental emissions and impacts from the processes necessary for the production of H_2.

The timespan is in 2050 and the quantified electrolyser’s characteristics have been defined with the help of scenarios, interviews and literature (see chapters 4 and 5). The literature used is the most recent one (from 2016 up to 2019) and interviews were conducted in order to get opinions from experts and to understand the most likely trends between 2019 and 2050. Missing data or background processes were taken from ecoinvent 3.4.

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…) are out of the scope of the study. The recycling systems are considered only for sensitivity analysis, as not enough information is available to conduct deep analysis. Some raw materials come from places outside the Netherlands, but the strongest focus has been applied to limit the geographical coverage in the NL (the electricity is produced in the NL) or in Europe. The same strategy has been applied than in Section 3.1.2 concerning the origin of materials. All the details on the material's origins can be found in the Excel file "Appendix, Life Cycle Inventories, Pilot-scale LCA and ex-ante large-scale LCA models".

An attributional approach is adopted since no evolution in hydrogen's demand or market is modelled within the LCA file.

6.1.3) Function, functional unit, alternatives, reference flows

To conduct the LCA, several flows must be defined.

- The function defines the purpose of the system under study. In the thesis, it is the production of hydrogen in kg, just as in the pilot-scale LCA models.
- The functional unit describes the function in quantifiable terms. The functional unit is defined as "1 kg of hydrogen" produced. In similitude with the pilot-scale LCA models, only a mass perspective is considered for simplification and there is no consideration of pressure or temperature.
- The alternatives of the technology are the PEM and the alkaline electrolysis. SMR is considered as BAU scenario type and its model is unchanged in comparison to Chapter 3. For each alternative (except SMR), one large-scale model was developed with flexible inputs, called LCA-parameters. These LCA-parameters enable to consider the studied technology in the different scenarios defined in Chapters 4 & 5.
- Based on this, the reference flows describe the different ways of obtaining the functional unit. They are consequently defined as:
    - To provide 1 kg of hydrogen from large-scale AE, scenario A
    - To provide 1 kg of hydrogen from large-scale AE, scenario B
    - To provide 1 kg of hydrogen from large-scale AE, scenario B1 (only for quick analyses)
    - To provide 1 kg of hydrogen from large-scale AE, scenario C
    - To provide 1 kg of hydrogen from large-scale PEM, scenario A
    - To provide 1 kg of hydrogen from large-scale PEM, scenario B
    - To provide 1 kg of hydrogen from large-scale PEM, scenario B1 (only for quick analyses)
    - To provide 1 kg of hydrogen from large-scale PEM, scenario C
    - To provide 1 kg of hydrogen from SMR

6.2) Life Cycle Inventory

6.2.1) Economic-Environment boundaries

The same definition and notes than the ones mentioned in Section 3.2.1 apply here. One further note must be added:

- An electrolysis reaction generates hydrogen *and* oxygen (with a ratio of 1:8). In the large-scale LCA models, oxygen has been modelled as an environmental flow directly sent to the environment. The interviews conducted (see Appendix 6) showed that industrials and companies would be interested in a potential reuse of oxygen – which would then become a product –, but no technology is seen as available to achieve such a purpose. That is why oxygen remains in this thesis an environmental flow.

6.2.2) Data collection and relating data to unit processes

6.2.2.1) Adjustment from the pilot-scale to the large-scale

Developing the ex-ante large-scale LCA model raised the question of boundaries and elements to consider. Transport of hydrogen and recycling systems have already been discussed in Section 5.2.

Basically, the pilot-scale LCA models and ex-ante large-scale LCA models will consider the same structure but a harmonization is necessary.

The pilot-scale LCA models are meant to be used as a basis to construct the ex-ante large-scale LCA models. Naturally, the pilot-scale LCA models were constructed from different resources and possess some differences in flows' description and quantification. When considering the materials/energy inventory from the pilot-scale LCA models, some inflows were too specific or dependent on the context or possessed an unclear role. For these reasons, the mentioned flows were "skipped" or not modelled in the ex-ante large-scale LCA model. In this sense, a selection of elements was necessary. After a discussion with the first supervisor, it has been decided that the more detailed the ex-ante large-scale LCA model is, the better it is. As long as the material/energy flow fulfilled a clearly defined purpose, it was kept. Finally, only a few flows from the pilot-scale LCA models were not modelled because of role's unclarity, irrelevance or lack of data (see the Excels "Appendix, Life Cycle Inventories, Pilot-scale LCA and ex-ante large-scale LCA models" and "Appendix, Origin of materials, pilot-scale LCA models" for all the details).

6.2.3) Cut-offs and flowcharts

The ex-ante large-scale LCA models do not consider the end of life of materials. Only a sensitivity analysis will consider some recycling processes.

Ideally, all processes and flows within a LCA study should consider a "cradle-to-grave" approach. In similitude with the pilot-scale LCA model, it is impossible to achieve due to a lack of data and knowledge at some stage in the process. Again, due to the simplification of the ex-ante large-scale LCA models, no cut-offs were applied.

Due to the construction of the LCA models, no unit process possesses more than one product of interest. Consequently, no unit process possesses multifunctionality with several outcomes and no allocation of the environmental impacts between the products of interests was necessary to implement

Figure 29 & **Figure 30** present the flowcharts for the ex-ante large-scale models. For clarity, several background processes and flows in **Figure 29** & **Figure 30** were gathered into common names, such as "anode/cathode". The outputs of these processes are "several flows". The Excel "Appendix, Life Cycle Inventories, Pilot-scale LCA and ex-ante large-scale LCA models" describe all the inflows/outflows in details and the Appendix 4 provide flowcharts for all the background processes/flows used for the ex-ante large-scale LCA.

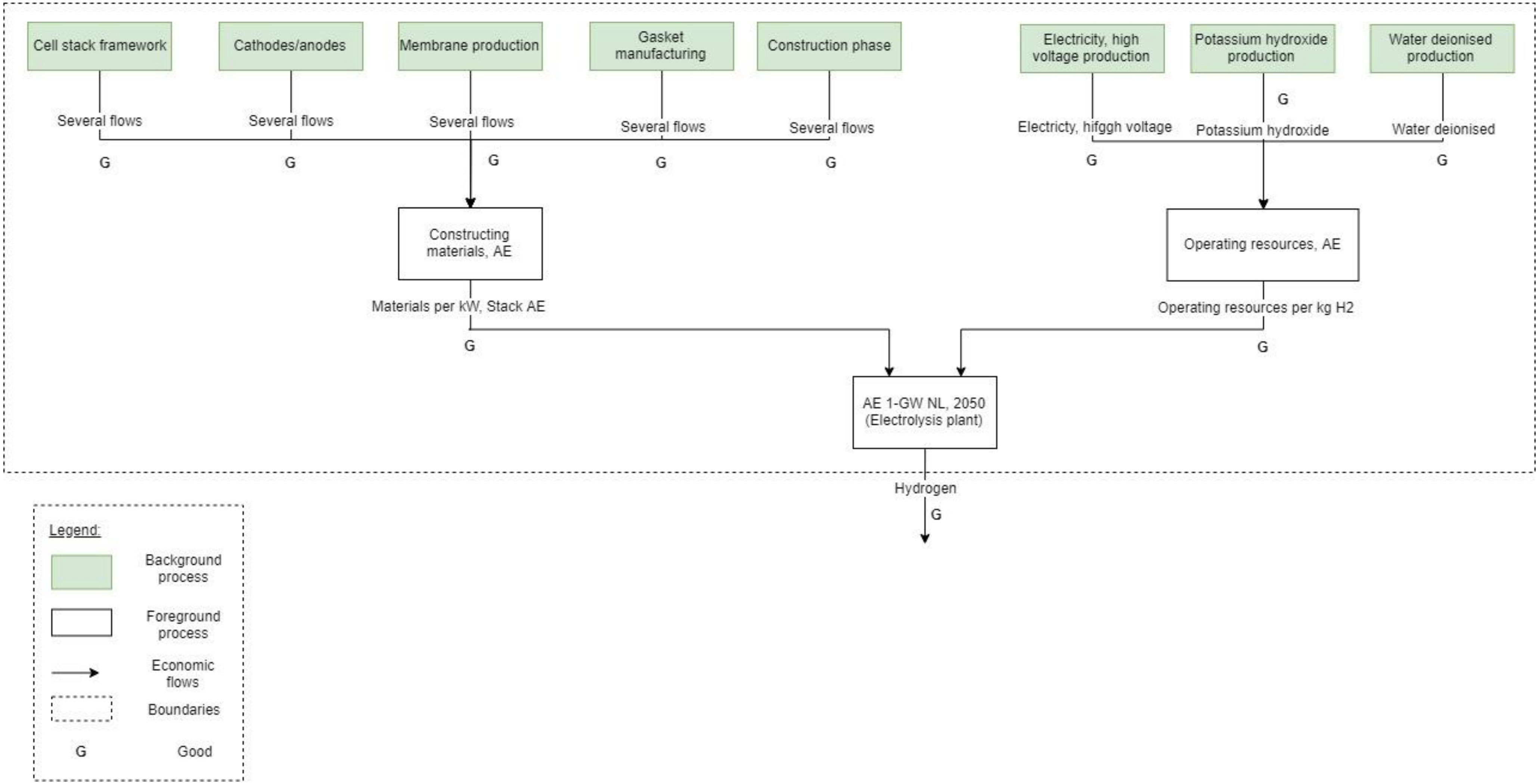


Figure 29. Flowchart for the ex-ante large-scale LCA model of the alkaline electrolyser.

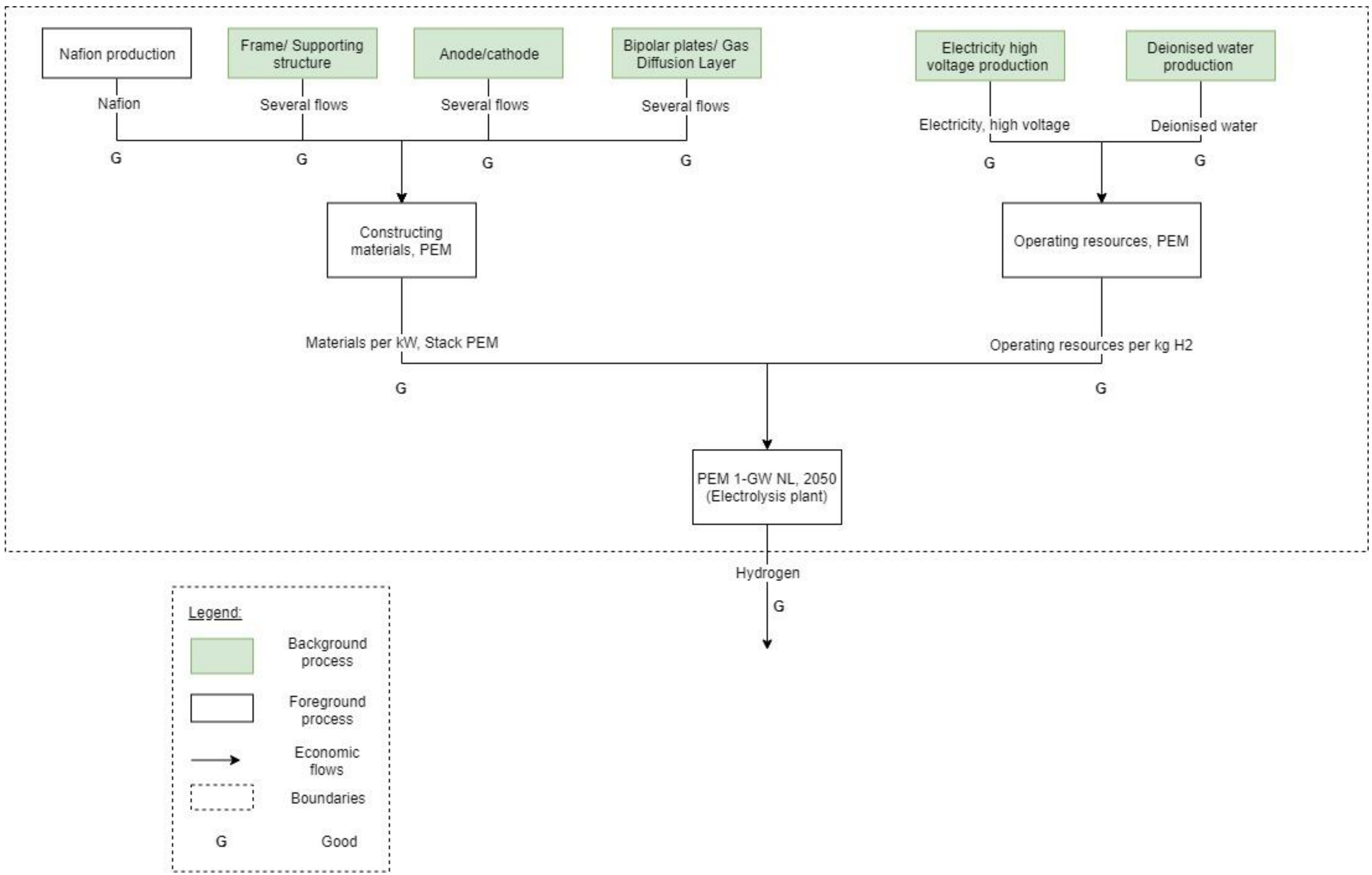


Figure 30. Flowchart for the ex-ante large-scale LCA model of PEM electrolyser.

6.2.4) LCA-parameters

The software OpenLCA enables the use of "parameters". A parameter is defined by the software's user and can be connected to any particular flow. The parameters can replace the numerical value that is manually added by the OpenLCA's user. For example, instead of having a steel flow defined with "3,000 kg", the steel flow can be defined with a parameter "steel use". The value of the "steel use" would be defined in another specific tab. The advantage of the parameter's use in comparison to a fixed value is the flexibility they offer for changing the value's input. In this way, the same system's alternative (for example AE 1-GW NL 2050) can be selected multiple times but have some variations in the "steel use" parameter's value (for example one case with "3,000" and another with "1,500"). This flexibility in parameters' values can be particularly helpful when scenarios are considered. More details on parameters can be found in the OpenLCA user's guide (Noi, Ciroth, & Srocka, 2017). For clarity, these specific parameters are now called LCA-parameters.

The list of LCA-parameters varies, depending on the unit process considered. They can be found in the OpenLCA file attached to the thesis. All parameters present in **Table 23** were implemented in OpenLCA as LCA-parameters.

Based on the list of LCA-parameters that can be found in the OpenLCA file, some formulas can be used within the software, at the unit "Constructing materials" has the output "Materials per kW" and the unit process "Operating resources" has the output "Operating resources per kg H_2".

The unit process "AE 1-GW NL, 2050 (Electrolysis plant)" considers the electrolysis plant performance and capacity through its whole lifetime. Its output is its total hydrogen production throughout its lifespan. Consequently, the total mass of hydrogen produced is deduced from the equation below:

$$Total\ H_2\ produced = production\ rate\ of\ the\ plant\ \left(\frac{kg}{h}\right) \times the\ entire\ lifespan\ of\ the\ plant\ (h) \times Wind\ coverage\ (\%)\ (Eq. 21)$$

The "Total H_2 produced" value is then associated with the "Operating resources per kg H_2" necessary as an input.

To define the mass of materials that are necessary to constitute a 1-GW scale plant, the number of stacks must be defined. This step is important because two factors need to be considered:

- Firstly, the stack capacity. If the stack's capacity is 20 MW, 50 of them are necessary to build a 1 GW (1,000 MW) plant
- Secondly, the stack's lifetime. If the plant's lifetime is worth 20 years and the stack's lifetime is worth 10 years, a replacement of all the stacks after 10 years is necessary.

Based on the two quantitative examples above, a 1 GW plant would require through its lifespan 20 stacks of a capacity of 20 MW. Therefore, the total number of stacks necessary to build a 1 GW plant can be calculated with the equation below:

$$Total\ stack\ number = \frac{Plant\ capacity\ (MW)}{Stack\ capacity\ (MW)} \times \frac{Plant\ lifetime\ (h)}{Stack\ lifetime\ (h)} \times Wind\ coverage\ (\%)\ (Eq. 22)$$

However, as the "Constructing materials" stage considers only the materials per kW (and not per stack), the "Constructing materials" inflow in the "AE 1-GW NL 2050 (Electrolysis plant)" must be multiplied by "Stack capacity". Finally, the parameter can be written as:

$$Material\ needed = \frac{Plant\ capacity\ (MW) \times Plant\ lifetime\ (h)}{Stack\ lifetime\ (h)} \times Wind\ coverage\ (\%)\ (Eq.23)$$

The “Materials needed” value is associated with the “Materials per kW” necessary as an input.

Equations 21 and 23 are the only calculated LCA-parameters added in the ex-ante large-scale LCA models.

6.3) Impact assessment

6.3.1) Impact categories, characterization and classification

The same definitions and concepts developed in Section 3.3.1 apply here. The ILCD family is kept for consistent comparisons. The analyses of the performances and some contribution analyses enable to detect the potential hotspots of the ex-ante large-scale electrolysers. **Table 5** in Chapter 3 provides the list of the different impact categories defined by the ILCD method.

6.3.2) Flows lacking a characterisation factor

Finally, some environmental flows in LCA’s impact assessment families lack a characterization factor because it would be irrelevant or because the model has not been developed yet. As a consequence, these flows are numerically quantified, but their environmental impacts are not calculated. The list of environmental flows lacking a characterization factor can be found in OpenLCA (sheet “LCIA checks”).

Reviewing all these flows would consume a significant amount of time but a quick oriented scan can be achieved and raise some questions. For example, in the impact category “Climate change”, the water emissions are not assessed environmentally. Even though water flows can be considered as natural flows, they are still a strong greenhouse gas. The influences between vapour and climate change are most likely hard to estimate and some assumptions could be developed on water balances, similar to the biogenic carbon approach. Another example concerns the water emissions (to air or water bodies) in the “Water Resource Depletion” impact category. The latter is supposed to evaluate the environmental burden of water’s depletion but does not seem to consider the water flows sent back to the environment. This “re-sent” water may have an influence on the environmental impact of water’s depletion, through some balancing effects. More research would be necessary in this direction.

6.3.3) Characterization results

The complete characterization results, the complete emissions per environmental flow, are present in the Excel appendix attached to the thesis “Inventory results, ex-ante large-scale LCA models”.

6.3.4) Scenario’s comparisons, AE:

The environmental performances from the two main system’s alternatives (AE and PEM) are compared depending on the four scenarios (including the specific case of “Scenario B1”). The results for the ex-ante large-scale AE model are presented in **Figure 31**.

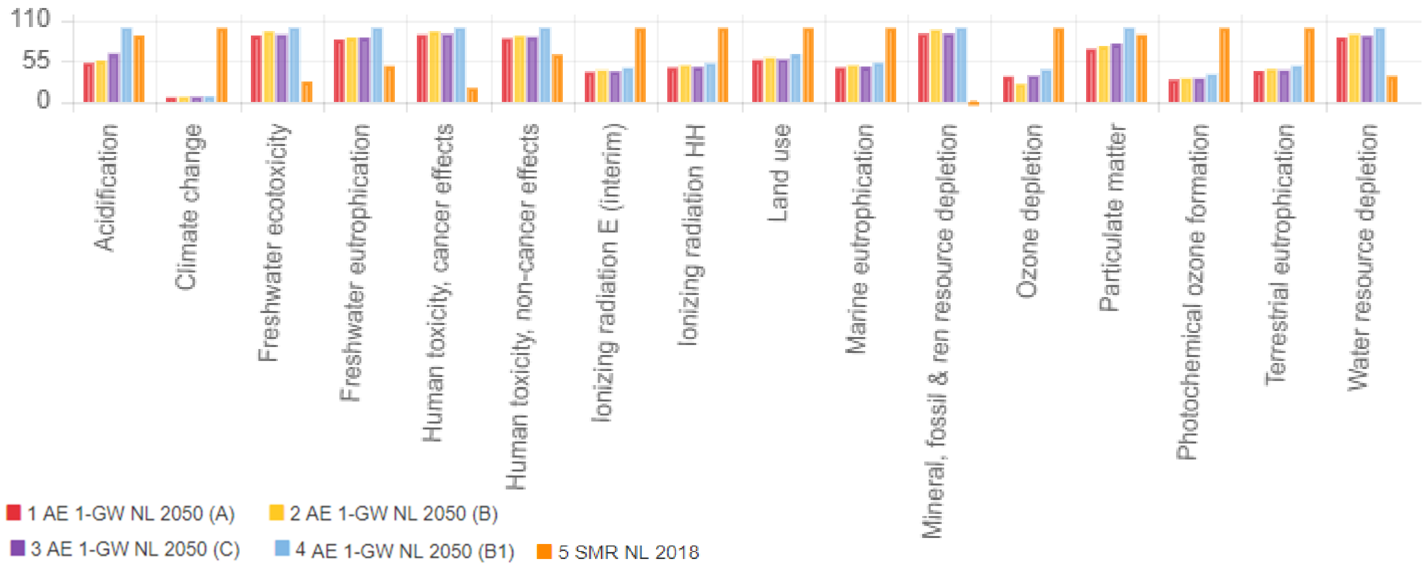


Figure 31. Relative environmental impacts from the ex-ante large-scale AE model, with the 4 scenarios (ILCD 2011 family).

When only the electrolysers are considered, an obvious result is that "Scenario B1" possesses the biggest environmental impacts' values in all impact categories. This result is not surprising since "Scenario B1" considers a large-scale installation with an unchanged system's performances in comparison to current times (2019). As "Scenario B1" is unlikely to occur in reality (see section 5.3), it will not be further considered. Globally, the "Scenario B" alternative provides the worst results in comparison to other alternatives. "Scenario B" performs better than "Scenario C" only in the impact categories "acidification", "ozone depletion" and "particulate matter". A contribution analysis can partly explain these changes in results. "Scenario C" performs always slightly worse than "Scenario A".

A contribution analysis explains why "Scenario B" performs better than any other scenario in the "ozone depletion" impact category. The main difference is explained with the "Constructing materials" unit process' emissions which are around 6 times lower in "Scenario B" than in "Scenario A" or "Scenario C" (10 times lower than in "Scenario B1"). The consumption of tetrafluoroethylene and steel are the main drivers for this reduction in CFC-11 eq. emissions. These flows are connected to the plant's capacity (1 GW for "Scenario A" and "Scenario C" and 100 MW for "Scenario B"). This result shows one limitation of comparing systems of different sizes, even though this difference makes sense with scenarios and the functional unit remains in all cases "1 kg of H_2".

When SMR is also considered, this alternative possesses the largest environmental impacts in "Climate change", "Ionizing radiation E and HH", "Land use, "Marine eutrophication", "Ozone depletion", "Particulate matter" and "Terrestrial eutrophication". If "Scenario B1" is excluded, 2 new impact categories are added to the previous list: "Acidification" and "Particulate matter". For the 6 remaining impact categories, SMR possesses much lower environmental impacts than AE or PEM. These results show that the primacy of electrolysers on SMR is not obvious, depending on the impact categories considered. Nevertheless, electrolysers have lower impacts than SMR in 10 out of 16 categories.

In general, the results are coherent with the scenarios. "Scenario A" considers the most optimistic development of green hydrogen's technologies and shows globally the lowest environmental impacts. "Scenario B" considers the most pessimistic development path and presents the largest environmental impacts globally. "Scenario C" considers a mixed evolution path and therefore and therefore possess lower environmental impacts than "Scenario B" but larger than "Scenario A".

6.3.5) Future and present's comparison, AE:

First, a comparison is achieved between AE NL 2017, AE NL 2018 and AE 1-GW NL 2050. Only "Scenario A" and B, the two most extreme scenario cases, are considered for simplicity. For the pilot-scale models (AE NL 2017 and AE NL 2018), the electricity comes from the Dutch grid. The ex-ante large-scale LCA models consider electricity from Dutch wind turbines. The main goal of this comparison is to study whether a switch from electricity from the grid to electricity from a renewable energy source is relevant in a sustainability's point of view. The comparison is shown in **Figure 32**.

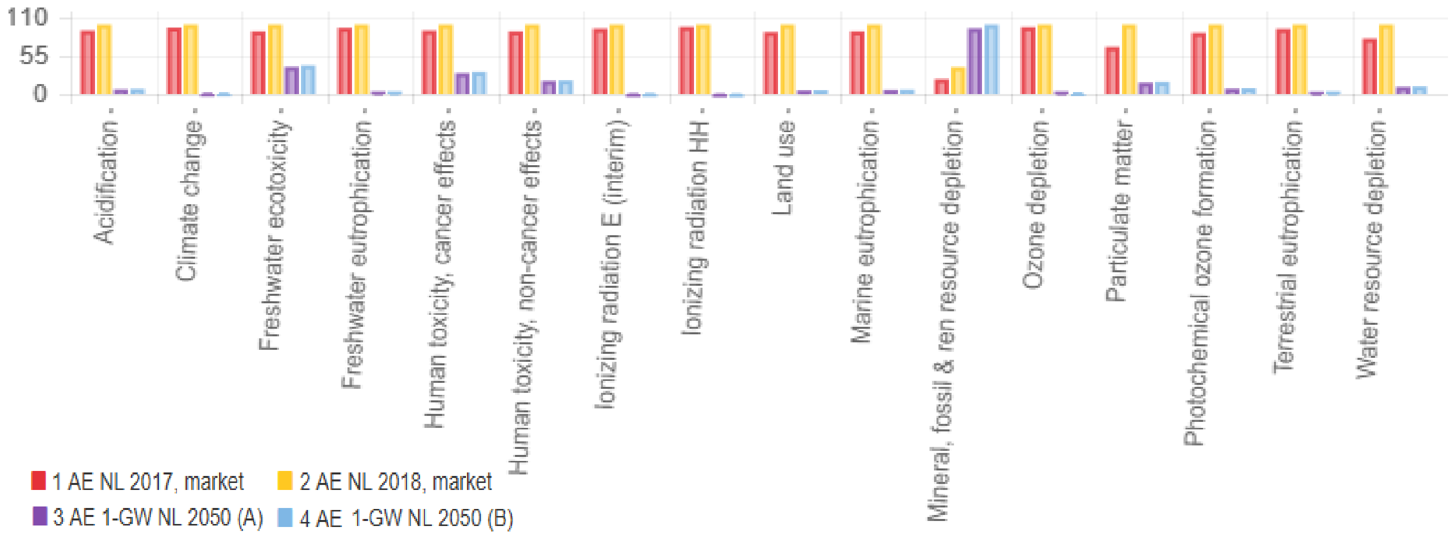


Figure 32. Comparison of the relative environmental performances between models AE NL 2017, AE NL 2018 (electricity from the Dutch grid) and AE 1-GW NL 2050 (A and B) (ILCD 2011 baseline).

As shown in **Figure 32**, a shift from electricity from the grid to electricity from wind turbines induces a large decrease in environmental impact for all impact categories, except in "Mineral, fossil & renewable resource depletion". The decrease varies depending on the impact category, from a factor 2 to a factor 94, with an averaged factor of 21. For the "Mineral, fossil & renewable resource depletion" impact category, a contribution analysis showed that the main difference between the "grid" case and the "wind" case comes from the "operating resources". The electricity production possesses an impact 4 times higher in "Mineral, fossil & renewable resource depletion" in the case where electricity comes from wind turbines than in the case where electricity comes from the grid. In the "wind" case, the electricity's production's impact is mainly influenced by the lead consumption for the wind turbines. Overall, from a sustainability perspective, operating a shift from electricity from the grid to electricity from wind energy would decrease significantly the environmental impact from hydrogen's production (except in "Mineral, fossil & renewable resource depletion").

Second, a comparison between AE NL 2017, AE NL 2018 (electricity from the wind) and AE 1-GW NL 2050 has been conducted (see **Figure 33**). The only difference with the previous case is the origin of electricity for the pilot-scale models (wind electricity instead of the grid's electricity).

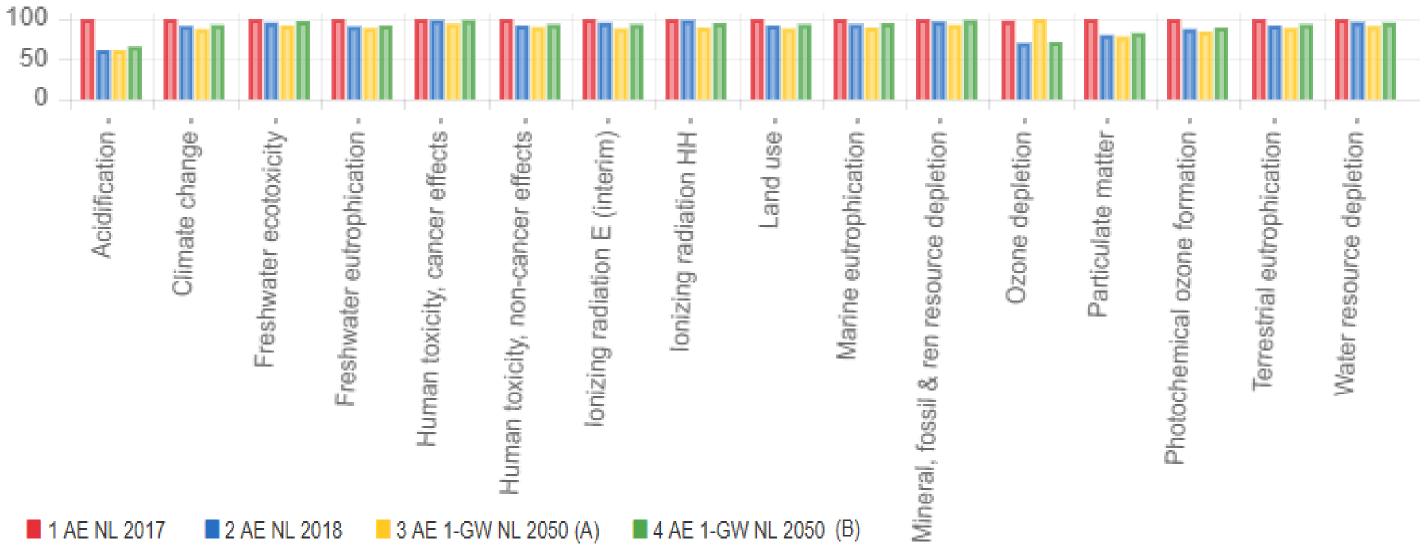


Figure 33. Comparison of the relative environmental performances between models AE NL 2017, AE NL 2018 (electricity from wind turbines) and AE 1-GW NL 2050 (A and B) (ILCD 2011 baseline).

The 2050 model ("Scenario A") possesses overall lower environmental impacts in the different impact categories in comparison to the two AE pilot-scale LCA models, except for the "ozone depletion" impact category. In that case, "Scenario A" possesses the worst environmental impact performance.

On the one hand, "Scenario B" possesses lower environmental impact values than AE NL 2017 model in all impact categories, with relative variations ranging from -1.40 to -34.35%. On the other hand, "Scenario B" performs worse than the "AE NL 2018" model in 12 out of 16 impact categories, with relative variations ranging from 1.24 to 6.55%. As the variations never exceed 6% in absolute values, these two alternatives can be considered as "equivalent".

A contribution analysis shows that the relatively high environmental impact from AE NL 2017 in the "acidification" impact category is mainly due to the contribution of the nickel market (10 times higher globally than all other alternatives).

A curious result is noticeable for the "Ozone depletion" impact category. Contrary to the other impact categories, "Scenario A" has worse performances than "Scenario B" (40% of difference). A contribution analysis on the two scenarios' alternatives shows that the change occurs with the "Constructing materials". The latter possesses an impact 6 times higher for "Scenario A" than "Scenario B". The consumption of tetrafluoroethylene and steel show the biggest change. If the steel's and tetrafluoroethylene's rates (in kg/kW) for "Scenario B" are higher than "Scenario A", the plant's scale is much smaller in "Scenario B" (100 MW) than "Scenario A" (1 GW). This the most likely reason for the differences observed. This assumption is supported by **Figure 31** where "Scenario B1" performs much worse than all other scenarios' alternatives.

In general, it can be deduced that going to a large-scale implementation would not *significantly* improve the environmental performances of the alkaline technology. Two main reasons can be mentioned for this:

- Firstly, the electricity production process is the highest contributor to the environmental impacts of the pilot-scale LCA models (see the contribution analyses in section 3.4.3). The same conclusion appears for the ex-ante large-scale LCA model (Section 6.4.4). Even though some other processes increase in the contribution to the environmental performances, the electricity production process remains the biggest contributor.

- Secondly, no significant changes are expected for the alkaline technology or no deep research has been conducted in this sense. Consequently, the current alkaline technology can be seen more or less as an "optimised" system that is not expected to change significantly in the long-term.

6.3.6) Scenario's comparison, PEM:

The environmental performances from the ex-ante large-scale PEM electrolysers depending on the four scenarios (including the specific case of "Scenario B1") are shown in **Figure 34**.

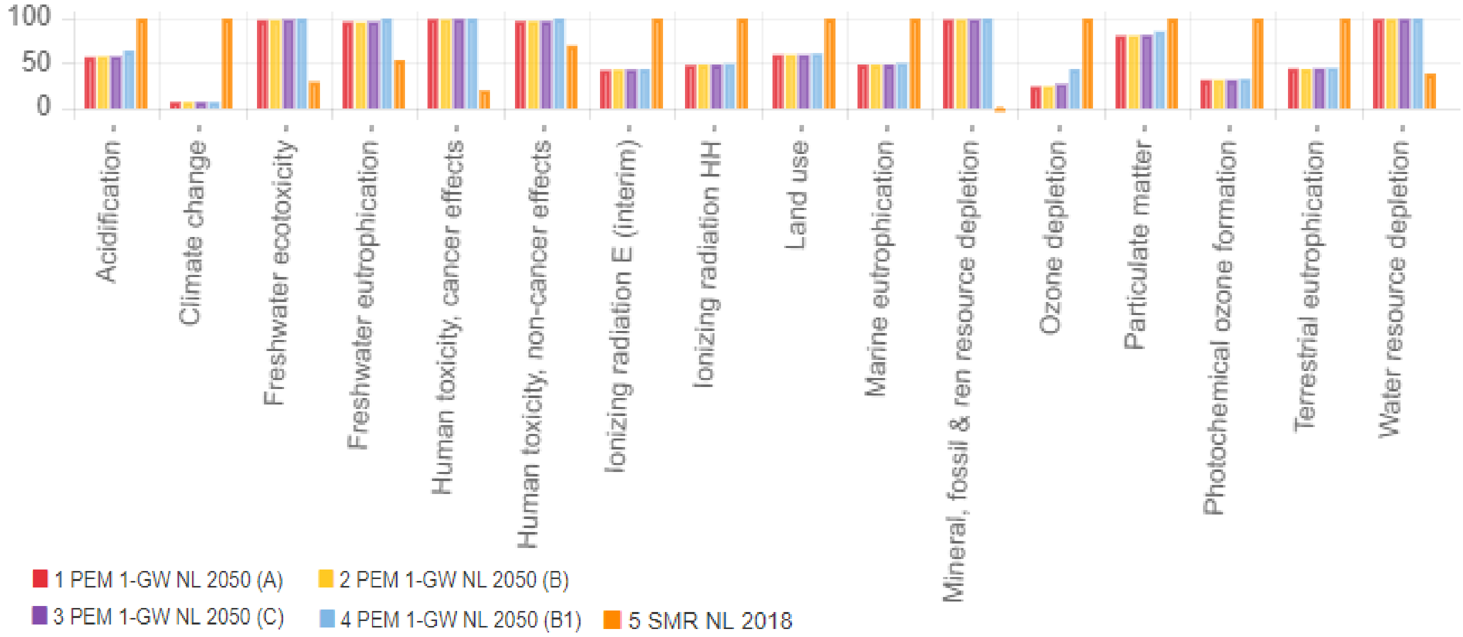


Figure 34. Relative environmental impacts from the large-scale PEM model, with the 4 scenarios (ILCD 2011 family).

The same conclusion for "Scenario B1" than in Section 6.3.4 can be applied here, with lower differences though, when only the electrolysers are considered. Overall, the environmental performances between the different scenarios are extremely similar with maximum values' variations of ca. 7%. The highest variations occur for the "ozone depletion" impact category. More surprisingly, "Scenario B" performs better than "Scenario C" in all impact categories, even though the variations are never higher than 1% (except in "ozone depletion").

In comparison with the same section for AE, the differences between the scenarios' alternatives are not so present for PEM. "Scenario A" performs better than "Scenario B". The latter performs better than "Scenario C", which is the only "unexpected" result, since "Scenario B" is modelled as the worst-case development of green hydrogen technology. The next section discusses a comparison between "Scenario B" and "Scenario C".

A contribution analysis' comparison between "Scenario B" and "Scenario C" shows that the only differences in environmental impacts' performances are due to the "Constructing materials" unit process. In more details, the consumption of Nafion and steel is higher in "Scenario C" than in "Scenario B" in all impact categories. For steel, the consumption is ca. 6 to 7 times higher in "Scenario C" than in "Scenario B" for "ozone depletion", "land use", "acidification" and "climate change". The Nafion consumption is around twice higher in "Scenario C" than in "Scenario B" for the same impact categories. The consumption of noble metals does not differ significantly between the two scenarios alternatives. These results show that even the upscaling effect can be counterbalanced by the size of the system considered. "Scenario C" consumes less steel and Nafion per kW than "Scenario B".

However, due to the capacity of the system (1 GW for “Scenario C” and 100 MW for “Scenario B”), the final consumption per kg of H_2 remains higher for “Scenario C” than for “Scenario B”. This result can also be seen as a limitation from LCA modelling in connection with scenarios. In this perspective, “Scenario B1” provides another vision, showing that if the parameters from “Scenario B” were applied on the same scale than “Scenario C” (1 GW), the environmental impacts would be heavier. As a conclusion, the benefits of upscaling effects can be counterbalanced by the upscaling of the system itself.

The lack of important differences between the PEM scenarios’ alternatives in comparison to AE scenarios’ alternatives can also be connected to the fact that the steel rate consumption variations are lower in PEM’s case (range: 7-10 kg/kW) than in AE’s case (10-30 kg/kW). As mentioned in Section 6.3.4, the steel’s consumption is one of the main factors for variations in the ozone depletion impact from AE’s scenarios.

The “Ozone depletion” impact category shows significant differences between “Scenario B” and “Scenario B1”. A contribution analysis shows that the “constructing materials” impact is 10 times higher in “Scenario B1” than “Scenario B”. The Nafion, titanium tetrachloride and steel consumptions and other elements have an impact increased by a factor 10. This is not a surprise since the plant’s scale in “Scenario B1” is 10 times higher than in “Scenario B”. The “operating resources” possess the same environmental impact in “Ozone depletion” in both scenarios.

SMR possesses the largest environmental impacts in 10 impact categories, the same than in Section 6.3.4. This time, the presence or absence of “Scenario B1” does not change the conclusion. For the remaining 6 impact categories, SMR possesses much lower impact categories than AE or PEM. These results show again that the primacy of electrolysers on SMR is not obvious depending on the impact categories considered. Nevertheless, electrolysers have lower impacts than SMR in 10 categories out of 16.

Overall, the most optimistic scenario (A) possesses the lowest environmental impacts. “Scenario C”, more optimistic than “Scenario B” sees its benefits counterbalanced by limited upscaling effects. In this sense, “Scenario B” performs slightly better than “Scenario C” in all impact categories.

6.3.7) Future and present’s comparison, PEM:

First, a comparison is achieved between PEM NL 2018a, PEM NL 2018b and PEM 1-GW NL 2050 (only “Scenario A” and B, the two most extreme scenario cases, are considered for simplicity). For the pilot-scale models (PEM NL 2018a and PEM NL 2018b), the electricity comes from the Dutch grid. The ex-ante large-scale LCA models consider electricity from Dutch wind turbines. The main goal of this comparison is to study whether a switch from electricity from the grid to electricity from a renewable energy source is relevant in a sustainability’s point of view. The comparison is shown in **Figure 35**.

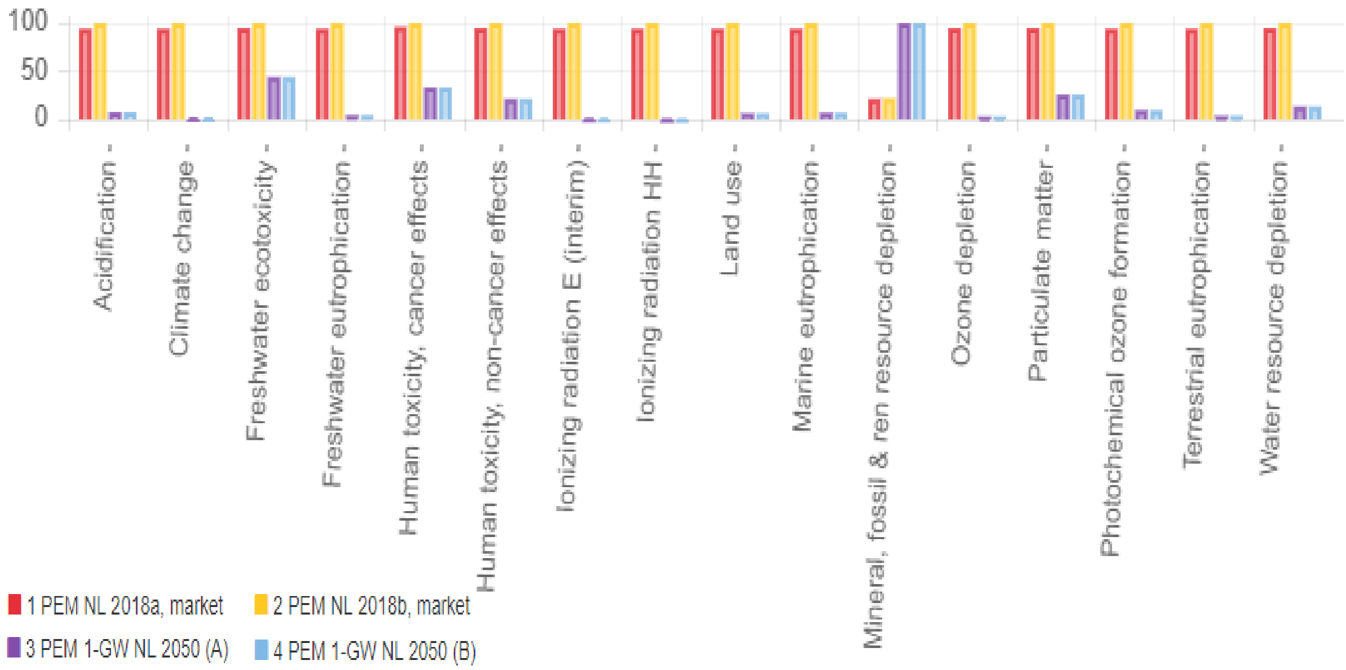


Figure 35. Comparison of the relative environmental performances between model's PEM NL 2018a, PEM NL 2018b (electricity from the grid) and PEM 1-GW NL 2050 (A and B) (ILCD 2011 family).

As shown in **Figure 35**, the shift from electricity from the grid to electricity from wind turbines induces a decrease in all impact categories, except in "Mineral, fossil & renewable resource depletion". The factor of decrease in the impact categories varies from factor 2 to 91 and is on average by a factor 21 (close results with alkaline systems). For the "Mineral, fossil & renewable resource depletion" impact category, a contribution analysis shows that the environmental impact from electricity production is 4.8 times higher when the electricity comes from wind turbines than if electricity comes from the grid. Similar to the alkaline case, the main contributor remains the lead consumption for the wind turbines construction. Overall, from a sustainability perspective, operating a shift from electricity from the grid to electricity from wind energy would decrease significantly the environmental impact from hydrogen's production (except in "Mineral, fossil & renewable resource depletion").

Second, a comparison between pilot-scale models for PEM (electricity from the wind) and the PEM 1-GW NL 2050 model is conducted (wind coverage 30%, 20 MW stack) (see **Figure 36**). The only difference with the previous case is the origin of electricity for the pilot-scale models (wind electricity instead of the grid's electricity).

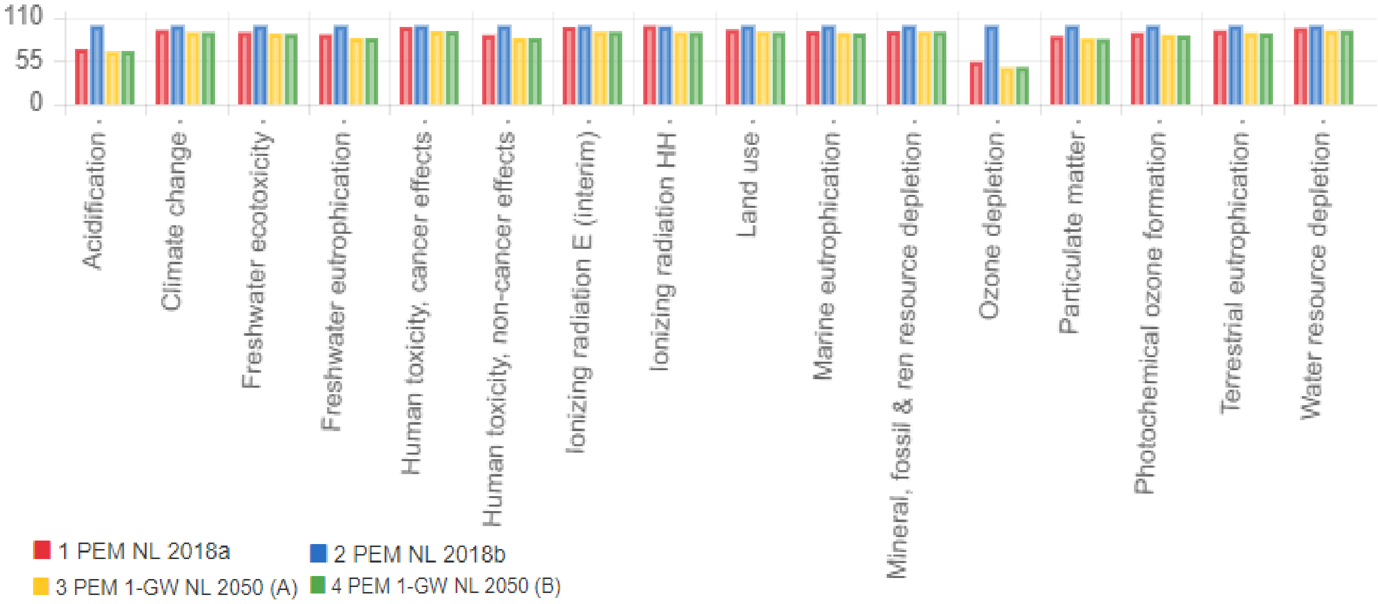


Figure 36. Comparison of the relative environmental performances between model's PEM NL 2018a, PEM NL 2018b (electricity from wind turbines) and PEM 1-GW NL 2050 (A and B) (ILCD 2011 family).

Overall, the 2050 model possesses lower environmental impacts in all impact categories in comparison to the pilot-scale LCA models. The relative decreases are in the range 1-53% depending on the reference (PEM NL 2018a or b).

The models PEM 1-GW NL, "Scenarios A & B" possess really similar performances with variations up to 2.40%. The relatively higher environmental impacts from PEM NL 2018b in the impact categories "Acidification", "Human toxicity, non-cancer effects", "Ozone depletion" and "Particulate matter" are mostly due to the "Constructing materials". The latter has an impact ca. 8 times higher in PEM NL 2018a than in PEM NL 2018b in the impact categories mentioned. The markets for platinum and steels are the main drivers for the change in impacts.

In general, it can be deduced that implementing the PEM technology on a large-scale would enable to decrease its environmental impact by 1 to 53%, but most of the time between 5 and 10%. In this sense, a large-scale implementation makes sense from a sustainability point of view, even though with limited effects. Again, contribution analyses show (Section 6.4.4) show that the electricity's production remains the largest contributor to the environmental impacts.

6.3.8) Comparison between AE and PEM (future):

A comparison between the alkaline and PEM electrolysers is made to compare their performances. To avoid too many dispersions, only scenarios A and B (the two most opposite cases) are considered. The comparison of the environmental performances is shown in **Figure 37**.

Figure 37. Comparison of environmental performances between AE and PEM, in 2050 (Scenarios A & B) (ILCD 2011 family).

Figure 37 shows that the performances between ex-ante large-scale alkaline and PEM electrolysers are close to each other. Overall, the PEM alternative still possesses higher environmental impact's values in 14 impact categories out of 16 in "Scenario A". The differences are usually in the range of 3-5%. A notable exception is the "ozone depletion" impact category with a variation of around 20%. However, the PEM alternative has a lower environmental impact's value than AE in all impact categories in "Scenario B". In this case, the differences in performances are worth around 1%, so they can be considered as negligible. Only the "acidification" impact category shows a higher difference of 7%.

Overall, at a large scale, alkaline and PEM electrolysers have close performances. If a choice has to be made, alkaline electrolysers possess a better average on environmental impacts than PEM. The "ozone depletion" impact category remains a hotspot for alkaline electrolysers with the consumption of steel and tetrafluoroethylene.

6.4) Interpretation

This LCA stage analyses the results for their consistencies, soundness, robustness. Based on these evaluations, interpretations, recommendations and conclusions can be drawn. Some consistency and completeness checks are made. The wind capacity factor is then discussed. After, some contribution analyses are conducted. Finally, three sensitivity analyses and Monte-Carlo projections are achieved.

6.4.1) Consistency check

The same check than in section 3.4.1 must be applied. Three main points can be discussed for the ex-ante large-scale LCA models:

- *Differences in data sources*: this topic has already been mentioned in Section 3.4.1. An LCI harmonization has been operated for the ex-ante large-scale LCA models (Section 6.2.4). In this sense, superfluous or relatively unclear flows were eliminated. This harmonization reinforces the comparability assessment.

- *Differences in technology's knowledge*: There are much more studies conducted on the potential future performances of PEM than alkaline electrolysers. Therefore, the projections for PEM electrolysers are more supported than for alkaline.
- *Uncertainties for LCA-parameters' values in the future*: the LCA-parameters' values for the future are based on projections and literature review. In order to decrease the potential limitations with them, the projections were commented by several experts (Hydrogenics, Nouryon, Nel Hydrogen and ENGIE, personal contact, 2019).

Apart from the three points mentioned above, no other serious consistency issue was found.

6.4.2) Completeness check

The same check than in Section 3.4.2 must be applied. Two main points can be discussed for the ex-ante large-scale LCA models:

- *Data reliability*: the data for background processes came from ecoinvent, one of the most prominent LCA databases, from academics' papers or were adjusted based on experts' opinions. Some data may not be adapted for a 2050 situation, but it would be the case for both alternatives (common processes for alkaline and PEM electrolysers). In this perspective, the consistency between the alternatives considered is deemed as strong enough.
- *Comparison with other similar LCAs*: due to the particular concept of comparing LCA studies on *existing* systems with LCAs on *potential* systems, an extensive comment on the comparison is made in Section 7.3.

6.4.3) The wind capacity factor:

The environmental performances from the ex-ante large-scale LCA models show no influence from the wind coverage's value. If the wind coverage is increased, the production volume from a single plant is increased, just as the material consumption (linear evolution). As the functional unit remains 1 kg of H_2, the environmental impact per kg of H_2 remains the same, no matter the wind coverage's value. Naturally, the absolute value of the environmental impact would change. A low value for wind coverage would mean a lower plant's capacity for hydrogen production and therefore, more plants would be required to fulfil a given demand for hydrogen.

In the thesis case, the wind coverage's value did not have an influence but would be an important factor in other studies (such as the one conducted in Section 7.2).

6.4.4) Contribution analyses:

The results of the different contribution analyses are shown in the graphs below. To avoid the presentation of too many graphs, only scenarios A and B (the two most extreme cases in scenario's descriptions) are considered. The contribution analyses give an overview of the contribution from different factors and enable to understand more how the environmental impacts from a system can be disaggregated.

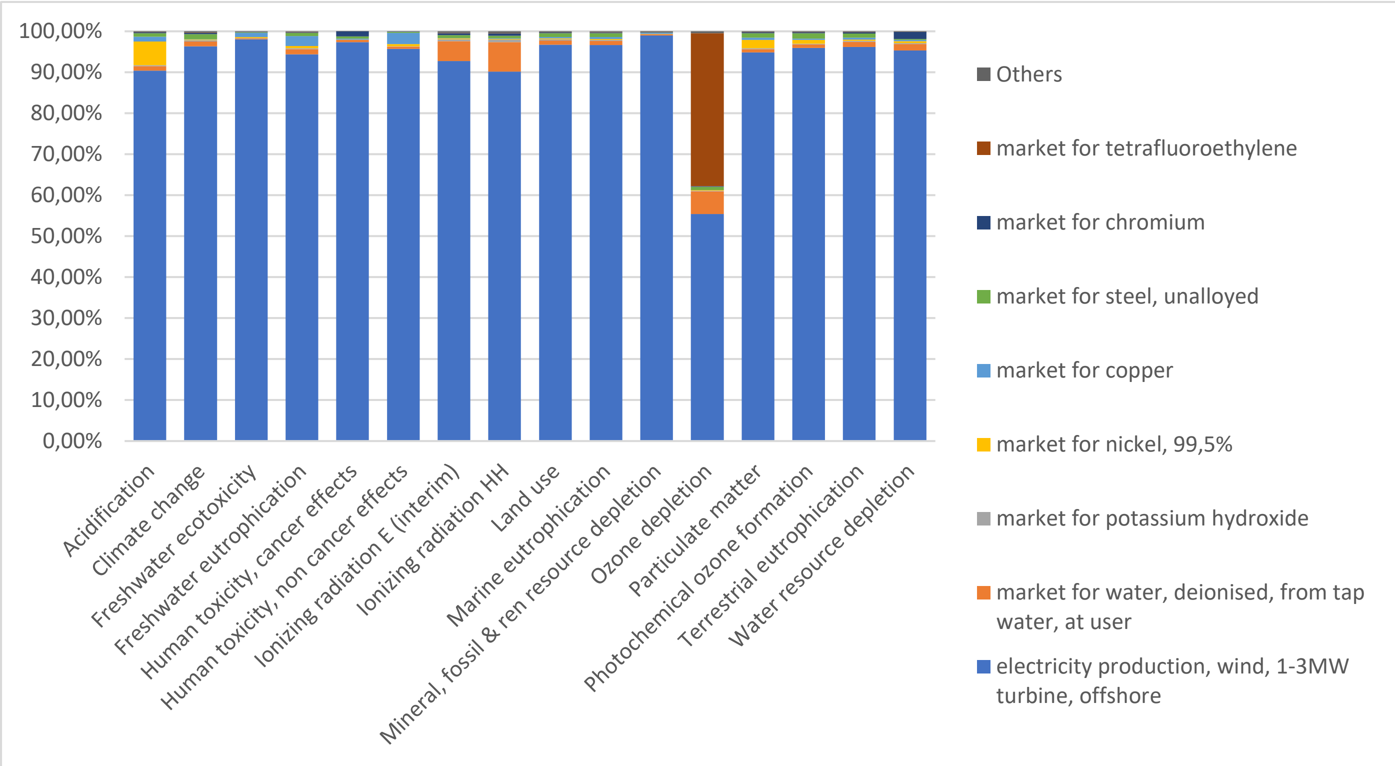


Figure 38. Contribution analysis AE 1-GW NL 2050 (“Scenario A”) (ILCD 2011 baseline).

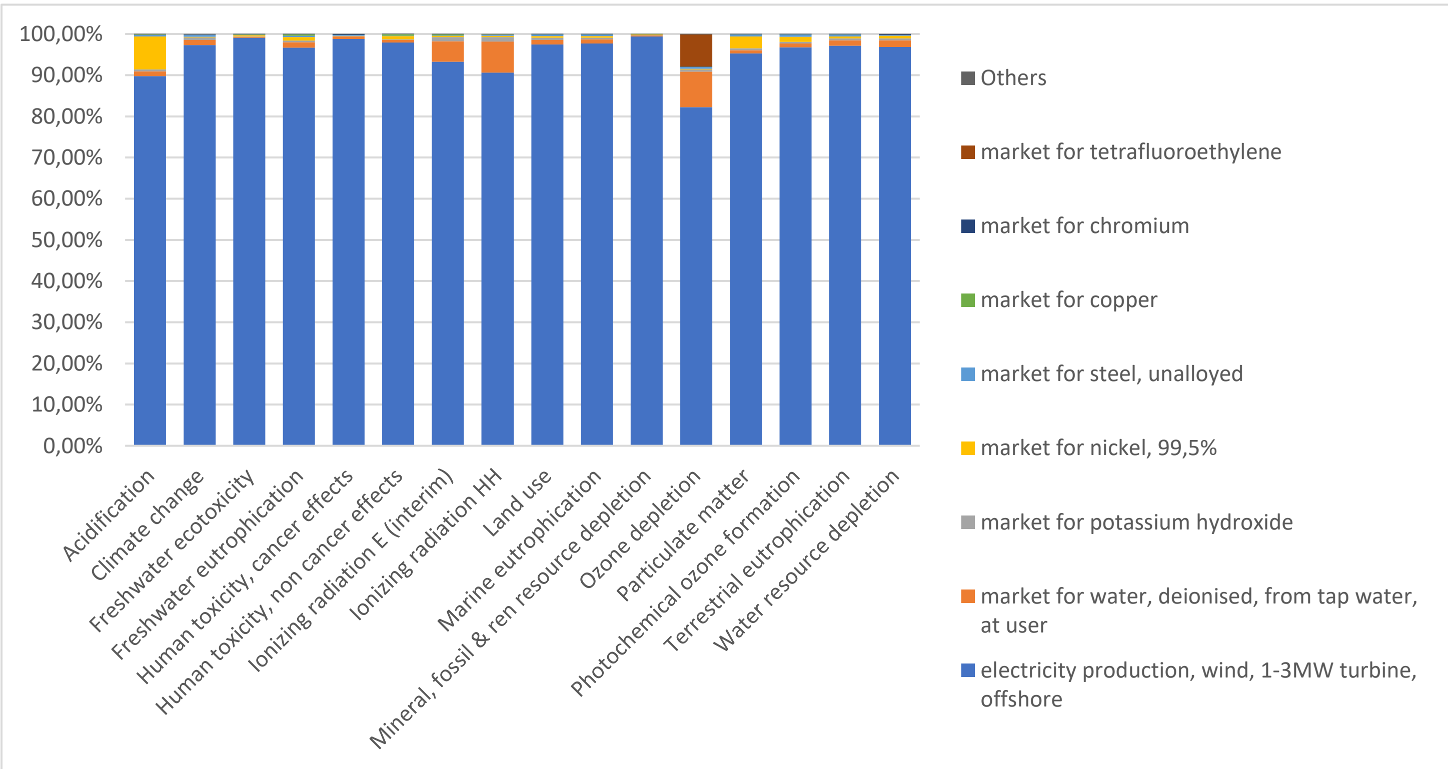


Figure 39. Contribution analysis AE 1-GW NL 2050 (“Scenario B”) (ILCD 2011 baseline).

Overall, the electricity production process is the largest contributor in all impact categories at ca. 90%. A noticeable exception is the “ozone depletion” impact category where the tetrafluoroethylene consumption possesses a much lower contribution in “Scenario B” (**Figure 39**, 8%) than in “Scenario A” (**Figure 38**, 37%). This is linked to the decreased scale of the plant in “Scenario B” (only 100 MW instead of 1 GW). In “Scenario B1”, the tetrafluoroethylene consumption possesses a contribution effect of 44% in the “ozone depletion” impact category, much more similar to “Scenario A”’s distribution.

Apart from this element, the contribution analyses are similar in their structures between “Scenario A” and “Scenario B” with only small variations to some contributors. For example, the “market for nickel” increases its contribution’s effect from 5.73% in “Scenario A” to 8.02% in “Scenario B”.

The same contribution analyses were conducted for PEM’s alternative.

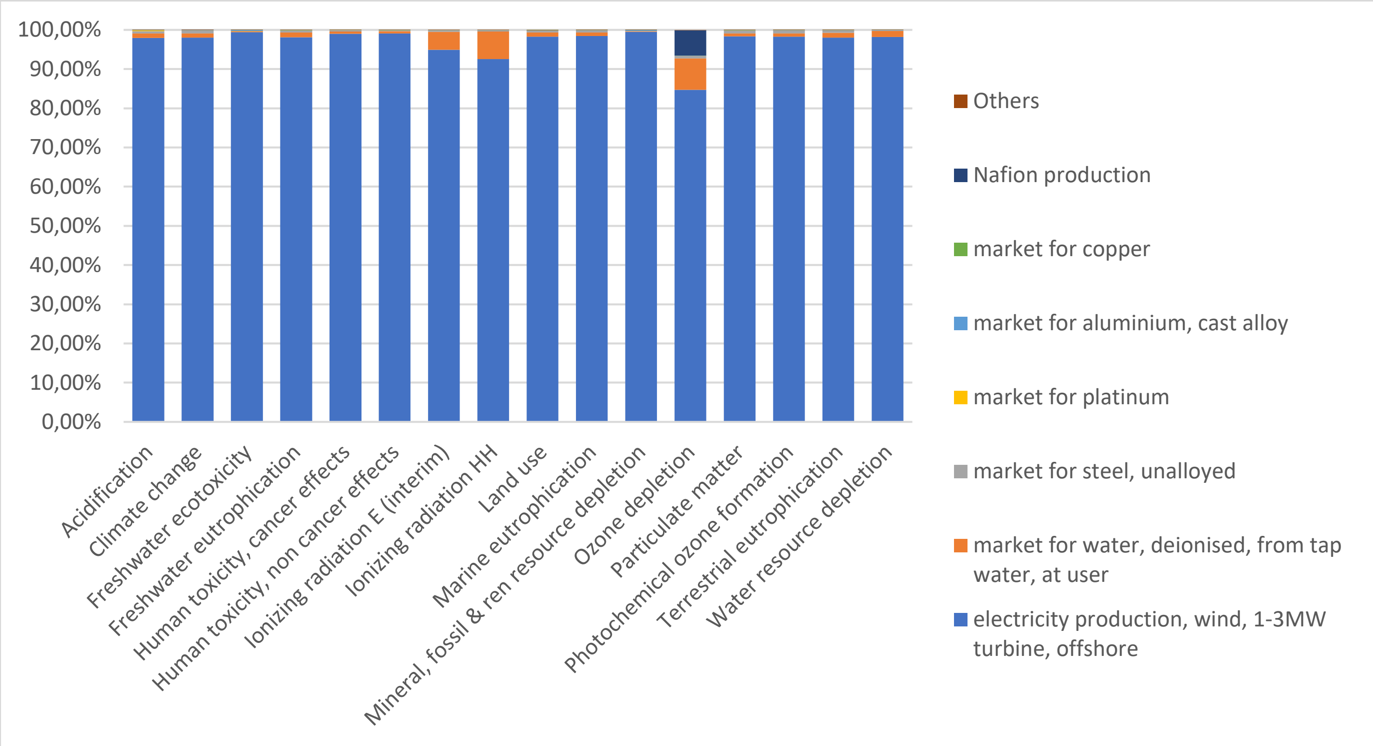


Figure 40. Contribution analysis PEM 1-GW NL 2050 (“Scenario A”) (ILCD 2011 baseline).

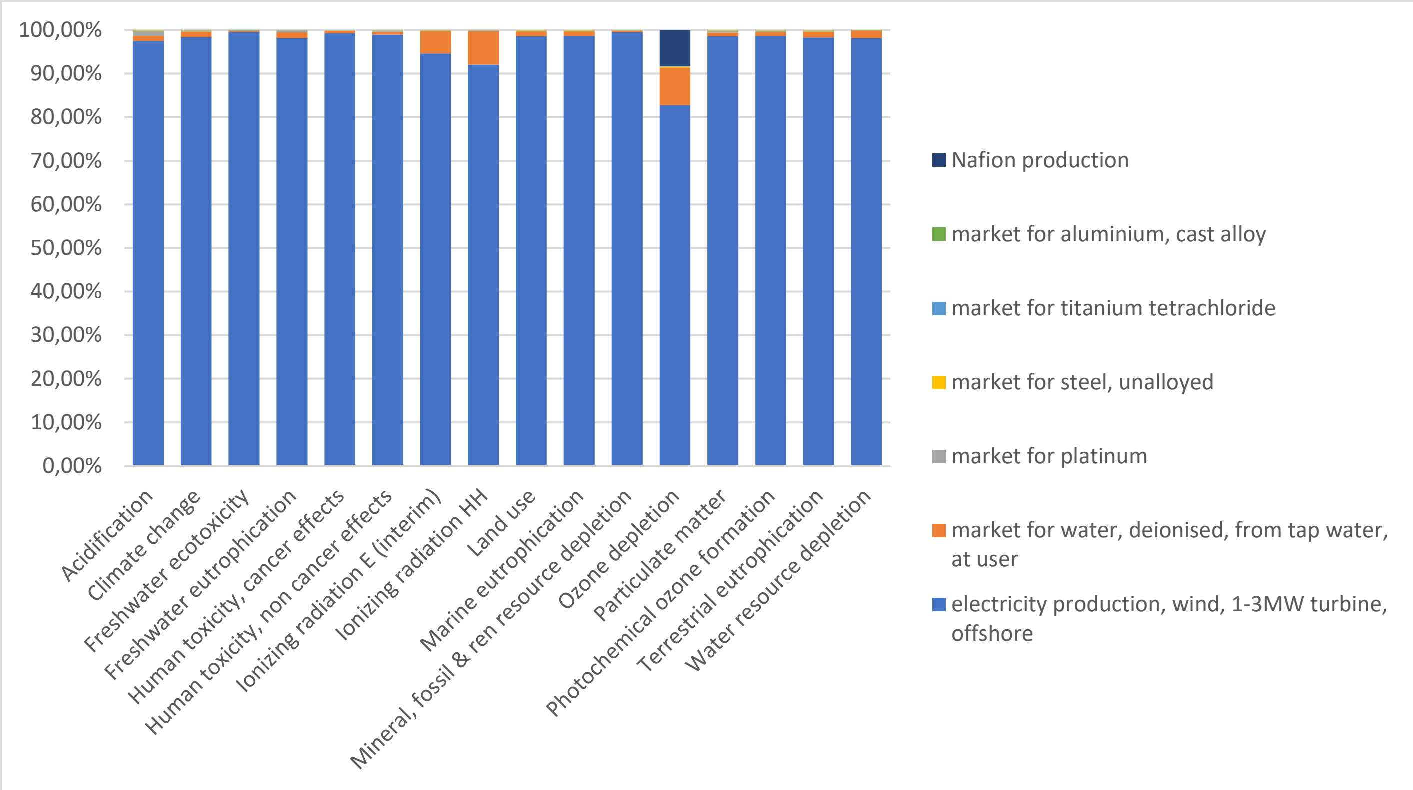


Figure 41. Contribution analysis PEM 1-GW NL 2050 (“Scenario B”) (ILCD 2011 baseline).

Again, the contribution analysis’ pattern is similar between the two scenarios, with only small variations in some contributor’s values. For example, the “Nafion production” contribution value in “ozone depletion” increases from 6.48% in “Scenario A” (**Figure 40**) to 8.23% on “Scenario B” (**Figure 41**) or the “market for water” contribution value in “Ionizing radiation HH” increases from 6.96% in “Scenario A” to 7.69% in “Scenario B”. In all cases, the “electricity production” remains the biggest contributory factor with contribution values higher than 90% in all impact categories.

In both cases (alkaline and PEM), despite all the potential improvements of the electrolysers mentioned in the thesis, the electricity production process remains the biggest contributor to environmental impacts, with some limited particular cases, such as the “ozone depletion” for alkaline electrolysers.

6.4.5) Sensitivity analyses:

6.4.5.1) Recycling systems:

A variation of the ex-ante large-scale LCA model was considered with simplified recycling processes implemented. The recycling technologies have been described in 5.2.2. The flowcharts can be seen in Appendix 11 and the relative environmental results are shown in **Figure 42**, below. Again, to avoid too many documents and for readability, only “Scenario A” was considered.

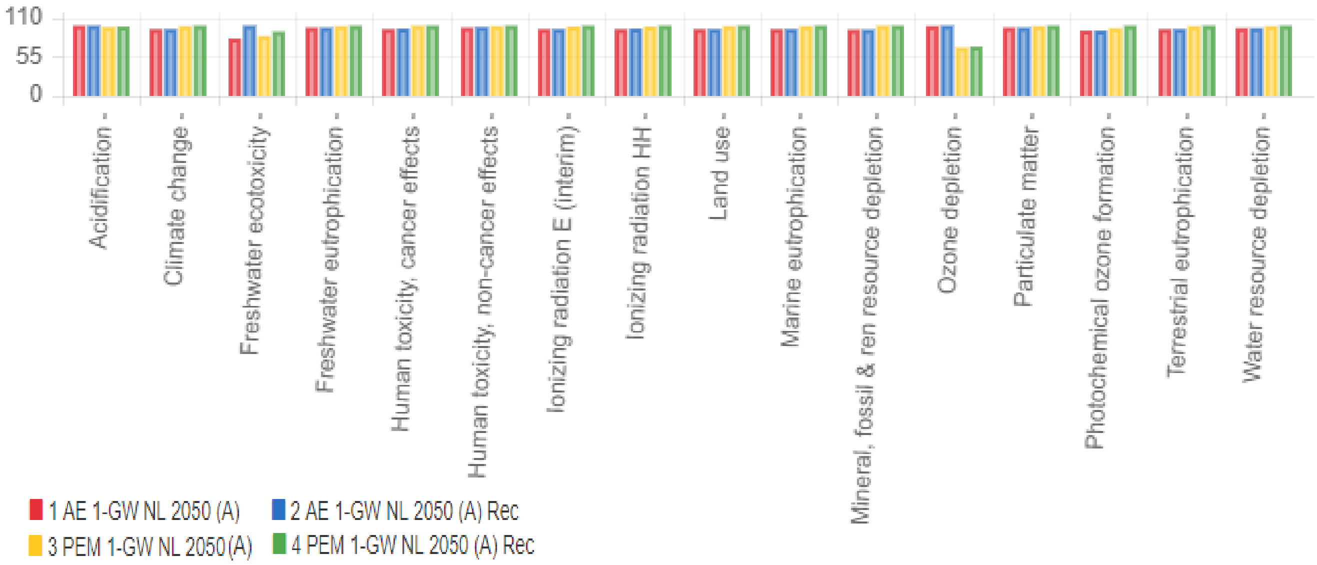


Figure 42. Comparison of AE and PEM environmental profiles, with or without recycling systems. "Rec" = recycling system connected ("Scenario A" and ILCD 2011 family).

For the two technologies (AE and PEM), implementing recycling technologies implies only a slight increase in environmental impacts (always lower than 1%). One exception exists: the freshwater ecotoxicity seems to be more sensitive to the implementation of recycling technologies, leading to a 10-20% increase in the impact's value. A contribution analysis shows that the increase in "freshwater ecotoxicity" impact's value is mainly due to the treatment of scrap steel (municipal incineration).

This result is coherent with the previous findings. As the recycling technologies modelled treat only materials from electrolysers and as the latter possess a negligible environmental impact, the impacts from recycling are low. Again, the electricity production process stays the main contributor.

6.4.5.2) Change of electricity origin:

Since the "electricity production" is the largest contributor to the electrolyser's environmental profile, an interesting possibility would be to change the electricity production's origin. The second biggest potential for renewable energy production in the NL is solar energy. Hence, the origin of the electricity for the "operating conditions" has been changed from "electricity, high voltage" from Dutch wind turbines (1-3 MW) to "electricity, low voltage" from slanted-roof photovoltaic installation, multi-silicon panels, in the Netherlands (electricity, high voltage from solar panels was not available in ecoinvent). A comparison between AE 1-GW NL 2050 and PEM 1-GW NL 2050, with wind or solar electricity, is shown in **Figure 43** ("Scenario A" only).

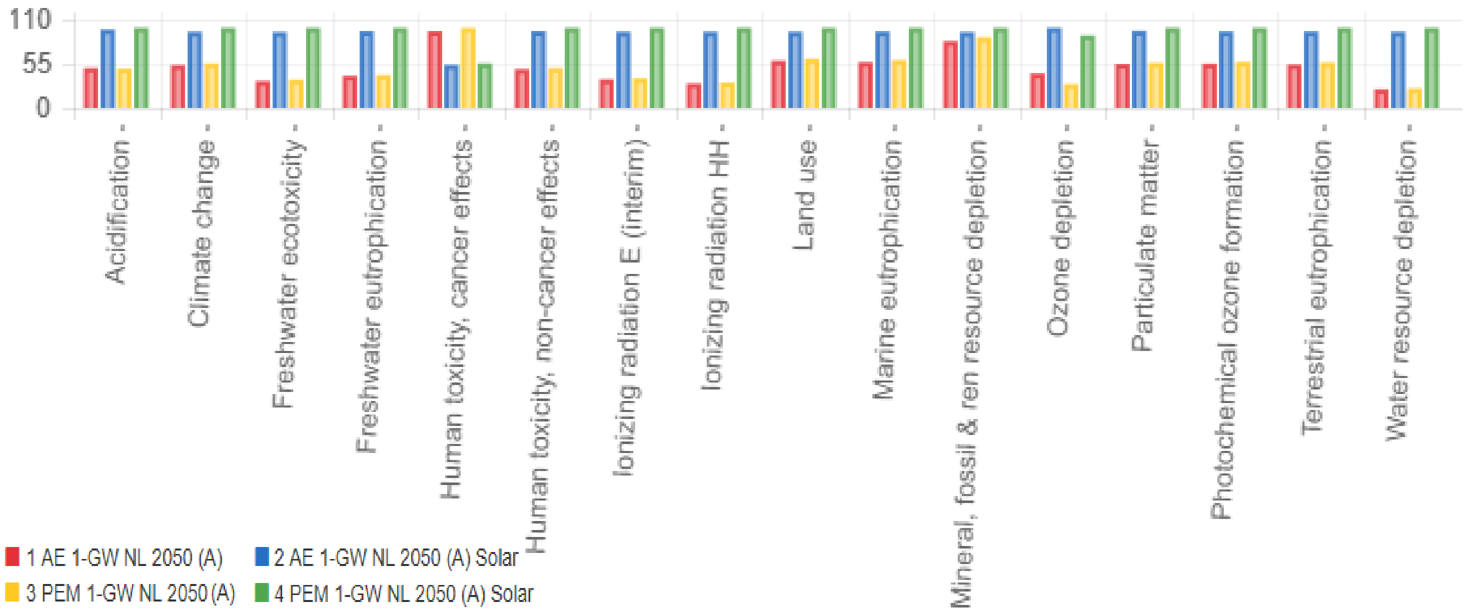


Figure 43. Comparison between the AE and PEM electrolysers' environmental profiles, with a change in the electricity origin (no indication = wind) ("Scenario A", ILCD 2011 family).

The results from **Figure 43** show that, globally, a shift from wind energy to solar increases the environmental impact in all impact categories by 50-100%, except in "human toxicity, cancer effects". The contribution analysis shows that the electricity's production from wind turbines has an impact almost twice higher than the electricity production from solar panels, in "Human toxicity, cancer effects". However, the electricity from the solar panels is only at a low-voltage, implying that further electrical equipment may be necessary to increase the voltage for proper use. Furthermore, the solar potential in the Netherlands is much lower than wind's potential, which implies perhaps a higher value in the impact. A shift in electricity production's origin from wind to solar is not shown as the most sustainable way for the Netherlands but may be interesting in more "adapted" countries such as Australia or Arabic countries.

6.4.5.3) National scale consideration

Instead of considering "1 kg of H_2 produced", the total amount of hydrogen necessary for the transport's sector in the NL in 2050 could be studied. The sensitivity analysis operated here is a change in the functional flow for scenarios A, B and C. Based on **Table 22**, the following reference flows are considered:

- To provide $9.1x10^8$ kg of hydrogen from large-scale AE, scenario A
- To provide $9.1x10^8$ kg of hydrogen from large-scale PEM, Scenario A
- To provide $1.3x10^8$ kg of hydrogen from large-scale AE, scenario B
- To provide $1.3x10^8$ kg of hydrogen from large-scale PEM, scenario B
- To provide $3.9x10^8$ kg of hydrogen from large-scale AE, scenario C
- To provide $3.9x10^8$ kg of hydrogen from large-scale PEM, scenario C

In each case, the complete demand for the Dutch hydrogen-car's fleet is fulfilled. The goal here is to consider the global impacts of the hydrogen systems implemented to satisfy the hydrogen cars' demand in scenarios A, B and C. The results are shown in **Figure 44**.

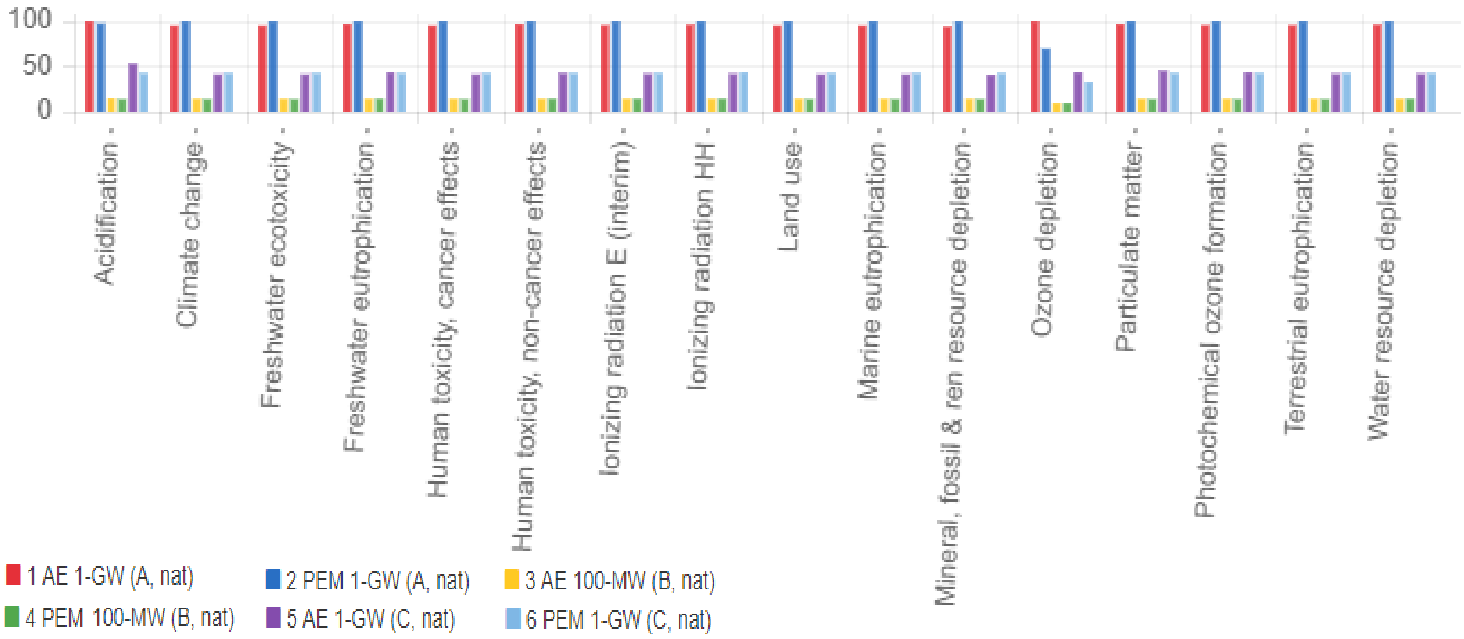


Figure 44. Relative environmental results of the national-scale production of green hydrogen, from wind-based electrolysis, AE and PEM, in scenarios A, B and C ("nat" = national) (ILCD 2011 baseline).

The results show that "Scenario A" performs much worse than the other scenarios. This result is expected since **Figure 44** considers the whole demand for Dutch hydrogen cars. In the case of "Scenario A", much more hydrogen is required and consumed than in "Scenario B" or C. This result shows that considering the absolute values must be made with perspective. Overall, "Scenario A" seems to be the most unsustainable option but the other comparisons in sections 6.3.4, 6.3.6 and 6.3.8 show that "Scenario A" possesses the best environmental performances for the production of 1 kg of H_2.

Alkaline and PEM alternatives possess similar performances in **Figure 44**, globally up to 5%. Some larger variations between the two alternatives appear for the "ozone depletion" and for "Mineral, fossil & renewable resources depletion". The former is due to the "Constructing materials" which has an impact almost 8 times higher with alkaline electrolysers than PEM. The main driver for this difference is the tetrafluoroethylene consumption for alkaline electrolysers. The change for "Mineral, fossil & renewable resources depletion" is mostly due to higher electricity consumption by PEM electrolysers than alkaline.

Nevertheless, a closer look to the numbers for the environmental emissions shows that virtually a linear relation is respected between "Scenarios A, B and C", for alkaline and PEM electrolysers, i.e., when the demand is twice increased, the emissions are twice increased (with variations lower to 10% in all impact categories, except in "ozone depletion" where the variation can reach ca. 30%). This result is consistent with the contribution analyses conducted in section 6.4.4 where the electricity production remains the biggest contributor to the system's environmental performances.

6.4.6) Monte-Carlo projections and uncertainties analyses:

As mentioned in the methodology, an uncertainty analysis can be conducted through a Monte-Carlo (MC) projection. The OpenLCA software enables to easily implement this analysis by comparing the difference in performances of two alternatives. Analysing the absolute values of a system's environmental performances can become quickly delicate to interpret. Each MC's run would define its own values for the LCA-parameters, therefore comparisons can be biased. Instead of comparing each alternative's environmental performances, analysing the difference between them would be more relevant, by literally subtracting the emissions of one alternative to the others (see **Figure 5**). In this way, the relative performances of the alternatives can be considered and the common LCA-parameters for the two alternatives possess the same values for each MC run. The perspective is no longer to consider the performances each alternative and then compare them but more to directly consider the performances relative to each other.

Several LCA-parameters were implemented in the ex-ante large-scale models. The total list can be found in Appendix 13. The maximum number of LCA-parameters were implemented to enable a maximum of flexibility. In total, 36 LCA-parameters were created for the model AE 1-GW NL 2050 and 23 for the model PEM 1-GW NL 2050. However, only the LCA-parameters that possessed expectations for the future or a range of possible values were adjusted depending on the scenarios. Consequently, 9 LCA-parameters were adjusted in the model AE 1-GW NL 2050 and 11 for the model PEM 1-GW NL 2050.

When a LCA-parameter had its value to be found in an interval in the future, a distribution law had to be defined. Several distribution laws exist (normal law, lognormal law, triangular distribution, etc). In the thesis, as no specific trend was available on the value's distribution, a uniform distribution was adopted for all parameters. This way, all potential values are equally considered during the MC runs. The LCA-parameters that possess a defined distribution are indicated in Appendix 13. Apart from the implemented parameters, all flows in the database ecoinvent 3.4 are defined with distribution laws (lognormal distribution).

The first MC projection with 1,000 runs considered the difference in environmental performances between PEM and AE. The scenarios (A, B and C) are irrelevant here as the LCA-parameters change their values at each MC run. The inventory results (Section 6.3) indicate that overall, PEM possesses higher environmental impact's values than AE, therefore, the difference considered was "1 kg of H_2 from PEM – 1 kg of H_2 from AE". The results are shown in **Table 25**.

Table 25. MC results for the "PEM-AE" difference's alternative

Impact category	Reference unit	Mean	Standard deviation	Minimum	Maximum	Median
Acidification	molc H^+ eq	-9.61E-04	8.97E-04	-4.33E-03	5.32E-04	-7.72E-04
Climate change	kg CO_2 eq	7.26E-03	1.90E-02	-5.91E-02	6.53E-02	7.10E-03
Freshwater ecotoxicity	CTUe	7.57E-01	2.10E+00	-1.50E+01	1.14E+01	7.63E-01
Freshwater eutrophication	kg P eq	-6.18E-06	3.82E-05	-2.71E-04	6.46E-04	-4.16E-06
Human toxicity, cancer effects	CTUh	5.69E-09	1.70E-08	-1.10E-07	9.84E-08	5.67E-09
Human toxicity, non-cancer effects	CTUh	-2.25E-08	2.94E-07	-7.65E-06	2.19E-06	-1.50E-11
Ionizing radiation E (interim)	CTUe	9.84E-10	3.94E-09	-1.51E-08	1.93E-08	8.65E-10
Ionizing radiation HH	kBq U_{235} eq	1.45E-04	2.01E-03	-2.30E-02	1.38E-02	1.62E-04
Land use	kg C deficit	1.22E-02	3.83E-02	-1.26E-01	1.57E-01	1.22E-02
Marine eutrophication	kg N eq	8.33E-06	2.47E-05	-7.52E-05	7.85E-05	8.39E-06
Mineral, fossil & ren resource depletion	kg Sb eq	1.10E-05	9.05E-06	-3.18E-05	5.74E-05	9.97E-06
Ozone depletion	kg CFC-11 eq	-6.90E-09	1.21E-08	-4.45E-08	2.85E-08	-7.10E-09
Particulate matter	kg $PM_{2.5}$ eq	-4.02E-05	5.20E-05	-2.30E-04	7.69E-05	-3.27E-05
Photochemical ozone formation	kg NMVOC eq	-4.18E-05	1.19E-04	-4.53E-04	2.40E-04	-3.09E-05
Terrestrial eutrophication	molc N eq	3.75E-05	2.48E-04	-9.01E-04	7.62E-04	4.47E-05
Water resource depletion	m^3 water eq	-3.44E-03	2.34E-02	-7.64E-02	6.28E-02	-3.22E-03

The mean of the difference between the two alternatives' performances is always lower than 1 and can be considered as particularly low. Naturally, some impact categories can be particularly sensitive where even a low value would have impacts. The standard deviation is always lower than 0.04, except in "freshwater ecotoxicity" where the standard deviation reaches 2.10. This result shows that there is hardly a wide variation around the mean value through the MC runs.

The results described above are consistent with contribution analyses (Section 6.4.4). The latter showed that electricity production remains the highest contributor to electrolyser's environmental performances. As no distribution law was defined for the electricity's production, all the results in the MC projections are clustered around a central value (mean).

The PEM alternative possesses, through the 1,000 MC runs, higher environmental impact's values in 9 out of 16 impact categories, even though the variations can be considered as negligible.

Another MC projection was achieved with 1,000 runs. The relative difference in environmental performances between SMR and AE was considered. The results are shown in **Table 26**.

Table 26. MC results for the "SMR-AE" difference's alternative

Impact category	**Reference unit**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**	**Median**
Acidification	molc H^+ eq	1.89E-03	1.91E-03	-7.34E-03	3.36E-02	1.84E-03
Climate change	kg CO_2 eq	1.07E+01	6.06E-01	9.58E+00	1.60E+01	1.06E+01
Freshwater ecotoxicity	CTUe	-4.73E+01	5.43E+01	-4.38E+02	1.34E+03	-4.35E+01
Freshwater eutrophication	kg P eq	-4.73E-04	9.73E-04	-1.95E-02	1.84E-03	-2.75E-04
Human toxicity, cancer effects	CTUh	-4.17E-07	5.01E-07	-8.35E-06	2.90E-06	-3.58E-07
Human toxicity, non-cancer effects	CTUh	-1.31E-06	4.89E-06	-8.79E-05	2.50E-05	-4.89E-07
Ionizing radiation E (interim)	CTUe	2.34E-07	9.62E-08	5.40E-08	1.01E-06	2.15E-07
Ionizing radiation HH	kBq U_{235} eq	6.26E-02	5.21E-02	6.71E-03	1.03E+00	5.00E-02
Land use	kg C deficit	1.00E+00	7.76E-01	-5.70E-01	1.01E+01	8.50E-01
Marine eutrophication	kg N eq	2.49E-04	2.70E-04	-1.21E-03	4.15E-03	2.18E-04
Mineral, fossil & ren resource depletion	kg Sb eq	-4.11E-04	3.56E-04	-3.86E-03	9.73E-03	-4.01E-04
Ozone depletion	kg CFC-11 eq	1.65E-07	5.27E-08	6.29E-08	6.39E-07	1.54E-07
Particulate matter	kg $PM_{2.5}$ eq	1.73E-04	2.62E-04	-1.26E-03	5.73E-03	1.48E-04
Photochemical ozone formation	kg NMVOC eq	1.09E-03	7.61E-04	-2.61E-03	1.17E-02	1.09E-03
Terrestrial eutrophication	molc N eq	2.75E-03	2.39E-03	-1.15E-02	4.47E-02	2.54E-03
Water resource depletion	m^3 water eq	-5.78E-01	1.78E-01	-1.98E+00	3.66E+00	-5.72E-01

Based on the results from **Table 26**, the SMR alternative performs worse than AE in 10 out of 16 impact categories. Overall, the differences in performances between the two alternatives remain low (below 1), except for a few impact categories. For example, the difference in performances is non-negligible for "climate change" (a variation of 10 kg of CO_2-eq) and for "freshwater ecotoxicity" (a variation of 47 CTUe).

A final MC projection was achieved with 1,000 runs. The relative difference in environmental performances between SMR and PEM was considered. The results are shown in **Table 27**.

Table 27. MC results for the “SMR-PEM” difference’s alternative

Impact category	Reference unit	Mean	Standard deviation	Minimum	Maximum	Median
Acidification	molc H^+ eq	2.73E-03	1.32E-03	-1.60E-03	1.30E-02	2.64E-03
Climate change	kg CO_2 eq	1.07E+01	5.50E-01	9.72E+00	1.31E+01	1.06E+01
Freshwater ecotoxicity	CTUe	-4.94E+01	3.02E+01	-2.88E+02	1.30E+02	-4.50E+01
Freshwater eutrophication	kg P eq	-4.71E-04	9.14E-04	-1.53E-02	3.53E-04	-2.65E-04
Human toxicity, cancer effects	CTUh	-4.14E-07	3.88E-07	-6.54E-06	2.77E-06	-3.71E-07
Human toxicity, non-cancer effects	CTUh	-1.55E-06	8.01E-06	-1.56E-04	7.07E-05	-5.33E-07
Ionizing radiation E (interim)	CTUe	2.31E-07	9.14E-08	8.40E-08	7.68E-07	2.10E-07
Ionizing radiation HH	kBq U_{235} eq	6.13E-02	4.32E-02	1.49E-02	5.86E-01	5.00E-02
Land use	kg C deficit	9.77E-01	7.80E-01	-7.58E-01	8.45E+00	8.29E-01
Marine eutrophication	kg N eq	2.38E-04	2.38E-04	-4.27E-04	1.66E-03	2.02E-04
Mineral, fossil & ren resource depletion	kg Sb eq	-4.28E-04	1.17E-04	-1.11E-03	-1.09E-04	-4.13E-04
Ozone depletion	kg CFC-11 eq	1.69E-07	4.50E-08	6.30E-08	4.12E-07	1.60E-07
Particulate matter	kg $PM_{2.5}$ eq	1.95E-04	1.82E-04	-3.89E-04	1.41E-03	1.81E-04
Photochemical ozone formation	kg NMVOC eq	1.05E-03	6.97E-04	-3.48E-03	5.11E-03	1.09E-03
Terrestrial eutrophication	molc N eq	2.59E-03	1.82E-03	-3.26E-03	1.67E-02	2.43E-03
Water resource depletion	m^3 water eq	-5.79E-01	1.09E-01	-1.04E+00	-2.44E-01	-5.72E-01

Based on the results from **Table 27**, the SMR alternative performs worse than AE in 10 out of 16 impact categories. Overall, the differences in performances between the two alternatives remain low (below 1), except for a few impact categories. For example, the difference in performances is non-negligible for “climate change” (a variation of 10 kg of CO_2-eq) and for “freshwater ecotoxicity” (a variation of 49 CTUe).

For the last two MC projections, the results and variations are similar. This is not a surprise since the alkaline and PEM electrolysers possess similar environmental performances as discussed in section 6.3.8. The means’ values of “SMR – PEM” or “SMR – AE” may seem particularly low, especially when the graphs from Figures 31 and 34 are considered. However, the environmental impacts of each alternative (electrolysers ad SMR) are already low, when the functional unit is 1 kg of H_2 produced. Consequently, a small variation can induce a large relative variation. Furthermore, as mentioned several times before, SMR possesses good performances in comparison to electrolysers in several impact categories.

Furthermore, another resource has been used to support the previous results. The Excel appendix from Beltran et al. (2018) offers the possibility to easily implement MC results and run some statistical tests. This time, no difference was considered but the MC results from 3 alternatives themselves (SMR NL 2018, AE 1-GW NL 2050 and PEM 1-GW NL 2050) were implemented. The Null Hypothesis Significance Testing (NHST) is one of the most common statistical tests used and evaluates whether the relative impacts of two alternatives are statistically significant from each other. In the thesis, the differences are always significant between SMR and AE 1-GW (or PEM). However, when AE 1-GW NL 2050 and PEM 1-GW NL 2050 are compared, the differences are never significant. This result confirms the previous findings that PEM and alkaline electrolysers possess closed performances and that SMR. Moreover, AE/PEM and SMR possess significant differences (better or worse performances). Other tests could be performed, such as the “discernibility” or the “overlap area” but were not conducted due to a lack of time.

Finally, the MC enabled to strengthen the results from Section 6.3 with a large number of runs and statistical tests. The relative differences in environmental performances between PEM and AE are negligible but present. On the contrary, SMR possesses non-negligible differences in its environmental impacts with AE or PEM, even though these differences can be low. In this sense, the production of hydrogen from electrolysers is more sustainable than the SMR option, globally.

7) Discussion and critical analyses

Now that the main results are found, this section will discuss the work achieved in the thesis (Phase 5 in the methodology overview). The chapter will consider the assumptions taken that are present in the thesis and will also provide recommendations for further works and/or improvements.

7.1) Limitations of the study

First, the limitations on the methodologies used are discussed, with a topic separation.

LCA models:

Different criticisms can be raised against LCA studies such as the data's age, the consistency or the completeness of data. Some of the limitations are already addressed in the LCA sections (Chapter 3 or 6). The boundaries' definition is a typical limitation that can be debated. Extending the boundaries of the system under study can be relevant and provide more realistic results but would require more time and investments. Some variations in the environmental profiles may occur depending on the final end-use that is considered, which could change the functional unit, etc. Differences may occur in infrastructures, chemical and physical conditions of the product (purity, pressure, etc.), scales and others, requiring new unit processes.

As an example, Balance of the Plant elements (heat exchanger, pipeline infrastructure, storage tank, compressor…) could be modelled. The environmental impact of the endpoint of the hydrogen use, the refuelling station, could also be estimated. Due to the practical constraint of the Master thesis, the limits were settled at the hydrogen's production, but more could be achieved for a more comprehensive model.

The Nafion production has been modelled based on the paper from Laforest et al. (2016) for the ex-ante large-scale LCA models (see the Excel "Appendix, Life Cycle Inventories, Pilot-scale and ex-ante large-scale LCA models"). However, the work from Weber, Peters, Baumann, & Weil (2018) provides a detailed Life Cycle Inventory for the production of the Nafion membrane. As this paper was communicated at a late stage in the thesis' process, only a quick implementation could have been made. The preliminary results show that updating the Nafion production process would change the environmental impacts' values by only 3 to 5%. In this sense, the change can be considered as negligible for now. Nevertheless, the work from Weber, Peters, Baumann, & Weil (2018) remains a good basis for further research and comparison in other studies about the Nafion topic.

Recycling aspects could also be more developed. In the thesis, no strong enough resources were found to model a recycling or treatment process for the tetrafluoroethylene, graphite, titanium and potassium hydroxide. More research in this field may fill the gaps and enable to develop a more comprehensive LCA model.

Technology analyses:

Generally, the more interviews, workshops, collaborations or literature review are achieved, the better the models are. The main limitations are then connected to practical limits present within the thesis. Four interviews were conducted in this study, several discussions were made with experts via meetings or phone calls and one collaboration was achieved with ENGIE France. More interviews or collaborations would most likely add relevant information in order to refine the models.

Change of the LCA-parameters considered:

The list of the relevant LCA-parameters for the upscaling process can also be discussed. Other LCA-parameters could be more studied and implemented in LCA models in further works. A few possibilities are indicated below:

- The electrolysers' losses since the latter will likely evolve in the future (Burkhardt et al., 2016)
- PEM electrolysers are not used to their full potential with their load hours values (Personal communication, Wulf, 2019)
- On a more detailed level: the current density in electrolyser or the output pressure could be considered. Some forecasts were found in the literature review and are indicated in the extended technological field in Appendix 7. They were not further implemented in the LCA models since they were not adapted to consider such parameters.
- The operating temperature is another element that could have influences and was not considered due to a lack of sufficiently consistent data.

The LCA-parameters from the list above have not been implemented due to a lack of data or possibilities for implementation.

Scenario's development:

For the scenario's development, only the final situation of the Netherlands in 2050 was considered. The transition aspects are not studied in the thesis. A few indications were still provided on the transitional period in the narratives to justify the final situation described. Nonetheless, a possibility would be to further study the transitional processes that may occur. A possibility is to use the backcasting approach. The latter consists in considering ideal situations in the future and, from them, to develop the different steps that are necessary to reach the mentioned ideal state. Transitional processes can hinder the development of a technology. For example, a transition in the hydrogen distribution through the gas network may be a sensitive aspect to deal. How to shift from a methane-based gas network to 100% hydrogen-based network in concrete? Gas blending may not be the most preferable option regarding the practical challenge and the emissions associated with it, but it may prove to be the most feasible one.

Some remarks can also be made in the scenarios from a technical perspective and could adjust the technological field. A high intercorrelation exists between the different elements of the electrolyser, as mentioned by Bareiß et al. (2019) and the ECN's workshop "Developing the supply chain for hydrogen" (Appendix 6.1). The evolution of one parameter will most likely influence the performance of another parameter, in a good or bad way. For example, the reduction in iridium loading will likely occur in combination with an improved catalyst with a higher surface area. In addition, most of the time, a trade-off must be set between the different electrolyser's components. For instance, a larger membrane would reduce the gas crossover effect but decrease the current density. These considerations become sensitive when the technological framework is considered. An optimistic scenario where all the parameters from an electrolyser are at their optimal values, like in "Scenario A", may be hardly achievable. Potentially, a more realistic scenario is to optimize one parameter at the expense of another one. Further detailed chemical studies are necessary to understand all the trade-offs occurring in an electrolyser and to know clearly which "combinations" of parameters are "physically" feasible. It is also possible that a more "realistic" combination of parameters for the future will not induce a significant change. As a matter of fact, the contribution analyses showed that the electrolyser contributes in a limited way to the environmental profile of green hydrogen production. Therefore, the relevance of improving, even more, the technological modelling can also be questioned. Due to resources and time constraints, "simplified" scenarios and LCA-parameters were used in the thesis. Further research could seek to refine even more the scenarios but a trade-off between the investment and its added value must always be considered.

7.2) Methodological reflections

This section discusses the areas of improvements in the methodological framework as presented in section 2.2, phase by phase.

Phase 1: more LCA-parameters could have been considered in the list and applied in the ex-ante large-scale LCA models (see **Table 23**). The selection of the most relevant parameters within the scope of the thesis was made, connected also to time constraints. The focus of the thesis was on the electrolyser's system. However, the thesis confirmed that the electricity's production remains the most important contributor to the environmental impacts, even when a shift is operated from the national grid to wind-based electricity and from lab-scale to large-scale systems. A new approach, requiring perhaps a new methodology, should seek on how to reduce the impacts from the wind turbine's construction and the recycling options.

For example, Wulf & Kaltschmitt (2018) assume that the upscaling effects on onshore wind parks in Germany will decrease impacts from the wind turbines on climate change by 16%. Caduff, Huijbregts, Althaus, Koehler, & Hellweg (2012) studied the impacts of upscaling processes with wind turbines and concluded that the global warming impact per kWh decreased by 14% for every doubling of the cumulative production. Their approach has been briefly considered for the thesis. Quick calculations show that if the reasoning from Caduff et al. (2012) is adopted, "Scenario A" would see the impact from wind turbines decreased by 61%. However, even at this stage, the preliminary results show that the electricity's production still remains the largest contributor to environmental impacts with variations of ca. 5% in general. Further works are necessary for a better understanding and implementation of the works from (Caduff et al., 2012). Nevertheless, their works and the ones from Wulf & Kaltschmitt (2018) provide a basis for further studies where a deeper focus can be put on the wind turbines modelling and its evolution in the future.

Phase 2: more interviews could have been conducted in order to get an even broader overview of the technological landscape linked to electrolysers. Some interviews could not have been conducted for different reasons such as time constraint, lack of responsiveness from the experts or lack of resources. At the same time, general trends can also be extrapolated from a certain point. After a certain number of interviews, the same opinions, ideas, objectives or equivalent can be repeated. At this stage, the different stakeholders can be associated with specific categories.

Concerning the type of interviews conducted, Adams (2015) mentions that Semi-Structured Interviews (SSI) cannot give a broad overview of the situation unless a huge amount of time and personnel are available. Other techniques such as standardized surveys may encompass a much larger group-sessions sample and the latter could be much more representative (Adams, 2015). However, the SSI's limitation is reduced within the thesis context since the PEM technology is not much developed. Therefore, there are not so many significant Dutch stakeholders in the green hydrogen field due to its early stage. This impression was confirmed along with the different interviews conducted (see Appendix 6).

Technology assessment (TA) is also a methodology that could be applied interestingly in further works. Technology assessment is rather broad in its definition and can include several methodologies or approaches. The main aim of TA is to analyse and evaluate all the potential consequences from a technology use or change in societal and environmental dimensions (Honkoop, 2017; Van Den Ende, Mulder, Knot, Moors, & Vergragt, 1998). Most of the time, TA is based on a constructive dialogue between the relevant stakeholders and is built through several steps such as "expert input", "technology mapping", "description of applications", "institutional dynamics" and more. A wide range of tools can be used for or considered as a TA such as the interviews, backcasting or the Delphi-method (Van Den Ende et al., 1998). The Technology Assessment was not implemented on intention, mostly due to time constraints. However, some sections of the thesis can be connected to TA, such as with the construction of scenarios, reminding the "technological forecasting" described by Van Den Ende et al. (1998). Consequently, the Technology Assessment is an option to search for further work and some connections can already be created between the thesis and TA.

Phase 3: The "What-if" scenarios type has been used to develop the visions for the green hydrogen technology development by 2050. However, some narratives were provided in order to explain the state-of-the-art of the technology in 2050. This narrative is quite close to the backcasting approach. In the thesis, the future visions were developed based on real Dutch projects and diversions occurred at the implementation's level (optimistic scenario, pessimistic scenario and mixed results). The Delphi method has not been used for practical constraints but could be implemented in further scenario's construction, since it enables more feedback and adjustment between the stakeholders in workshops.

GMA implies a selection of a finite number of dimensions/perspectives. Some perspectives are therefore "skipped" for practical reasons, even though they could be relevant to consider. A longer project with more means would enable to consider further and more detailed dimensions. In the thesis, 8 dimensions were considered for the morphological field, 13 parameters (and their variations) were defined in the technological field and implemented in the ex-ante large-scale LCA model. Longer, more ambitious and detailed projects could analyse or implement even more dimensions.

GMA considers in theory societal approach and general trends, at the macrolevel. The scenarios developed from GMA can be rather broad. By contrast, LCA considers a much more micro level with quantifications of the mass/energy flows. Normally, LCAs are supposed to be as specific as possible whereas GMA is rather broad. To bridge this difference in tools, the technological field was created and helped to create links between the general scenarios and the specific technological evolutions. Further research in scenarios' methodologies may enable either to improve the connections between LCA and GMA or to find a better combination between LCAs and scenarios.

Phase 4: The modelling of processes in a future state is connected to uncertainty issues. For the management of the inherent limitations of an ex-ante LCA modelling, Arvidsson et al. (2018) provide some recommendations. For these authors, three aspects are especially relevant: the choice of the technology alternatives, the modelling of foreground systems and the modelling of background systems. For the first aspect, Arvidsson et al. (2018) mention the fact that some uncertainties already appear in selecting which alternative technologies are the most relevant to study, as no one can be sure which alternative will be promoted finally. Therefore, these authors recommend conducting a cradle-to-gate study of emerging production technologies with different future scenarios to take into account the plurality of alternatives.

To modelling the foreground systems, Arvidsson et al. (2018) recommend using scenarios illustrating the likely development of some technological parameters, the status quo case and the extreme cases. This approach is partly adopted in the thesis as two possible electrolysis' technologies were considered (PEM and alkaline) and with optimistic or pessimistic development's path. Due to time constraints and lack of data, no other option was considered, although other alternatives could possess potential (high-temperature solid electrolysis, nuclear-based electrolysis…).

To modelling the background systems (such as the electricity mix composition for example), the same approach than for the foreground systems can be applied. Again, this approach was partly adopted with the construction of the technological field (see Section 4.4). However, a proper application of the approach described by Arvidsson et al. (2018) would require extensive work that is not applicable in the thesis and must be recognised as one of its limitations. In this perspective, some research has been conducted within the CML department in Leiden University to develop a version of ecoinvent extrapolated for 2050. The use of this version in further research can prove to be valuable since background processes would implement expected evolutions on parameters. For example, the environmental impacts from wind turbines may be extrapolated to decrease in 2050, due to upscaling effects in the large wind-parks constructed between 2019 and 2050.

Additionally, the software OpenLCA possesses an option that has not been used in the thesis: "bulk replace". It enables to update the full database used (ecoinvent in the thesis), based on specific assumptions. Further works could research how to potentially use this option to update a database for specific conditions, such as a future scenario.

For the development of the ex-ante large-scale LCA models, a selection of the inflows/outflows has been made based on the pilot-scale LCA models. However, the pilot-scale LCA models differ in assumptions, the level of details provided and in the inventories. A problem raised quickly: how to create a "standardised/harmonised" model for the future to increase the comparability factor? Assumptions and choices were made for the ex-ante large-scale LCA model's construction (see the Excel "Appendix, Life Cycle Inventories, Pilot-scale LCA and ex-ante large-scale LCA models" for all the details). Caduff et al. (2012) have made a harmonization between different Life Cycle Inventories for wind turbines. Their works were one source of inspiration for the construction of the Life Cycle Inventory for the ex-ante large-scale LCA models. However, there is a need for more systematic and "constructed" method to be used for this kind of action. To the knowledge of the author, no methodology aiming to extrapolate the future constitution of the technology based on existing pilot installations exists.

Phase 5: More uncertainty analyses could be conducted on the final results. The MC projections were used to consider the relative differences of alternatives in the ex-ante large-scale LCA models but could be extended to this phase. Beltran et al. (2018) describe several other possible tests to use such as the "impact category relevance" or the "overlap area". Other methodologies or new suggestions could be applied here when necessary.

7.3) Links to literature and prospective

This section discusses the results of the thesis within the literature and the new elements that are added.

Some comparisons were achieved with other LCA studies to detect potential irrelevance in the results. LCA studies comparisons must always be considered with perspective as many choices in the modelling can justify differences. Nevertheless, some comparisons (when possible) were done with the works from Ghandehariun & Kumar (2016), Koj et al. (2017), Mori et al. (2014;), Schmidt et al. (2018) and Wulf & Kaltschmitt (2018). Different LCAs use different impact assessment families and different boundaries with the location's specific features, making the comparisons delicate to achieve. When all comparisons are achieved with the precautions required, 57% of the time, the models in the thesis possess lower environmental impact than the models in the resources. The factor of variation can vary between a difference of tenth to a difference of hundreds. The most probable reasons for differences concern again the impact assessment method used and the origin of the different flows (some studies consider European context whereas others are in America). Furthermore, all the resources mentioned consider existing (or about to exist) systems when the thesis considers future systems. The most consistent comparison was achieved with the work from Koj et al. (2017) as the authors consider the same impact assessment family than in the thesis (ILCD 2011). In this case, for all impact categories where results were given, the environmental performances of the electrolysers were lower by a factor 10 in the thesis than in the models from Koj et al. (2017). The most likely reason to explain the difference is the context of the system studied (Koj et al. (2017) modelled systems in Spain, Germany and Austria) and the origin of electricity (Koj et al. (2017) considered electricity from the national grid for each case).

Bareiß et al. (2019) evaluate the evolution of PEM electrolysers in the future and the authors claim that the electricity production is responsible for a much larger share of impacts in comparison to the influence of the electrolyser itself. This remark has been confirmed in the thesis and the electricity production is likely to remain the largest contributor to the environmental impacts in general for green hydrogen's production. Bareiß et al. (2019) also mention that PEM electrolysis, due to its high-power density, should have a lower global warming impact result than alkaline electrolysis when using the same electricity input. When the same input of electricity is considered for both PEM and alkaline electrolysers, in the ex-ante large-scale LCA models, the alkaline and PEM technologies possess virtually the same impacts on global warming, with the ILCD 2011 assessment method (variation of the values of 1.5%).

Based on the methodological reflection from the previous section, a generalised framework that could be reused in further research combining LCA and GMA can be extracted. To the knowledge of the author, no study has performed an integration of LCA and GMA, as comprehensive as in this thesis. The thesis from Honkoop and Rijnsburger combined LCA and scenarios but did not develop so deeply about the parameters' evolutions (Honkoop, 2017; Rijnsburger, 2016).

In the thesis, a combination has been operated between the ex-ante LCA methodology and GMA. As mentioned in Section 7.2, a "technological" field was developed to connect the GMA framework with LCA models. This element, included in the methodological framework, adds to the existing body of literature. Naturally, the methodological framework is always prone to improvements in further work.

The combination used in the thesis could be extended to any comparison between the present and a future state, between a quantified system analysis tool (Mass-flow analysis, Environmental Input-Output Analysis, LCA…) on the one hand and scenarios in general on the other hand. The same overall methodological framework as the one described in Chapter 2 could be followed.

- Firstly, a baseline model would be constructed with the quantitative environmental tool. Analyses of this model should provide a state-of-the-art of the current situation and a list of relevant parameters to consider for upscaling processes.
- Secondly, activities and technology analyses would be conducted with different approaches possible (Technology Assessment being one of them). The technology analyses would enable to discover and understand different perspectives and to get the basic elements for constructing scenarios.
- Thirdly, based on the inputs from the first two phases, the scenarios for the future would be developed. Again, multiple approaches are possible for the scenario's construction.
- Fourthly, the scenarios constructed will have to be translated into quantified inputs for the quantitative environmental tool. Comparisons can then be made between the system performances at the current situation and the ones from the future.

- Fifthly and finally, reflections, comments and critical perspective are necessary to fairly judge the outputs from the study and to make the outcomes the most relevant possible.

7.4) Broader perspective

This section discusses the contextualisation of the system that can also bring relevant insights. The questions related to the implementation of the technology within a particular place or framework will be addressed.

In the thesis, the demand for hydrogen cars was considered although no reflection has been made concerning the hydrogen consumption in the FCEV. The average consumption value of 1 kg H_2/100 km is based on existing models. Likely some improvements will occur in the future and the car's requirements may decrease. The impacts from the refuelling stations construction (or adjustments of oil-based stations) are another aspect that can be discussed in further work.

The geographical-dependency may have influences on some parameters. For example, if electrolysers are to be deployed in desertic countries – such as Arabic countries, Saharan regions or Australia – water consumption can become a critical factor. These regions have a lot of potential for solar-based electrolysis but also water resource scarcities. A potential solution to be investigated is the reuse of water produced by the fuel cell. As a matter of fact, an electrolyser consumes water to produce hydrogen, but a fuel cell (for example in a car) consumes hydrogen to produce water. A possibility would be to close the loop and invent some kind of a storage system inside the car to collect the water and then exchange it at a refuelling station. This option may reduce the water scarcity issue but needs to be correctly evaluated and assessed.

In further works, more connections to the economic perspectives may be valuable. Some indications are already provided in Appendix 14 and there is already plenty of references that analyse the economic aspects of hydrogen's technology (Ball & Wietschel, 2009; Gielen & Simbolotti, 2005; Parks, Boyd, Cornish, & Remick, 2014; Reddi, Elgowainy, Rustagi, & Gupta, 2017). Nevertheless, economic considerations can always be valuable in societal problems.

The storage option is also one of the most important topics discussed within hydrogen technologies and for the energy transition in general. Several options exist for hydrogen's storage: storage in salt caverns, conversion into methanol which is easily dealt with an existing infrastructure or liquefaction. Simple storage in a hydrogen car is also an important topic with either highly-compressed gas (several hundred bars) or extremely cold liquid (ca. -270°C). Some works have already been conducted on this with chemical considerations on the most promising materials to be used for storage tanks or control systems (Fărcaş, Sita, Dobra, & Tîrnovan, 2013; Singh et al., 2015). Further research in these topics would generate necessary insights for the development of a hydrogen economy.

Lastly, as a final thought, the oxygen's use has been mentioned in the interview from Stedin (see Appendix 6.2). As a matter of fact, there is a ratio of 1:8 between the production of hydrogen and oxygen. A relevant question is to know whether some possibilities exist on the reuse of the oxygen produced. In this case, a multifunctional process would appear in the LCA model and allocations would be necessary. The LCAs models from the thesis would need to be updated. However, no paper has been found by the author on the reuse of oxygen. This topic was mentioned with ENGIE but no significant project seems to consider potential reuse of the oxygen produced due to technical challenges.

7.5) Recommendations

This section provides recommendations for further work to improve the results or already apply them when they are already usable.

Origin of electricity:

The two electrolysers possess similar performances, so the main focus should be put on the electricity's origin. The possibilities for decreasing environmental impacts are already mentioned in section 7.2. The solar potential in the Netherlands could also be more studied as a potential alternative to electricity from wind turbines. Solar energy remains one of the main renewable energy source used for electrolysis (van Wijk, 2017). Even though a sensitivity analysis showed that electricity production from solar systems will likely increase the environmental impacts (see section 6.4.5.2), more research is necessary. The electricity from solar energy modelled in ecoinvent is "low voltage" instead of "high voltage". Furthermore, multi-Silicon photovoltaic panels were considered in the mentioned sensitivity analysis. Other technologies exist as well (mono-Silicon, thin films or plastic concepts) and may be more adapted for Dutch use.

The criticality of materials:

The criticality of different noble metals, particularly iridium and platinum, are factors to be further discussed in other research. The results from the thesis show that the environmental impacts from their use are negligible when the whole lifespan of the electrolyser is considered. Even changing the impact assessment method has not changed their contribution effects (see Appendix 8.2) Nevertheless, the use of these noble metals may imply some geopolitical strategic decisions or tensions that must be dealt with. In this perspective, further research on recycling processes for noble metals, their resources' locations and geopolitical factors would be an added-value.

Recycling:

Recycling aspects were already mentioned in section 5.2.2 and Appendix 11. However, deeper research would definitely add values to LCA studies, making the models more consistent and complete in their approach. The sensitivity analysis conducted in Section 6.4.5.1 showed that it was the treatment of steel, a "common" element in comparison to rarest metals, that could have some environmental impacts. Therefore, the recycling technologies for "common" elements should also be more studied to see how their environmental performances may evolve in the future. Furthermore, if electrolysers were to be applied on large-scale, it is necessary to consider in advance the EoL flows' management (and not afterwards).

National perspective:

The thesis mostly considered the environmental impacts related to the production of 1 kg of H_2. The differences between the alternatives concerned mostly the electrolyser used (PEM or alkaline) and the technical scale (plant of 1 GW, 100 MW, optimistic development path, etc.). The sensitivity analysis in section 6.4.5.3 shows that a broader consideration could add some new perspectives. Looking at the complete demand for hydrogen fuel is not particularly relevant in itself. The results would become more relevant if the whole Dutch demand for fuel is considered (gasoline, diesel, electric and hydrogen). LCA models for the production each fuel would be required and then, scenarios comparison can be achieved. In this sense, the environmental impacts of the fuel production for the NL by 2050 could be assessed and compared based on different combinations possible for the Dutch car's fleet. Several questions can be raised to develop a sustainable society. For example: should a balance be found between battery-based electric and hydrogen cars? Or should one technology be more promoted than another? This kind of study would also combine LCA and scenarios but on a more global perspective. The use of scenarios and GMA would be relevant but LCAs may face more limitations due to the scale considered (conflict between broad scenarios and specific LCAs).

Other alternatives or improvements for hydrogen's production:

Other alternatives for the hydrogen's production exist such as the AEM electrolyser. This alternative has not been further developed in the thesis but possesses some potentials that would likely deserve a dedicated project conducted on it and some LCA analyses. Some studies have already been conducted to provide an overview of the potentials and the challenges to overcome (Vincent & Bessarabov, 2018). In the electrolysis' field, some discussions have appeared on how to potentially use the sea's water for electrolysers (Meier, 2014; US2018/0148356A1, 2018). This aspect is still at a research phase but can decrease the water resource problem. Other alternatives exist or will appear and would require appropriate studies on the moment.

8) Conclusion

All along this thesis, detailed LCA analyses were conducted with a specific focus on the two most promising alternatives for green hydrogen technologies: the PEM and alkaline electrolyser.

Four pilot-scales models were developed (named “AE NL 2017”, “AE NL 2018”, “PEM NL 2018a” and “PEM NL 2018b”), based on literature review and different activities (contacts with experts, workshop, interviews…). Then some scenarios were developed to describe a potential future situation in the NL by 2050 with three main development’s pathways. Finally, ex-ante large-scale LCA models were implemented with adjustments on values based on expected evolutions.

The Research Question was *“What are the environmental impacts for a large-scale hydrogen fuel production from wind-based electrolysis in the Netherlands and the options to improve them?”*

To answer this, several sub-questions were defined and will be answered below.

1) *What are the environmental profiles of the two electrolysers’ alternatives?*

The pilot-scale LCA models provide the answers to this question. Chapter 3 provides all the details. The model AE NL 2018 performs the best in comparison to the others, but its performances are quickly followed by the ones from PEM NL 2018a and PEM NL 2018b. The last two possess similar performances. Overall, the electricity’s production remains the largest contributor to all environmental impact categories.

For the model AE NL 2017, the nickel consumption possesses some influences (ca. 40%) in “acidification”, “climate change” and “freshwater ecotoxicity”. The tetrafluoroethylene consumption is responsible for around 25% of the “ozone depletion” impact.

For the model AE NL 2018, the “electricity production” predominance is even more important. The “market for water” is non-negligible in some impact categories such as “Ionizing radiation HH” and “ozone depletion” but never exceeds ca. 15% of contribution effect.

For the model PEM NL 2018a, the “electricity production” is the biggest contributor to all impact categories. The water consumption possesses a non-negligible contribution’s effect in “Ionizing radiation (E and HH)” and “Ozone depletion” at around 10-15%. The tetrafluoroethylene is also responsible for around 12% of the “ozone depletion” impact.

For the model PEM NL 2018b, the “electricity production” is the biggest contributor to all impact categories, in an even more extreme way than PEM NL 2018a. The water consumption is noticeable in “Ionizing radiations (E and HH)” and “Ozone depletion” at 5-8% and the tetrafluoroethylene consumption in ozone depletion at around 7%

2) *Which parameters are the most relevant for the transition from a pilot-scale to a large-scale perspective?*

Based on the answers to the previous sub-question, the obvious parameters that should be considered are the consumption of water, tetrafluoroethylene and nickel in alkaline electrolysers and the consumption of water, tetrafluoroethylene in PEM electrolysers (see **Table 9**). As the intention of the thesis is to focus on the electrolyser’s technology, no deep considerations were made for the wind turbine’s technology producing the electricity.

Another parameter that is considered for PEM electrolysers is the rare metals even though their contribution’s effects in environmental impacts were negligible in the pilot-scale LCA models. The noble metals consumption is one of the main objections against the development of PEM electrolysers and can become relevant factors in the years to come. The membrane considered for electrolysers is a product named Nafion and has usually been a problematic product to model, so its role may become non-negligible. Hence, these metals and the Nafion membrane were considered as relevant for parameters for PEM electrolysers.

3) *What are possible scenarios for a large-scale production of sustainable hydrogen in the Netherlands?*

Based on several documents, reports, interviews and contacts, some scenarios were constructed for the green hydrogen development in the NL by 2050. The General Morphological Approach (GMA) methodology was used and resulted in **Table 10**. The latter considers more a societal perspective with political or societal implications. To create a stronger connection with LCA's methodology – much more quantitative in its approach – **Table 17** provides numerical data quantifying different LCA-parameters and their expected evolutions. Three main scenarios were considered:

- *Scenario A "Full hydrogen Power"* which considers the most optimistic development's pathway for green hydrogen in the Netherlands.
- *Scenario B "No to wind-based Hydro"* which considers the most pessimistic development's pathways for green hydrogen in the Netherlands.
- *Scenario C "Mixed results"* where some regions (in the North) successfully implemented green hydrogen technologies, unlike other regions.

Connections were made between scenarios' assumptions from **Table 10** and LCA-parameters' values projections in **Table 17**. This combination resulted in **Table 23** where the LCA-parameters' values for each scenario are defined. In this way, scenarios and LCA were successfully combined to generate ex-ante large-scale LCA models.

4) *How will evolve the environmental profiles between the pilot-scale (current situation) and the large-scale implementation (scenario situation)?*

In total, two ex-ante large-scale LCA models were developed, one for each electrolyser's alternative. These two models were subdivided into 3 new alternatives to consider the scenario's perspective (each time with the sign (A), (B) or (C)). The analyses of the LCA show that overall, the environmental performances of the two electrolysers' alternatives become more balanced, except in "ozone depletion" where "AE 1-GW NL 2050" performs significantly worse than the other alternatives. Apart from this particular impact category, the environmental performances from the models are similar. Even considering scenarios A and B, the two most opposite in the development's paths, has not changed noticeably the environmental performances. When one considers the details, the model AE 1-GW NL 2050 (A) performs better than the other alternatives with impacts usually reduced by 5% in comparison to PEM 1-GW NL 2050 (A). Only in "acidification" and "ozone depletion" is "AE 1-GW NL 2050 (A)" performing worse than PEM 1-GW NL 2050 (A).

When a comparison on the contribution analyses is conducted between pilot-scale and ex-ante large-scale models, some evolutions are noticeable.

For the alkaline electrolyser, the contribution from nickel consumption in "acidification" is still present in the ex-ante large-scale model but decreased significantly (from 27% in "AE NL 2017" to 6% in AE 1-GW NL 2050 (A)). The tetrafluoroethylene consumption in "ozone depletion" increased from 25% in AE NL 2017 to 37% in AE 1-GW NL 2018. Apart from these specific cases, the electricity production becomes in general even more predominant in its relative contribution to the environmental performances of the alkaline electrolyser with a shift from pilot-scale to large-scale. Either there are some increases (of ca. 5-10%, some specific cases at 60% in comparison with AE NL 2017) or minor decreases (- 1 to 2% in comparison with AE NL 2018).

For the PEM electrolyser, the "electricity production" was already significantly present for its contribution effect in models PEM NL 2018a and PEM NL 2018b. The consumption for water and tetrafluoroethylene were still noticeable in some impact categories for the pilot-scale LCA models. The shift towards the ex-ante large-scale PEM model does not actually change so much the pattern: the "electricity production" remains the biggest contributor to the environmental impacts with an average contribution among impact categories of 97%. As the consumption of noble metals and Nafion are expected to decrease, despite the upscaling effects and the shift to renewable energy sources, the contribution from electricity production remains as influential as before.

Answer to the main Research Question:

Finally, the global Research Question can be answered with the previous paragraphs. The LCAs conducted in this thesis showed that the major contributor to the environmental impacts from large-scale electrolysers remains the electricity's production. All the research conducted about the electrolyser system itself, its components and potential evolutions, showed that these elements are unlikely to influence significantly the environmental performances. The alkaline technology is slightly more efficient than PEM electrolysers in most of the impact categories (except "acidification" and "ozone depletion") in an optimistic technology development's pathway. If the technology development's pathway is more pessimistic, the PEM technology is slightly more efficient.

The options to improve the environmental impacts from wind-based electrolysis are still numerous. The first action would be to focus on the electricity production's system (the wind turbines in the thesis) since they have the biggest contribution effect. Some attention can also be paid to the water and tetrafluoroethylene consumption since these factors become more prominent in "acidification" and "ozone depletion" impact categories.

Numerous recommendations can be indicated for further research and some are developed in section 7.5. Most importantly, a deeper focus on the electricity's production system would enable to decrease even more the environmental impacts from green hydrogen production. Broader considerations and contextualisation would also support more the conclusions from the thesis.

References

Acar, C., & Dincer, I. (2014). Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *International Journal of Hydrogen Energy*, *39*(1), 1–12. https://doi.org/10.1016/j.ijhydene.2013.10.060

Adams, W. C. (2015). Conducting Semi-Structured Interviews. In *Handbook of Practical Program Evaluation: Fourth Edition* (pp. 492–505). https://doi.org/10.1002/9781119171386.ch19

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286–1294. https://doi.org/10.1111/jiec.12690

Babic, U., Suermann, M., Büchi, F. N., Gubler, L., & Schmidt, T. J. (2017). Critical Review—Identifying Critical Gaps for Polymer Electrolyte Water Electrolysis Development. *Journal of The Electrochemical Society*, *164*(4), F387–F399. https://doi.org/10.1149/2.1441704jes

Ball, M., & Weeda, M. (2015). The hydrogen economy - Vision or reality? *International Journal of Hydrogen Energy*, *40*(25), 7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032

Ball, M., & Wietschel, M. (2009). *The Hydrogen Economy: Opportunities and Challenges.* Cambridge: Cambridge University Press. https://doi.org/https://doi.org/10.1017/CBO9780511635359

Bareiß, K., de la Rua, C., Möckl, M., & Hamacher, T. (2019). Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. *Applied Energy*, *237*(November 2018), 862–872. https://doi.org/10.1016/j.apenergy.2019.01.001

Beltran, A. M., Prado, V., Vivanco, D. F., Henriksson, P. J. G., Guinée, J. B., & Heijungs, R. (2018). Quantified uncertainties in comparative Life Cycle Assessment: what can be concluded? *Environmental Science and Technology*, (52), 2152–2161. https://doi.org/10.1021/acs.est.7b06365

Bertuccioli, L., Chan, A., Hart, D., Lehner, F., Madden, B., & Standen, E. (2014). *Study on development of water electrolysis in the EU*. *LC-GC North*. Retrieved from https://www.fch.europa.eu/sites/default/files/FCHJUElectrolysisStudy_FullReport (ID 199214).pdf

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis - A review. *Journal of Cleaner Production*, *85*, 151–163. https://doi.org/10.1016/j.jclepro.2013.07.048

Birkeland, C. (2011). *Assessing the Life Cycle Environmental Impacts of Offshore Wind Power Generation and Power Transmission in the North Sea*.

Biswas, W. K., Thompson, B. C., & Islam, M. N. (2013). Environmental life cycle feasibility assessment of hydrogen as an automotive fuel in Western Australia. *International Journal of Hydrogen Energy*, *38*(1), 246–254. https://doi.org/10.1016/j.ijhydene.2012.10.044

Blauwevinvis. (2019). Aantal personenauto's in Nederland 2019 | Auto en Vervoer: Auto. Retrieved May 14, 2019, from https://auto-en-vervoer.infonu.nl/auto/188341-aantal-personenautos-in-nederland-2019.html

Bockris, J. O. M. (2013). The hydrogen economy: Its history. *International Journal of Hydrogen Energy*, *38*(6), 2579–2588. https://doi.org/10.1016/j.ijhydene.2012.12.026

Burkhardt, J., Patyk, A., Tanguy, P., & Retzke, C. (2016). Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply. *Applied Energy*, *181*, 54–64. https://doi.org/10.1016/j.apenergy.2016.07.104

Caduff, M., Huijbregts, M. A. J., Althaus, H. J., Koehler, A., & Hellweg, S. (2012). Wind power electricity: The bigger the turbine, the greener the electricity? *Environmental Science and Technology*, *46*(9), 4725–4733. https://doi.org/10.1021/es204108n

Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy*, *38*(12), 4901–4934. https://doi.org/10.1016/j.ijhydene.2013.01.151

CBS. (2014). Dutch car fleet to break 8 million barrier. Retrieved June 20, 2019, from https://www.cbs.nl/en-gb/news/2014/34/dutch-car-fleet-to-break-8-million-barrier

CBS. (2016). *Transport and mobility 2016*. Retrieved from https://www.cbs.nl/-/media/_pdf/2016/38/2016-transport-and-mobility.pdf

CBS. (2017). Forecast: 18.4 million inhabitants in 2060. Retrieved May 14, 2019, from https://www.cbs.nl/en-gb/news/2017/51/forecast-18-4-million-inhabitants-in-2060

CBS. (2019). Personenauto's. Retrieved May 14, 2019, from https://www.cbs.nl/nl-nl/maatschappij/verkeer-en-vervoer/transport-en-mobiliteit/infra-vervoermiddelen/vervoermiddelen/categorie-vervoermiddelen/personenauto-s

CBS StatLine. (2017). Prognose bevolking; kerncijfers, 2017-2060. Retrieved May 14, 2019, from https://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83783ned&D1=0,10,12,19-21&D2=0-4&D3=33&HDR=T,G1&STB=G2&CHARTTYPE=1&VW=T

CPB, & PBL. (2015). Cahier mobiliteit; Toekomstverkenning Welvaart en Leefomgeving, 1–82. Retrieved from http://www.wlo2015.nl/wp-content/uploads/PBL_2015_WLO_Mobiliteit_1686.pdf

Cucurachi, S., Van Der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of Emerging Technologies. In *Procedia CIRP*. https://doi.org/10.1016/j.procir.2017.11.005

Demir, M. E., & Dincer, I. (2017). Cost assessment and evaluation of various hydrogen delivery scenarios. *International Journal of Hydrogen Energy*, *43*(22), 10420–10430. https://doi.org/10.1016/j.ijhydene.2017.08.002

Devrim, Y., Erkan, S., Baç, N., & Eroglu, I. (2012). Nafion/titanium silicon oxide nanocomposite membranes for PEM fuel cells. *Interntional Journal of Energy Research*, *33*(4), 435–442. https://doi.org/10.1002/er

DIFFER. (2019). Hydrogen fuel from thin air. Retrieved April 11, 2019, from https://www.differ.nl/news/research_proposal_hydrogen_fuel_from_thin_air_awarded

Dincer, I., & Acar, C. (2017). Innovation in hydrogen production. *International Journal of Hydrogen Energy*, *42*(22), 14843–14864. https://doi.org/10.1016/j.ijhydene.2017.04.107

Duclos, L., Svecova, L., Laforest, V., Mandil, G., & Thivel, P. X. (2016). Process development and optimization for platinum recovery from PEM fuel cell catalyst. *Hydrometallurgy*, *160*, 79–89. https://doi.org/10.1016/j.hydromet.2015.12.013

EC-JRC. (2010). *ILCD Handbook: Framework and Requirements for Life Cycle Impact Assessment Models and Indicators*. *International Reference Life Cycle Data System (ILCD) Handbook*. https://doi.org/10.2788/38719 ecoinvent. (2018). ecoinvent. Retrieved December 16, 2018, from https://www.ecoinvent.org/home.html

energinet, & TenneT. (2018). COBRAcable. Retrieved May 14, 2019, from http://www.cobracable.eu/

ESMAP, & Solargis. (2016). Global Solar Atlas. Retrieved January 31, 2019, from https://globalsolaratlas.info/?c=52.509535,9.272461,7&s=51.917168,4.295654

European Commission. (2019). Renewable energy directive.

European Commission Directorate General Mobility & Transport. (2017). *The transition to a Zero Emission Vehicles fleet for cars in the EU by 2050 Pathways and impacts :* Retrieved from http://www.eafo.eu/sites/default/files/The transition to a ZEV fleet for cars in the EU by 2050 EAFO study November 2017.pdf

Fărcaş, A. C., Sita, V., Dobra, P., & Tîrnovan, R. (2013). Energy efficient design and control for PEM water electrolyzer and hydrogen storage system. *IFAC Proceedings Volumes (IFAC-PapersOnline)*, *2*(PART 1), 32–36. https://doi.org/10.3182/20130522-3-RO-4035.00033

Fitzer, E., Foley, A., Frohs, W., Hauke, T., Heine, M., Jäger, H., & Sitter, S. (2012). Fibers, 15. Carbon Fibers. In *Ullmann's Encyclopedia of Industrial Chemistry* (p. 22).

Franetzki, M. (2008, March 28). Kite power generator. Retrieved March 14, 2018, from https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2008034421

Gahleitner, G. (2013). Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *International Journal of Hydrogen Energy*, *38*(5), 2039–2061. https://doi.org/10.1016/j.ijhydene.2012.12.010

Gemini Wind park. (2018). About Gemini Wind Park. Retrieved May 14, 2019, from https://geminiwindpark.nl/about-gemini-wind-park.html

Ghandehariun, S., & Kumar, A. (2016). Life cycle assessment of wind-based hydrogen production in Western Canada. *International Journal of Hydrogen Energy*, *41*(22), 9696–9704. https://doi.org/10.1016/j.ijhydene.2016.04.077

Gielen, D., & Simbolotti, G. (2005). *Prospects for hydrogen and fuel cells*. OECD/IEA.

Gigler, J., & Weeda, M. (2018). Outlines of a Hydrogen Roadmap. *TKI Nieuw Gas*, 1–105. Retrieved from https://www.topsectorenergie.nl/sites/default/files/uploads/TKI Gas/publicaties/20180514 Roadmap Hydrogen TKI Nieuw Gas May 2018.pdf

Global Wind Energy Council. (2018). *Global Wind Report 2017*. Retrieved from www.gwec.net

Guinée, J. (2001). Handbook on Life Cycle Assessment, part 2A (p. 101). Springer Netherlands. https://doi.org/10.1007/BF02978784

Guinée, J. (2002). *Handbook on Life Cycle Assessment*. Springer Netherlands.

H-TEC, S. (2019a). Ready. Set. Supply. ME 100/350. Germany.

H-TEC, S. (2019b). Ready. Set. Supply. ME 450/1400. Germany.

Heijungs, R., Henriksson, P. J. G., & Guinée, J. B. (2017). Pre-calculated LCI systems with uncertainties cannot be used in comparative LCA. *International Journal of Life Cycle Assessment*, *22*(3), 461. https://doi.org/10.1007/s11367-017-1265-3

Henriksson, P. J. G., Heijungs, R., Dao, H. M., Phan, L. T., De Snoo, G. R., & Guinée, J. B. (2015). Product carbon footprints and their uncertainties in comparative decision contexts. *PLoS ONE*, *10*(3), 1–11. https://doi.org/10.1371/journal.pone.0121221

Höjer, M., Ahlroth, S., Dreborg, K. H., Ekvall, T., Finnveden, G., Hjelm, O., … Palm, V. (2008). Scenarios in selected tools for environmental systems analysis. *Journal of Cleaner Production*, *16*(18), 1958–1970. https://doi.org/10.1016/j.jclepro.2008.01.008

Honkoop, H. P. (2017). *Life Cycle Assessment of selected future applications of Photo electrochemical water splitting*. Leiden University/ TU Delft.

Huang, Y. F., Gan, X. J., & Chiueh, P. Te. (2017). Life cycle assessment and net energy analysis of offshore wind power systems. *Renewable Energy*, *102*, 98–106. https://doi.org/10.1016/j.renene.2016.10.050

Hussain, M. M., & Dincer, I. (2005). Life Cycle Assessment of Hydrogen Fuel Cell and Gasoline Vehicles. *Electric and Hybrid Vehicles*, *31*, 275–286. https://doi.org/10.1016/B978-0-444-53565-8.00011-7

HyBalance. (2018). HyBalance – Green Energy Project Denmark. Retrieved November 4, 2018, from http://hybalance.eu/

Hydrogen Council. (2017). *How hydrogen empowers the energy transition*.

Hydrogenics. (2018a). Energy Transition calls for 100 % renewable energy systems.

Hydrogenics. (2018b). OnSite Hydrogen Generation HyLYZER ® PEM Electrolysis Technology. Europe. Retrieved from www.hydrogenics.com

HyTechCycling. (2016). New recycling and dismantling technologies. Retrieved May 24, 2019, from http://hytechcycling.eu/

IPCC. (2014). *Climate Change 2014: Mitigation of Climate Change*. *Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/CBO9781107415416

Janssen, A. (2017). *De rol van Rotterdam in de waterstof-economie*. Retrieved from https://www.portofrotterdam.com/en/news-and-press-releases/joining-forces-for-a-biorefinery-in-rotterdam

John, P., Henriksson, G., Guinée, J. B., & Heijungs, R. (2014). A protocol for horizontal averaging of unit process data — including estimates for uncertainty. *International Journal of Life Cycle Assessment*, 429–436. https://doi.org/10.1007/s11367-013-0647-4

Kennisinstituut voor Mobiliteitsbeleid. (2018). Kerncijfers Mobiliteit 2018 | Mobiliteitsbeeld en Kerncijfers Mobiliteit 2018. Retrieved May 14, 2019, from https://www.kimnet.nl/mobiliteitsbeeld/kerncijfers-mobiliteit-2018

Koj, J. C., Wulf, C., Schreiber, A., & Zapp, P. (2017). Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. https://doi.org/10.3390/en10070860

Koroneos, C., Dompros, A., Roumbas, G., & Moussiopoulos, N. (2014). Life cycle assessment of hydrogen fuel production processes. *International Journal of Hydrogen Energy*, *29*(14), 1443–1450. https://doi.org/10.1016/j.ijhydene.2004.01.016

Küçükkaya, E. (2019). 23.Dünya Hidrojen Enerjisi Kongresi İstanbul'da Düzenlenecek! Retrieved August 8, 2019, from https://www.enerjiportali.com/23-dunya-hidrojen-enerjisi-kongresi-istanbulda-duzenlenecek/

Laforest, V., Mandil, G., Svecova, L., Thivel, P.-X., Lupsea, M., & Duclos, L. (2016). Environmental assessment of proton exchange membrane fuel cell platinum catalyst recycling. *Journal of Cleaner Production*, *142*, 2618–2628. https://doi.org/10.1016/j.jclepro.2016.10.197

Lee, C. H., Lee, Y. B., Kim, K. M., Jeong, M. G., & Lim, D. S. (2013). Electrically conductive polymer composite coating on aluminum for PEM fuel cells bipolar plate. *Renewable Energy*, *54*, 46–50. https://doi.org/10.1016/j.renene.2012.08.071

Lee, J. Y., Rao, S. V., Kumar, B. N., Kang, D. J., & Reddy, B. R. (2010). Nickel recovery from spent Raneynickel catalyst through dilute sulfuric acid leaching and soda ash precipitation. *Journal of Hazardous Materials*, *176*(1–3), 1122–1125. https://doi.org/10.1016/j.jhazmat.2009.11.137

Lesage, P., Mutel, C., Schenker, U., & Margni, M. (2019). Are there infinitely many trucks in the technosphere, or exactly one? How independent sampling of instances of unit processes affects uncertainty analysis in LCA. *International Journal of Life Cycle Assessment*, *24*(2), 338–350. https://doi.org/10.1007/s11367-018-1519-8

Lopes, T., Paganin, V. A., & Gonzalez, E. R. (2011). Hydrogen sulfide tolerance of palladium-copper catalysts for PEM fuel cell anode applications. *International Journal of Hydrogen Energy*, *36*(21), 13703–13707. https://doi.org/10.1016/j.ijhydene.2011.07.126

Lotrič A., Stropnik R., Mori M., Drobnič B., Jurjevčič B., & Sekavčnik M. (2017). *D2.1 Assessment of critical materials and components in FCH technologies: New technologies and strategies for fuel cells and Hydrogen Technologies in the phase of recycling and dismantling*. Retrieved from http://hytechcycling.eu/wp-content/uploads/D2.1-Identification-of-critical-materials.pdf%0Ahttp://hytechcycling.eu/wp-content/uploads/D2.4-Recommendation-and-perspective-on-EU-regulatory-framework.pdf%0Ahttp://hytechcycling.eu/wp-content/uploads/D2.5-Stud

Ludwig-Bölkow-Systemtechnik GmbH. (2018). Wasserstoff Daten - Hydrogen Data. Retrieved April 5, 2019, from http://www.h2data.de/

Marčeta Kaninski, M. P., Seović, M. M., Miulović, S. M., Žugić, D. L., Tasić, G. S., & Šaponjić, D. P. (2013). Cobalt-chrome activation of the nickel electrodes for the HER in alkaline water electrolysis-Part II. *International Journal of Hydrogen Energy*, *38*(4), 1758–1764. https://doi.org/10.1016/j.ijhydene.2012.11.117

Mawdsley, J. R., Carter, J. D., Wang, X., Niyogi, S., Fan, C. Q., Koc, R., & Osterhout, G. (2013). Composite-coated aluminum bipolar plates for PEM fuel cells. *Journal of Power Sources*, *231*, 106–112. https://doi.org/10.1016/j.jpowsour.2012.12.074

McPhy. (2017). Electrolyzers for continuous and automated hydrogen production, and/or of large quantity. Retrieved April 24, 2019, from https://mcphy.com/en/our-products-and-solutions/electrolyzers/large-capacity/

Meier, K. (2014). Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials: Techno-economic assessment for an offshore-based hydrogen production approach with state-of-the-art technology. *International Journal of Energy and Environmental Engineering*, *5*(2–3), 1–12. https://doi.org/10.1007/s40095-014-0104-6

Miller, S. A., & Keoleian, G. A. (2015). Framework for analyzing transformative technologies in life cycle assessment. *Environmental Science and Technology*, *49*(5), 3067–3075. https://doi.org/10.1021/es505217a

Miquel, J. M. B., Munoz, C. A., Sanchez, I. B., Desclaux, D. F., & Saenz, F. J. S. (2018). *US2018/0148356A1*. USA.

Morales, L. C. (2009). *Using Backcasting to evaluate Carbon-Free Hydrogen and Battery Electric*

Transport Scenarios in the Netherlands Using Backcasting to evaluate Carbon-Free Hydrogen and Battery Electric Transport Scenarios in the Netherlands. TU Delft/Leiden University.

Mori, M., Jensterle, M., Mržljak, T., & Drobnič, B. (2014). Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy. *International Journal of Life Cycle Assessment*, *19*(11), 1810–1822. https://doi.org/10.1007/s11367-014-0790-6

Nel Hydrogen. (2016). *Nel Hydrogen Electrolyser: The world's most efficient and reliable electrolyser*. Retrieved from https://nelhydrogen.com/assets/uploads/2017/01/Nel_Electrolyser_brochure.pdf

Nel Hydrogen. (2019). Atmospheric Alkaline Electrolyser. Retrieved April 24, 2019, from https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, *67*, 597–611. https://doi.org/10.1016/j.rser.2016.09.044

Noack, C., Burggraf, F., Hosseiny, S. S., Lettenmeier, P., Kolb, S., Belz, S., … Schneider, G.-S. (2015). Studie über die Planung einer Demonstrationsanlage zur Wasserstoff-Kraftstoffgewinnung durch Elektrolyse mit Zwischenspeicherung in Salzkavernen unter Druck. *BMWi*, 298.

Noi, C. Di, Ciroth, A., & Srocka, M. (2017). *openLCA 1.7, Comprehensive User Manual*.

Nouryon. (2018a). AkzoNobel and Gasunie looking to convert water into green hydrogen using sustainable electricity. Retrieved April 10, 2019, from https://www.nouryon.com/news-and-events/news-overview/2018/jan/akzonobel-gasunie-looking-convert-water-into-green-hydrogen-using-sustainable-electricity/

Nouryon. (2018b). Nouryon, Tata Steel, and Port of Amsterdam partner to develop the largest green hydrogen cluster in Europe. Retrieved April 10, 2019, from https://www.nouryon.com/news-and-events/news-overview/2018/oct/Nouryon-Tata-Steel-and-Port-of-Amsterdam-partner-to-develop-the-largest-green-hydrogen-cluster-in-Europe/

ODYSSEE-MURE. (2019). Change in distance travelled by car. Retrieved May 14, 2019, from http://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html

Ørsted. (2018). Borssele 1&2. Retrieved May 14, 2019, from https://orsted.nl/nl/Onze-windparken/Borssele-1-and-2-EN

Ørsted. (2019). Orsted participates in tender for Holland Coast South 3-4 offshore wind farm. Retrieved April 10, 2019, from https://orsted.com/en/Media/Newsroom/News/2019/03/Orsted-participates-in-tender-for-Holland-Coast-South-3-4-offshore-wind-farm

Parks, G., Boyd, R., Cornish, J., & Remick, R. (2014). *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration*. https://doi.org/10.2172/1130621

Patterson, T., Esteves, S., Carr, S., Zhang, F., Reed, J., Maddy, J., & Guwy, A. (2014). Life cycle assessment of the electrolytic production and utilization of low carbon hydrogen vehicle fuel. *International Journal of Hydrogen Energy*, *39*(14), 7190–7201. https://doi.org/10.1016/j.ijhydene.2014.02.044

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, *31*(1), 55–71. https://doi.org/10.1016/j.renene.2005.03.002

Poggi-varaldo, H. M., & Romero-casta, T. (2017). Harvesting energy from leachates in microbial fuel cells using an anion exchange membrane, *2*, 0–8. https://doi.org/10.1016/j.ijhydene.2017.08.201

PopulationPyramid.net. (2017). Population of Netherlands 2050. Retrieved May 14, 2019, from https://www.populationpyramid.net/netherlands/2050/

Port of Rotterdam. (2019). Kick-off for designing a gigawatt electrolysis plant. Retrieved from https://www.portofrotterdam.com/en/news-and-press-releases/kick-off-for-designing-a-gigawatt-electrolysis-plant

Ravikumar, D., Sinha, P., Seager, T. P., & Fraser, M. P. (2015). An anticipatory approach to quantify energetics of recycling CdTe photovoltaic systems. *Progress in Photovoltaics: Research and Applications*, (24), 2–6. https://doi.org/10.1002/pip

Reddi, K., Elgowainy, A., Rustagi, N., & Gupta, E. (2017). Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen. *International Journal of Hydrogen Energy*, *42*(34), 21855–21865. https://doi.org/10.1016/j.ijhydene.2017.05.122

Rijnsburger, A. M. (2016). *Assessing the environmental impacts of emerging technologies*.

Ritchey, T. (2011a). Modeling Alternative Futures with General Morphological Analysis. *Wicked Problems – Social Messes*, 7–18. https://doi.org/10.1007/978-3-642-19653-9_2

Ritchey, T. (2011b). *Wicked Problems - Social messes decision support modelling with Morphological Analysis* (Hardcover). https://doi.org/10.1007/978-3-642-19653-9

Sapountzi, F. M., Gracia, J. M., Weststrate, C. J. (Kee. J., Fredriksson, H. O. A., & Niemantsverdriet, J. W. (Hans. (2017). Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Progress in Energy and Combustion Science*, *58*, 1–35. https://doi.org/10.1016/j.pecs.2016.09.001

Schmidt, X. C., Topriska, E., Kolokotroni, M., & Azapagic, A. (2018). Environmental sustainability of renewable hydrogen in comparison with conventional cooking fuels. *Journal of Cleaner Production*, *196*, 863–879. https://doi.org/10.1016/j.jclepro.2018.06.033

Senthil Velan, V., Velayutham, G., Hebalkar, N., & Dhathathreyan, K. S. (2011). Effect of SiO2 additives on the PEM fuel cell electrode performance. *International Journal of Hydrogen Energy*, *36*(22), 14815–14822. https://doi.org/10.1016/j.ijhydene.2011.03.041

Sibum, H., Güther, V., Roidl, O., Habashi, F., Uwe Wolf, H., & Siemers, C. (2000). Titanium, Titanium alloys and Titanium compounds. In *Ullmann's Encyclopedia of Industrial Chemistry* (p. 35). https://doi.org/10.1016/0016-0032(54)90914-x

Singh, S., Jain, S., Ps, V., Tiwari, A. K., Nouni, M. R., Pandey, J. K., & Goel, S. (2015). Hydrogen: A sustainable fuel for future of the transport sector. *Renewable and Sustainable Energy Reviews*, *51*, 623–633. https://doi.org/10.1016/j.rser.2015.06.040

Smolinka, T., Wiebe, N., Sterchele, P., Palzer, A., Lehner, F., Jansen, M., … Zimmermann, F. (2018). *Industrialisierung der Wasser elektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme*.

Spath, P. L., & Mann, M. K. (2004). Life Cycle Assessment of Renewable Hydrogen Production via Wind / Electrolysis. *National Renewable Energy Laboratory*, (February).

Spielmann, M., Scholz, R. W., Tietje, O., & Haan, P. de. (2005). Scenario Modelling in Prospective LCA of Transport Systems. *International Journal of Life Cycle Assessment*, *10*(5), 325–335. https://doi.org/10.1065/lca2004.10.188

Statista. (2019a). Netherlands: number of inhabitants, by province 2018. Retrieved June 20, 2019, from https://www.statista.com/statistics/753196/total-number-of-inhabitants-in-the-netherlands-by-province/

Statista. (2019b). Netherlands: total population 1950-2018. Retrieved June 24, 2019, from https://www.statista.com/statistics/519720/total-population-of-the-netherlands/

Sutton, A. (2016). *Nafion : properties, structure and applications*. Retrieved from https://catalogue.leidenuniv.nl/primo-explore/fulldisplay?docid=UBL_ALMA51318446110002711&context=L&vid=UBL_V1&lang=en_US&search_scope=All_Content&adaptor=Local Search Engine&tab=all_content&query=any,contains,Nafion&sortby=rank&offset=0

TenneT. (2017). Gasunie to join North Sea Wind Power Hub consortium. Retrieved May 9, 2019, from https://www.tennet.eu/news/detail/gasunie-to-join-north-sea-wind-power-hub-consortium/

TenneT. (2019). NorNed. Retrieved May 14, 2019, from https://www.tennet.eu/our-grid/international-connections/norned/

TenneT, & Gasunie. (2019). *Infrastructure Outlook 2050*.

The Physics Factbook. (2005). Energy Density of Hydrogen. Retrieved May 14, 2019, from https://hypertextbook.com/facts/2005/MichelleFung.shtml

Thomas, D., Mertens, D., Meeus, M., Van der Laak, W., & Francois, I. (2016). *Power-to-Gas Roadmap for Flanders*.

Thomas, Denis. (2016). *Alkaline vs PEM electrolysers: lessons learnt from Falkenhagen and WindGas Hamburg*. Retrieved from http://www.hydrogendays.cz/2016/admin/scripts/source/presentations/PL 05_ Denis Thomas_HDs2016.pdf

tools4dev. (2014). How to do semi- structured interviews.

TopGear Nederland. (2019). Hoeveel auto's rijden er in Nederland? Retrieved May 14, 2019, from https://topgear.nl/autonieuws/hoeveel-autos-rijden-er-in-nederland-cijfers-2019/

Topriska, E., Kolokotroni, M., Dehouche, Z., Novieto, D. T., & Wilson, E. A. (2016). The potential to generate solar hydrogen for cooking applications : Case studies of Ghana , Jamaica and Indonesia, *95*. https://doi.org/10.1016/j.renene.2016.04.060

Topriska, E., Kolokotroni, M., Dehouche, Z., & Wilson, E. (2015). Solar hydrogen system for cooking applications: Experimental andnumerical study. *Renewable Energy*, *83*, 717–728. https://doi.org/10.1016/j.renene.2015.05.011

Treyer, K., & Ruiz, E. M. (2014). *market for electricity, high voltage - NL - Ecoinvent 3.5 dataset documentation*.

Tymoczko, J., Calle-Vallejo, F., Schuhmann, W., & Bandarenka, A. S. (2016). Making the hydrogen evolution reaction in polymer electrolyte membrane electrolysers even faster. *Nature Communications*, *7*, 1–6. https://doi.org/10.1038/ncomms10990

U.S. National Library of Medicine. (2019). PubChem. Retrieved May 27, 2019, from https://pubchem.ncbi.nlm.nih.gov/

UNFCCC. (2015). *Convention on Climate Change: Climate Agreement of Paris.* Paris. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Valente, A., Martin-Gamboa, M., Iribarren, D., & Dufour, J. (2017). *D2.2 Existing end-of-life* *technologies applicable to FCH products*. Retrieved from http://hytechcycling.eu/wp-content/uploads/D2.2-EoL-technologies.pdf

Van Den Ende, J., Mulder, K., Knot, M., Moors, E., & Vergragt, P. (1998). Traditional and Modern Technology Assessment: Toward a Toolkit. *Technological Forecasting and Social Change*, *58*(1–2), 5–21. https://doi.org/10.1016/s0040-1625(97)00052-8

Van der Bruggen, B. (2009). *LCA study of demineralised water production in power plants*. KU Leuven.

van Wijk, A. (2017). *The Green Hydrogen Economy in the Northern Netherlands*. Groningen.

van Wijk, A., van der Roest, E., & Boere, J. (2017). *Solar power to the people (NL)*. *Allied Waters* (Colophon). IOS Press BV. https://doi.org/10.3233/978-1-61499-832-7-i

van Wijk, A., van Rhee, G., Reijerkerk, J., Hellinga, C., & Lucas, H. (2019). *Naar een groene waterstofeconomie in Zuid-Holland, een visie voor 2030*.

Vincent, I., & Bessarabov, D. (2018). Low cost hydrogen production by anion exchange membrane electrolysis: A review. *Renewable and Sustainable Energy Reviews*, *81*(May 2017), 1690–1704. https://doi.org/10.1016/j.rser.2017.05.258

VoltaChem. (2014). VoltaChem. Retrieved March 19, 2019, from https://voltachem.com/

Wang, Y., & Northwood, D. O. (2009). The development of bipolar plate materials for polymer electrolyte membrane fuel cells (PEMFC). In R. Esposito & A. Conti (Eds.), *Polymer electrolyte membrane fuel cells and electrocatalysts* (p. 30).

Weber, S., Peters, J. F., Baumann, M., & Weil, M. (2018). Life Cycle Assessment of a Vanadium Redox Flow Battery. *Environmental Science & Technology*, *52*, 10864–10873. research-article. https://doi.org/10.1021/acs.est.8b02073

Weinzettel, J., Reenaas, M., Solli, C., & Hertwich, E. G. (2009). Life cycle assessment of a floating offshore wind turbine. *Renewable Energy*, *34*(3), 742–747. https://doi.org/10.1016/j.renene.2008.04.004

Wender, B. (2016). *Developing Anticipatory Life Cycle Assessment Tools to Support Responsible Innovation*. Arizona State University. Retrieved from http://search.proquest.com/openview/3caa5e4f5a10e025dd209d91a6b9a2ba/1?pq-origsite=gscholar&cbl=18750&diss=y

Wernet, G. (2018). *Ecoinvent 3.5 dataset documentation, water production, deionised, from tap water, at user Europe without Switzerland Dataset*.

World Bank Group, ESMAP, DTU, & Vortex. (2018). Global Wind Atlas. Retrieved January 31, 2019, from https://globalwindatlas.info/area/Netherlands

World population review. (2019). Netherlands Population 2019 (Demographics, Maps, Graphs). Retrieved May 14, 2019, from http://worldpopulationreview.com/countries/netherlands-population/

Worldometers. (2019). Netherlands Population (2019). Retrieved May 14, 2019, from https://www.worldometers.info/world-population/netherlands-population/

Wulf, C., & Kaltschmitt, M. (2018). Hydrogen supply chains for mobility-Environmental and economic assessment. *Sustainability (Switzerland)*, *10*(6), 1–26. https://doi.org/10.3390/su10061699

Wulf, C., Reuß, M., Grube, T., Zapp, P., Robinius, M., Hake, J. F., & Stolten, D. (2018). Life Cycle Assessment of hydrogen transport and distribution options. *Journal of Cleaner Production*, *199*, 431–443. https://doi.org/10.1016/j.jclepro.2018.07.180

Zeng, K., & Zhang, D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress in Energy and Combustion Science*, *36*(3), 307–326. https://doi.org/10.1016/j.pecs.2009.11.002

Zorn, T. (2008). *Designing and conducting semi-structured interviews for research*. *Waikato Management School, Waikato*. https://doi.org/M412165200 [pii]\r10.1074/jbc.M412165200

Zulehner, W., Neuer, B., & Rau, G. (2000). Silicon. In *Ullmann's Encyclopedia of Industrial Chemistry* (p. 30). https://doi.org/10.1002/14356007.a23

Appendix

Below are presented all the different appendices that were mentioned in the thesis or that can be relevant for some topics.

1) Hydrogen chemical characteristic

Some fundamental hydrogen's chemical characteristics are communicated in this section.

Weight	Volume at STP [a]	Energy Content	Equivalent volume of gasoline [b]
0.09 g	0.001 Nm^3 (1 litre)	0.00351 kWh	0.0003 litres
0.09 kg	1 Nm^3	3.54 kWh	0.36 litres
1 kg	11.13 Nm^3	39.4 kWh	4 litres

[a] STP = Standard temperature and pressure (0°C and 1atm)

[b] Gasoline equivalent calculated using SHEC labs fuel energy equivalence calculator [19]

Mass Flow Rate		Volumetric Flow Rate	
41.7 g/h	1 kg/day	0.46 Nm^3/h	11.13 Nm^3/day
1 kg/h	24 kg/day	11.13 Nm^3/h	267.12 Nm^3/day
41.7 kg/h	1 t/day	464.12 Nm^3/h	11,130 Nm^3/day
1 t/h	24 t/day	11,130 Nm^3/h	267,120 Nm^3/day

Figure 45. Conversion factors between hydrogen quantities (upper part) and hydrogen flow rates (lower part) (extracted from Bertuccioli et al. (2014, p.52))

Different resources give an average energy density of hydrogen at 140 MJ/kg with the higher heating value (Ludwig-Bölkow-Systemtechnik GmbH, 2018; Singh et al., 2015; The Physics Factbook, 2005; van Wijk et al., 2019).

2) Data inventories for the Pilot-scale LCA models

The electronic file attached ("Appendix, Life Cycle Inventories, Pilot-scale and ex-ante large-scale LCA models") to the thesis describes the materials and energy flows from the pilot-scale LCA models and the adjustments that were applied in the ex-ante large-scale LCA models.

The tables below provide an overview of the purpose and use of each flow that is defined in the pilot-scale LCAs (AE NL 2017, AE NL 2018, PEM NL 2018a and PEM NL 2018b). The goal here is to clearly understand the reason for each flow's consumption.

Table 28. Description of the materials/energy consumption in the pilot-scale model AE NL 2017.

Model	**AE NL 2017** (Koj et al., 2017)			
Level of unit process	*Materials*	*Origin/purpose*	*Value*	*Unit*
	Constructing materials (per AEL - 6 MW)			
Cell stack framework	Copper	Manufacture of the cell stack framework (Koj et al., 2017)	0.33	kg/kW
	Unalloyed steel	Constituent of the framework (Koj et al., 2017)	33.33	kg/kW
Cell	Nickel	Raney Nickel cathodes (Koj et al., 2017)	3.17	kg/kW
	Aluminium	Constituent of the Raney Nickel cathodes (Koj et al., 2017)	0.075	kg/kW

	Calendered rigid plastic	Plastic cell frames or used for the anode/cathode as a catalyst layer or as a sealant "Anodes and cathodes materials (Koj et al., 2017; Valente et al., 2017)	0.13	kg/kW
	Polytetrafluoroethylene	Used as gasket material/diaphragm (Koj et al., 2017; Valente et al., 2017)	0.013	kg/kW
	Acrylonitrile butadiene styrene	constituents for gasket manufacturing (Koj et al., 2017)	0.0267	kg/kW
	Polyphenylene sulfide	Membrane production (Koj et al., 2017)	0.0567	kg/kW
	Polysulfones	Membrane production (Koj et al., 2017)	0.0433	kg/kW
	N-Methyl-2-pyrrolidone	Membrane production (Koj et al., 2017)	0.217	kg/kW
	Aniline	Input for aramid fibres (necessary for gasket manufacturing) (Koj et al., 2017)	0.0081	kg/kW
	Acetic anhydride	Input for aramid fibres (necessary for gasket manufacturing) (Koj et al., 2017)	0.009	kg/kW
	Terephthalic acid	Input for aramid fibres (necessary for gasket manufacturing) (Koj et al., 2017)	0.0147	kg/kW
	Nitric acid	Input for aramid fibres (necessary for gasket manufacturing) (Koj et al., 2017)	0.0055	kg/kW
	Hydrochloric acid	Input for aramid fibres (necessary for gasket manufacturing) (Koj et al., 2017)	0.0217	kg/kW
	Graphite	constituents for gasket manufacturing (Koj et al., 2017)	0.0717	kg/kW
	Lubricating oil	constituents for gasket manufacturing (Koj et al., 2017)	8.00E-05	kg/kW
	Zirconium oxide	Membrane production (Koj et al., 2017)	0.183	kg/kW
	Carbon monoxide	Manufacturing of Nickel Raney cathodes (Koj et al., 2017)	0.025	kg/kW
	Decarbonized water	Likely used as cooling water (Koj et al., 2017)	1.83	kg/kW
	Deionized water	Likely used as cooling water (Koj et al., 2017)	14.33	kg/kW
	Electricity	Need for the construction phase (Koj et al., 2017)	6	MJ/kg
	Heat	Likely for heat exchanger (BOP) (Koj et al., 2017)	14.67	MJ/kg
	Steam	Unclear role, likely for BOP element (Koj et al., 2017)	0.117	MJ/kg
	Industrial machine production	Construction phase (Koj et al., 2017)	2.67E-05	kg/kW
	Plaster mixing	Construction phase (Koj et al., 2017)	0.13	kg/kW
	Operation—per Functional Unit			
	Electricity	Reactant (Koj et al., 2017)	180	MJ/kg of H2
	Deionized water	Reactant (Koj et al., 2017)	10	kg/kg of H2
	Nitrogen	Cleaning purposes (Koj et al., 2017)	0.29	g/kg of H2
	Potassium hydroxide	electrolyte (Koj et al., 2017; Valente et al., 2017)	1.9	g/kg of H2
	Steam	Used during the run-up to heat up the system (Koj et al., 2017)	0.11	kg/kg of H2

Table 29. Description of the materials/energy consumption in the pilot-scale model AE NL 2018.

Model	**AE NL 2018** (Wulf & Kaltschmitt, 2018)		
Materials	*Origin/purpose*	*Value*	*Unit*
Constructing materials (per AEL – 1.23 MW)			
Steel, low alloy	Constituent of the framework (Koj et al., 2017)	10.49	kg/kW
Aluminium	Constituent of the Raney Nickel cathodes (Koj et al., 2017)	0.0512	kg/kW
Chrome	Catalyst for the electrodes (Marčeta Kaninski et al., 2013)	0.163	kg/kW
Nickel	Raney Nickel cathodes (Koj et al., 2017)	0.163	kg/kW
Polyethylene granulate	Can be used as a diaphragm or a sealant (Valente et al., 2017)	0.0407	kg/kW
Operation—per Functional Unit			
Electricity	Reactant (Wulf & Kaltschmitt, 2018)	49	kWh/kg of H2
Water	Reactant (Wulf & Kaltschmitt, 2018)	19	kg/kg of H2
Potassium hydroxide	Electrolyte (Wulf & Kaltschmitt, 2018)	0.85	g/kg of H2

Table 30. Description of the materials/energy consumption in the pilot-scale model PEM NL 2018a.

Model	**PEM NL 2018a** (Wulf & Kaltschmitt, 2018)		
Materials	*Origin/purpose*	*Value*	*Unit*
Constructing materials (per AEL – 2.3 MW)			
Steel, low alloy	Constituent of the framework (Koj et al., 2017; Valente et al., 2017)	15.86	kg/kW
Reinforcing steel	Constituent of the framework (Koj et al., 2017; Valente et al., 2017)	0.705	kg/kW
Aluminium	Composite coating for bipolar plates (C. H. Lee, Lee, Kim, Jeong, & Lim, 2013; Mawdsley et al., 2013)	0.233	kg/kW
Platinum-group metals	Anodes and cathodes materials (catalyst layers) (Valente et al., 2017)	1.01E-04	kg/kW
Graphite	Composite coating for bipolar plates (Mawdsley et al., 2013; Wang & Northwood, 2009)or gas diffusion layer level at the cathode side (Valente et al., 2017)	9.25E-04	kg/kW
Titan	Gas diffusion layer (anode and cathode) (Valente et al., 2017)	3.35E-04	kg/kW
Nafion	Membrane, electrolyte (Valente et al., 2017)	2.56E-03	kg/kW
Solvent	Solvent needed but no more information provided/found	4.85E-04	kg/kW
Cast iron	Personal assumption: supporting structure? Frame?	1.15E-01	kg/kW
Copper	Electrodes coating or catalyst (Lopes, Paganin, & Gonzalez, 2011; Tymoczko, Calle-Vallejo, Schuhmann, & Bandarenka, 2016)	2.86E-04	kg/kW
Silicon	Added to improve the performance at the catalyst layer or the membrane or used as a gas diffusion layer (Devrim, Erkan, Baç, & Eroglu, 2012; Senthil Velan, Velayutham, Hebalkar, & Dhathathreyan, 2011)	5.73E-04	kg/kW
Operation—per Functional Unit			
Electricity	Reactant (Wulf & Kaltschmitt, 2018)	50	kWh/kg of H2
Water	Reactant (Wulf & Kaltschmitt, 2018)	19	kg/kg of H2

Table 31. Description of the materials/energy consumption in the pilot-scale model PEM NL 2018b.

Model	**PEM NL 2018b** (Schmidt et al., 2018)		
Materials	*Origin/purpose*	*Value*	*Unit*
Constructing materials (per AEL – 11.4 kW)			
Perfluorosulfonyl fluoride	Proxy for the Nafion membrane/electrolyte (Schmidt et al., 2018)	9.49E-05	kg/kW
Iridium dioxide (IrO2)	Anodes and cathodes materials (catalyst layers) (Schmidt et al., 2018; Valente et al., 2017)	1.61E-05	kg/kW
Platine	Cathode/Anodes and cathodes materials (catalyst layers) (Schmidt et al., 2018; Valente et al., 2017)	6.05E-06	kg/kW
Graphite (81%), vinyl ester (19%)	Bipolar plate (Schmidt et al., 2018)	3.77E-03	kg/kW
Titanium	Gas diffusion layer (anode and cathode) (Schmidt et al., 2018; Valente et al., 2017)	2.25E-04	kg/kW
Woven carbon fibre (70%)	Cathode gas layer diffusor (Schmidt et al., 2018)	2.25E-04	kg/kW
Rubber (frame seal)	Frame seal/ sealant (Schmidt et al., 2018; Valente et al., 2017)	8.07E-05	kg/kW
Rubber (gasket)	Gasket (Schmidt et al., 2018)	1.71E-05	kg/kW
Operation—per Functional Unit			
Electricity	Reactant (Schmidt et al., 2018)		
Water	Reactant (Schmidt et al., 2018)		

3) Tables for the different contribution analyses

The tables in this section provide more details on the contribution analyses. Each foreground processes as shown in the flowcharts from sections 3.2.2 and 6.2.3 possess at least one flow for description. Apart from that, all the contributions lower than 1% were deleted.

Table 32. Contribution analysis for AE NL 2017 (based on Koj, Wulf, Schreiber, & Zapp) for the different impact categories from ILCD-2011 baseline.

Impact category		**Process**	**Amount**	**Unit**
Acidification				
100.00%		Hydrogen production, AE NL 2017, wind	0.00870	molc H+ eq
	61.48%	Operating resources, AE NL 2017, wind	0.00535	molc H+ eq
		58.95% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.50% comes from the market for steam, in the chemical industry		
	36.86%	Cells, AE NL 2017	0.00321	molc H+ eq
		36.78% comes from the market for nickel, 99.5%		
	01.65%	Cell stack framework, AE NL 2017	0.00014	molc H+ eq
		01.16% comes from the market for steel, unalloyed		
Climate change				
100.00%		Hydrogen production, AE NL 2017, wind	0.83950	kg CO2 eq
	96.03%	Operating resources, AE NL 2017, wind	0.80621	kg CO2 eq
		90.22% comes from electricity production, wind, 1-3MW turbine, offshore		
		04.14% comes from the market for steam, in the chemical industry		
		01.14% comes from the market for water, deionised, from tap water, at the user		

	02.43%	Cell stack framework, AE NL 2017	0.02043	kg CO2 eq
		02.38% comes from the market for steel, unalloyed		
	01.53%	Cells, AE NL 2017	0.01286	kg CO2 eq
		01.29% comes from the market for nickel, 99.5%		
Freshwater ecotoxicity				
100.00%		Hydrogen production, AE NL 2017, wind	52.56360	CTUe
	96.69%	Operating resources, AE NL 2017, wind	50.82130	CTUe
		96.28% comes from electricity production, wind, 1-3MW turbine, offshore		
	02.45%	Cells, AE NL 2017	1.28728	CTUe
		02.37% comes from the market for nickel, 99.5%		
	00.87%	Cell stack framework, AE NL 2017	0.45501	CTUe
		00.64% comes from the market for copper		
Freshwater eutrophication				
100.00%		Hydrogen production, AE NL 2017, wind	0.00058	kg P eq
	91.64%	Operating resources, AE NL 2017, wind	0.00053	kg P eq
		89.35% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.25% comes from the market for water, deionised, from tap water, at the user		
	05.33%	Cells, AE NL 2017	3.09018E-5	kg P eq
		05.23% comes from a market for nickel, 99.5%		
	03.03%	Cell stack framework, AE NL 2017	1.75871E-5	kg P eq
		01.59% comes from the market for steel, unalloyed		
		01.45% comes from the market for copper		
Human toxicity, cancer effects				
100.00%		Hydrogen production, AE NL 2017, wind	3.858512-7	CTUh
	98.11%	Operating resources, AE NL 2017, wind	3.78550E-7	CTUh
		97.29% comes from electricity production, wind, 1-3MW turbine, offshore		
	01.28%	Cell stack framework, AE NL 2017	4.92486E-9	CTUh
		01.14% comes from the market for steel, unalloyed		
	00.62%	Cells, AE NL 2017	2.37734E-9	CTUh
		00.59% comes from the market for nickel, 99.5%		
Human toxicity, non-cancer effects				
100.00%		Hydrogen production, AE NL 2017, wind	9.52217E-7	CTUh
	92.84%	Operating resources, AE NL 2017, wind	8.84025E-7	CTUh
		91.81% comes from electricity production, wind, 1-3MW turbine, offshore		
	05.06%	Cells, AE NL 2017	4.81778E-8	CTUh
		05.02% comes from the market for nickel, 99.5%		
	02.10%	Cell stack framework, AE NL 2017	2.00142E-8	CTUh
		01.67% comes from the market for copper		
Ionizing radiation E (interim)				
100.00%		Hydrogen production, AE NL 2017, wind	1.62667E-7	CTUe

	96.54%	Operating resources, AE NL 2017, wind	1.57043E-7	CTUe
		87.45% comes from electricity production, wind, 1-3MW turbine, offshore		
		04.72% comes from the market for water, deionised, from tap water, at the user		
		03.41% comes from the market for steam, in the chemical industry		
	02.06%	Cells, AE NL 2017	3.34617E-9	CTUe
		01.85% comes from the market for nickel, 99.5%		
	01.41%	Cell stack framework, AE NL 2017	2.28783E-9	CTUe
		01.33% comes from the market for steel, unalloyed		
Ionizing radiation HH				
100.00%		Hydrogen production, AE NL 2017, wind	0.04323	kBq U235 eq
	96.66%	Operating resources, AE NL 2017, wind	0.04178	kBq U235 eq
		85.91% comes from electricity production, wind, 1-3MW turbine, offshore		
		07.18% comes from the market for water, deionised, from tap water, at the user		
		02.47% comes from the market for steam, in the chemical industry		
		01.01% comes from the market for potassium hydroxide		
	02.11%	Cells, AE NL 2017	0.00091	kBq U235 eq
		01.88% comes from the market for nickel, 99.5%		
	01.24%	Cell stack framework, AE NL 2017	0.00054	kBq U235 eq
		01.16% comes from the market for steel, unalloyed		
Land use				
100.00%		Hydrogen production, AE NL 2017, wind	1.28928	kg C deficit
	95.42%	Operating resources, AE NL 2017, wind	1.23018	kg C deficit
		91.13% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.76% comes from the market for steam, in the chemical industry		
		01.05% comes from the market for water, deionised, from tap water, at the user		
	02.59%	Cells, AE NL 2017	0.03343	kg C deficit
		02.44% comes from the market for nickel, 99.5%		
	01.99%	Cell stack framework, AE NL 2017	0.02567	kg C deficit
		01.83% comes from the market for steel, unalloyed		
Marine eutrophication				
100.00%		Hydrogen production, AE NL 2017, wind	0.00103	kg N eq
	95.42%	Operating resources, AE NL 2017, wind	0.00098	kg N eq
		92.46% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.61% comes from the market for steam, in the chemical industry		
	02.52%	Cells, AE NL 2017	2.59205E-5	kg N eq
		02.37% comes from the market for nickel, 99.5%		
	02.05%	Cell stack framework, AE NL 2017	2.10908E-5	kg N eq
		01.74% comes from the market for steel, unalloyed		
Mineral, fossil & ren resource depletion				
100.00%		Hydrogen production, AE NL 2017, wind	0.00041	kg Sb eq
	98.34%	Operating resources, AE NL 2017, wind	0.00041	kg Sb eq

		98.03% comes from electricity production, wind, 1-3MW turbine, offshore		
	01.40%	Cells, AE NL 2017	5.79164E-6	kg Sb eq
		01.25% comes from the market for nickel, 99.5%		
	00.26%	Cell stack framework, AE NL 2017	1.08073E-6	kg Sb eq
		00.18% comes from the market for copper		
Ozone depletion				
100.00%		Hydrogen production, AE NL 2017, wind	6.45922E-8	kg CFC-11 eq
	71.75%	Operating resources, AE NL 2017, wind	4.63434E-8	kg CFC-11 eq
		60.13% comes from electricity production, wind, 1-3MW turbine, offshore		
		06.30% comes from the market for water, deionised, from tap water, at the user		
		04.93% comes from the market for steam, in the chemical industry		
	26.58%	Cells, AE NL 2017	1.71712E-8	kg CFC-11 eq
		25.20% comes from the market for tetrafluoroethylene		
		01.05% comes from the market for nickel, 99.5%		
	01.67%	Cell stack framework, AE NL 2017	1.07764E-9	kg CFC-11 eq
		01.63% comes from the market for steel, unalloyed		
Particulate matter				
100.00%		Hydrogen production, AE NL 2017, wind	0.00097	kg PM2.5 eq
	81.43%	Operating resources, AE NL 2017, wind	0.00079	kg PM2.5 eq
		78.68% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.71% comes from the market for steam, in the chemical industry		
	16.38%	Cells, AE NL 2017	0.00016	kg PM2.5 eq
		16.27% comes from market for nickel, 99.5%		
	02.19%	Cell stack framework, AE NL 2017	2.12391E-5	kg PM2.5 eq
		01.92% comes from market for steel, unalloyed		
Photochemical ozone formation				
100.00%		Hydrogen production, AE NL 2017, wind	0.00332	kg NMVOC eq
	89.38%	Operating resources, AE NL 2017, wind	0.00297	kg NMVOC eq
		86.56% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.69% comes from market for steam, in the chemical industry		
	07.93%	Cells, AE NL 2017	0.00026	kg NMVOC eq
		07.80% comes from market for nickel, 99.5%		
	02.69%	Cell stack framework, AE NL 2017	8.92533E-5	kg NMVOC eq
		02.47% comes from market for steel, unalloyed		
Terrestrial eutrophication				
100.00%		Hydrogen production, AE NL 2017, wind	0.00964	molc N eq
	94.35%	Operating resources, AE NL 2017, wind	0.00910	molc N eq
		90.86% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.83% comes from market for steam, in the chemical industry		
		01.22% comes from market for water, deionised, from tap water, at user		
	03.38%	Cells, AE NL 2017	0.00033	molc N eq

		03.23% comes from market for nickel, 99.5%		
	02.27%	Cell stack framework, AE NL 2017	0.00022	molc N eq
		02.01% comes from market for steel, unalloyed		
Water resource depletion				
100.00%		Hydrogen production, AE NL 2017, wind	0.95902	m3 water eq
	95.12%	Operating resources, AE NL 2017, wind	0.91221	m3 water eq
		92.67% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.61% comes from market for water, deionised, from tap water, at user		
	04.09%	Cells, AE NL 2017	0.03921	m3 water eq
		03.99% comes from market for nickel, 99.5%		
	00.79%	Cell stack framework, AE NL 2017	0.00760	m3 water eq
		00.66% comes from the market for steel, unalloyed		

Table 33. Contribution analysis for the model AE NL 2018 (based on Wulf & Kaltschmitt) for the different impact categories from ILCD 2011 baseline.

Impact category		Process	Amount	Unit
Acidification				
100.00%		Hydrogen production, AE NL 2018, wind	0.00536	molc H+ eq
	96.06%	Operating resources, AE NL 2018, wind	0.00515	molc H+ eq
		93.76% comes from the electricity's production, wind, 1-3MW turbine, offshore		
		02.29% market for water, deionised, from tap water, at user		
	03.94%	Constructing Materials, AE NL 2018	0.00021	molc H+ eq
		03.16% comes from the market for nickel, 99.5%		
Climate change				
100.00%		Hydrogen production, AE NL 2018, wind	0.76857	kg CO2 eq
	98.97%	Operating resources, AE NL 2018, wind	0.76065	kg CO2 eq
		96.58% comes from the electricity's production, wind, 1-3MW turbine, offshore		
		02.38% comes from market for water, deionised, from tap water, at user		
	01.03%	Constructing Materials, AE NL 2018	0.00792	kg CO2 eq
		00.74% comes from the market for steel, low-alloyed		
Freshwater ecotoxicity				
100.00%		Hydrogen production, AE NL 2018, wind	50.19937	CTUe
	99.27%	Operating resources, AE NL 2018, wind	49.83204	CTUe
		98.79% comes from electricity production, wind, 1-3MW turbine, offshore		
	00.73%	Constructing Materials, AE NL 2018	0.36733	CTUe
		00.48% comes from the market for steel, low-alloyed		
Freshwater eutrophication				
100.00%		Hydrogen production, AE NL 2018, wind	0.00053	kg P eq
	98.54%	Operating resources, AE NL 2018, wind	0.00052	kg P eq
		95.93% comes from electricity production, wind, 1-3MW turbine, offshore		

		02.60% comes from market for water, deionised, from tap water, at user		
	01.46%	Constructing Materials, AE NL 2018	7.72677E-6	kg P eq
		01.03% comes from the market for steel		
Human toxicity, cancer effects				
100.00%		Hydrogen production, AE NL 2018, wind	3.82107E-7	CTUh
	97.44%	Operating resources, AE NL 2018, wind	3.72321E-7	CTUh
		96.28% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.15% comes from market for water, deionised, from tap water, at user		
	02.56%	Constructing Materials, AE NL 2018	9.78609E-9	CTUh
		01.75% comes from market for steel, low-alloyed		
Human toxicity, non-cancer effects				
100.00%		Hydrogen production, AE NL 2018, wind	8.79752E-7	CTUh
	98.56%	Operating resources, AE NL 2018, wind	8.67101E-7	CTUh
		97.38% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.18% comes from market for water, deionised, from tap water, at user		
	01.44%	Constructing Materials, AE NL 2018	1.26508E-8	CTUh
		01.11% comes from market for steel, low-alloyed		
Ionizing radiation E (interim)				
100.00%		Hydrogen production, AE NL 2018, wind	1.55713E-7	CTUe
	98.94%	Operating resources, AE NL 2018, wind	1.54057E-7	CTUe
		89.53% comes from electricity production, wind, 1-3MW turbine, offshore		
		09.38% comes from market for water, deionised, from tap water, at user		
	01.06%	Constructing Materials, AE NL 2018	1.65534E-9	CTUe
		00.65% comes from the market for steel, low-alloyed		
Ionizing radiation HH				
100.00%		Hydrogen production, AE NL 2018, wind	0.04277	kBq U235 eq
	98.90%	Operating resources, AE NL 2018, wind	0.04230	kBq U235 eq
		85.08% comes from electricity production, wind, 1-3MW turbine, offshore		
		13.79% comes from market for water, deionised, from tap water, at user		
	01.10%	Constructing Materials, AE NL 2018	0.00047	kBq U235 eq
		00.63% comes from the market for steel, low-alloyed		
Land use				
100.00%		Hydrogen production, AE NL 2018, wind	1.18942	kg C deficit
	98.98%	Operating resources, AE NL 2018, wind	1.17728	kg C deficit
		96.80% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.16% comes from market for water, deionised, from tap water, at user		
	01.02%	Constructing Materials, AE NL 2018	0.01213	kg C deficit
		00.75% comes from the market for steel, low-alloyed		
Marine eutrophication				

100.00%		Hydrogen production, AE NL 2018, wind	0.00096	kg N eq
	99.08%	Operating resources, AE NL 2018, wind	0.00095	kg N eq
		97.12% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.95% comes from market for water, deionised, from tap water, at user		
	00.92%	Constructing Materials, AE NL 2018	8.77419E-6	kg N eq
		00.63% comes from the market for steel, low-alloyed		
Mineral, fossil & ren resource depletion				
100.00%		Hydrogen production, AE NL 2018, wind	0.00040	kg Sb eq
	99.80%	Operating resources, AE NL 2018, wind	0.00040	kg Sb eq
		99.30% comes from electricity production, wind, 1-3MW turbine, offshore		
	00.20%	Constructing Materials, AE NL 2018	8.01616E-7	kg Sb eq
		00.09% comes from the market for steel, low-alloyed		
Ozone depletion				
100.00%		Hydrogen production, AE NL 2018, wind	4.62336E-8	kg CFC-11 eq
	99.06%	Operating resources, AE NL 2018, wind	4.57980E-8	kg CFC-11 eq
		82.33% comes from electricity production, wind, 1-3MW turbine, offshore		
		16.71% comes from market for water, deionised, from tap water, at user		
	00.94%	Constructing Materials, AE NL 2018	4.35600E-10	kg CFC-11 eq
		00.68% comes from the market for steel, low-alloyed		
Particulate matter				
100.00%		Hydrogen production, AE NL 2018, wind	0.00078	kg PM2.5 eq
	97.89%	Operating resources, AE NL 2018, wind	0.00076	kg PM2.5 eq
		96.34% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.54% comes from market for water, deionised, from tap water, at user		
	02.11%	Constructing Materials, AE NL 2018	1.63259E-5	kg PM2.5 eq
		01.07% comes from market for nickel, 99.5%		
Photochemical ozone formation				
100.00%		Hydrogen production, AE NL 2018, wind	0.00291	kg NMVOC eq
	98.60%	Operating resources, AE NL 2018, wind	0.00287	kg NMVOC eq
		96.88% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.71% comes from market for water, deionised, from tap water, at user		
	01.40%	Constructing Materials, AE NL 2018	4.06378E-5	kg NMVOC eq
		00.78% comes from the market for steel, low-alloyed		
Terrestrial eutrophication				
100.00%		Hydrogen production, AE NL 2018, wind	0.00891	molc N eq
	98.90%	Operating resources, AE NL 2018, wind	0.00881	molc N eq
		96.37% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.51% comes from market for water, deionised, from tap water, at user		
	01.10%	Constructing Materials, AE NL 2018	9.82403E-5	molc N eq
		00.74% comes from the market for steel, low-alloyed		

Water resource depletion				
100.00%		Hydrogen production, AE NL 2018, wind	0.92005	m3 water eq
	97.88%	Operating resources, AE NL 2018, wind	0.90050	m3 water eq
		94.67% comes from electricity production, wind, 1-3MW turbine, offshore		
		03.20% comes from market for water, deionised, from tap water, at user		
	02.12%	Constructing Materials, AE NL 2018	0.01955	m3 water eq
		01.12% comes from the market for chromium		

Table 34. Contribution analysis for the model PEM NL 2018a (based on Wulf & Kaltschmitt) for the different impact categories from ILCD 2011 baseline

Impact category		**Process**	**Amount**	**Unit**
Acidification				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00536	molc H+ eq
	97.90%	Operating resources, PEM NL 2018a, wind	0.00525	molc H+ eq
		95.62% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.29% comes from market for water, deionised, from tap water, at user		
	02.10%	Constructing materials, PEM NL 2018a	0.00011	molc H+ eq
		01.72% comes from market for steel, low-alloyed		
Climate change				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.79371	kg CO2 eq
	97.73%	Operating resources, PEM NL 2018a, wind	0.77567	kg CO2 eq
		95.43% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.30% comes from market for water, deionised, from tap water, at user		
	02.27%	Constructing materials, PEM NL 2018a	0.01803	kg CO2 eq
		02.02% comes from market for steel, low-alloyed		
Freshwater ecotoxicity				
100.00%		Hydrogen production, PEM NL 2018a, wind	51.73267	CTUe
	98.28%	Operating resources, PEM NL 2018a, wind	50.84316	CTUe
		97.82% comes from electricity production, wind, 1-3MW turbine, offshore		
		00.46% comes from market for water, deionised, from tap water, at user		
	01.72%	Constructing materials, PEM NL 2018a	0.88951	CTUe
		01.32% comes from market for steel, low-alloyed		
Freshwater eutrophication				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00055	kg P eq
	96.97%	Operating resources, PEM NL 2018a, wind	0.00053	kg P eq
		94.46% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.51% comes from market for water, deionised, from tap water, at user		
	03.03%	Constructing materials, PEM NL 2018a	1.66303E-5	kg P eq
		02.82% comes from market for steel, low-alloyed		

Human toxicity, cancer effects				
100.00%		Hydrogen production, PEM NL 2018a, wind	3.99643E-7	CTUh
	95.04%	Operating resources, PEM NL 2018a, wind	3.79822E-7	CTUh
		93.94% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.10% comes from market for water, deionised, from tap water, at user		
	04.96%	Constructing materials, PEM NL 2018a	1.98208E-8	CTUh
		04.75% comes from market for steel, low-alloyed		
Human toxicity, non-cancer effects				
100.00%		Hydrogen production, PEM NL 2018a, wind	9.13930E-7	CTUh
	96.79%	Operating resources, PEM NL 2018a, wind	8.84548E-7	CTUh
		95.65% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.13% comes from market for water, deionised, from tap water, at user		
	03.21%	Constructing materials, PEM NL 2018a	2.93816E-8	CTUh
		03.03% comes from market for steel, low-alloyed		
Ionizing radiation E (interim)				
100.00%		Hydrogen production, PEM NL 2018a, wind	1.59973E-7	CTUe
	98.05%	Operating resources, PEM NL 2018a, wind	1.56860E-7	CTUe
		88.93% comes from electricity production, wind, 1-3MW turbine, offshore		
		09.13% comes from market for water, deionised, from tap water, at user		
	01.95%	Constructing materials, PEM NL 2018a	3.11316E-9	CTUe
		01.79% comes from market for steel, low-alloyed		
Ionizing radiation HH				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.04386	kBq U235 eq
	98.12%	Operating resources, PEM NL 2018a, wind	0.04303	kBq U235 eq
		84.67% comes from electricity production, wind, 1-3MW turbine, offshore		
		13.45% comes from market for water, deionised, from tap water, at user		
	01.88%	Constructing materials, PEM NL 2018a	0.00083	kBq U235 eq
		01.73% comes from market for steel, low-alloyed		
Land use				
100.00%		Hydrogen production, PEM NL 2018a, wind	1.22815	kg C deficit
	97.76%	Operating resources, PEM NL 2018a, wind	1.20060	kg C deficit
		95.66% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.09% comes from market for water, deionised, from tap water, at user		
	02.24%	Constructing materials, PEM NL 2018a	0.02755	kg C deficit
		02.06% comes from market for steel, low-alloyed		
Marine eutrophication				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00099	kg N eq
	98.09%	Operating resources, PEM NL 2018a, wind	0.00097	kg N eq
		96.19% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.89% comes from market for water, deionised, from tap water, at user		

	01.91%	Constructing materials, PEM NL 2018a	1.88793E-5	kg N eq
		01.73% comes from market for steel, low-alloyed		
Mineral, fossil & ren resource depletion				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00041	kg Sb eq
	99.41%	Operating resources, PEM NL 2018a, wind	0.00041	kg Sb eq
		98.92% comes from electricity production, wind, 1-3MW turbine, offshore		
		00.49% comes from market for water, deionised, from tap water, at user		
	00.59%	Constructing materials, PEM NL 2018a	2.44039E-6	kg Sb eq
		00.34% comes from the market for aluminium, cast alloy		
Ozone depletion				
100.00%		Hydrogen production, PEM NL 2018a, wind	5.37179E-8	kg CFC-11 eq
	86.69%	Operating resources, PEM NL 2018a, wind	4.65678E-8	kg CFC-11 eq
		72.31% comes from electricity production, wind, 1-3MW turbine, offshore		
		14.38% comes from market for water, deionised, from tap water, at user		
	13.31%	Constructing materials, PEM NL 2018a	7.15003E-9	kg CFC-11 eq
		11.49% comes from market for tetrafluoroethylene		
		01.66% comes from market for steel, low-alloyed		
Particulate matter				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00079	kg PM2.5 eq
	97.39%	Operating resources, PEM NL 2018a, wind	0.00077	kg PM2.5 eq
		95.89% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.50% comes from market for water, deionised, from tap water, at user		
	02.61%	Constructing materials, PEM NL 2018a	2.07098E-5	kg PM2.5 eq
		02.34% comes from market for steel, low-alloyed		
Photochemical ozone formation				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00300	kg NMVOC eq
	97.61%	Operating resources, PEM NL 2018a, wind	0.00293	kg NMVOC eq
		95.95% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.66% comes from market for water, deionised, from tap water, at user		
	02.39%	Constructing materials, PEM NL 2018a	7.16856E-5	kg NMVOC eq
		02.15% comes from market for steel, low-alloyed		
Terrestrial eutrophication				
100.00%		Hydrogen production, PEM NL 2018a, wind	0.00919	molc N eq
	97.76%	Operating resources, PEM NL 2018a, wind	0.00898	molc N eq
		95.33% comes from electricity production, wind, 1-3MW turbine, offshore		
		02.43% comes from market for water, deionised, from tap water, at user		
	02.24%	Constructing materials, PEM NL 2018a	0.00021	molc N eq
		02.03% comes from market for steel, low-alloyed		
Water resource depletion				

100.00%		Hydrogen production, PEM NL 2018a, wind	0.93974	m3 water eq
	97.70%	Operating resources, PEM NL 2018a, wind	0.91816	m3 water eq
		94.57% comes from electricity production, wind, 1-3MW turbine, offshore		
		03.13% comes from market for water, deionised, from tap water, at user		
	02.30%	Constructing materials, PEM NL 2018a	0.02159	m3 water eq
		02.16% comes from market for steel, low-alloyed		

Table 35. Contribution analysis for the model PEM NL 2018b (based on Schmidt et al.) for the different impact categories from ILCD 2011 baseline.

Impact category		**Process**	**Amount**	**Unit**
Acidification				
100.00%		Hydrogen production, PEM NL 2018b	0.00781	molc H+ eq
	70.55%	Operating resources, PEM NL 2018b, wind	0.00551	molc H+ eq
		69.75% comes from electricity production, wind, 1-3MW turbine, offshore		
	29.45%	Cell components, PEM NL 2018b	0.00230	molc H+ eq
		29.35% comes from market for platinum		
Climate change				
100.00%		Hydrogen production, PEM NL 2018b	0.84036	kg CO2 eq
	96.88%	Operating resources, PEM NL 2018b, wind	0.81414	kg CO2 eq
		95.77% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.11% comes from market for water, deionised, from tap water, at user		
	03.12%	Cell components, PEM NL 2018b	0.02622	kg CO2 eq
		02.78% comes from the market for platinum		
Freshwater ecotoxicity				
100.00%		Hydrogen production, PEM NL 2018b	56.63711	CTUe
	95.16%	Operating resources, PEM NL 2018b, wind	53.89478	CTUe
		94.94% comes from electricity production, wind, 1-3MW turbine, offshore		
	04.84%	Cell components, PEM NL 2018b	2.74234	CTUe
		04.82% comes from the market for platinum		
Freshwater eutrophication				
100.00%		Hydrogen production, PEM NL 2018b	0.00063	kg P eq
	89.26%	Operating resources, PEM NL 2018b, wind	0.00056	kg P eq
		88.13% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.12% comes from market for water, deionised, from tap water, at user		
	10.74%	Cell components, PEM NL 2018b	6.71427E-5	kg P eq
		10.68% comes from the market for platinum		
Human toxicity, cancer effects				
100.00%		Hydrogen production, PEM NL 2018b	4.06301E-7	CTUh
	98.74%	Operating resources, PEM NL 2018b, wind	4.01163E-7	CTUh
		98.18% comes from electricity production, wind, 1-3MW turbine, offshore		

	01.26%	Cell components, PEM NL 2018b	5.13763E-9	CTUh
		01.25% comes from the market for platinum		
Human toxicity, non-cancer effects				
100.00%		Hydrogen production, PEM NL 2018b	1.04682E-6	CTUh
	89.24%	Operating resources, PEM NL 2018b, wind	9.34194E-7	CTUh
		88.74% comes from electricity production, wind, 1-3MW turbine, offshore		
	10.76%	Cell components, PEM NL 2018b	1.12630E-7	CTUh
		10.73% comes from the market for platinum		
Ionizing radiations E (interim)				
100.00%		Hydrogen production, PEM NL 2018b	1.62406E-7	CTUe
	97.66%	Operating resources, PEM NL 2018b, wind	1.58610E-7	CTUe
		93.08% comes from electricity production, wind, 1-3MW turbine, offshore		
		04.59% comes from market for water, deionised, from tap water, at user		
	02.34%	Cell components, PEM NL 2018b	3.79547E-9	CTUe
		02.20% comes from the market for platinum		
Ionizing radiation HH				
100.00%		Hydrogen production, PEM NL 2018b	0.04373	kBq U235 eq
	97.12%	Operating resources, PEM NL 2018b, wind	0.04247	kBq U235 eq
		90.24% comes from electricity production, wind, 1-3MW turbine, offshore		
		06.88% comes from market for water, deionised, from tap water, at user		
	02.88%	Cell components, PEM NL 2018b	0.00126	kBq U235 eq
		02.73% comes from the market for platinum		
Land use				
100.00%		Hydrogen production, PEM NL 2018b	1.29720	kg C deficit
	97.25%	Operating resources, PEM NL 2018b, wind	1.26156	kg C deficit
		96.24% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.01% comes from market for water, deionised, from tap water, at user		
	02.75%	Cell components, PEM NL 2018b	0.03564	kg C deficit
		02.65% comes from the market for platinum		
Marine eutrophication				
100.00%		Hydrogen production, PEM NL 2018b	0.00106	kg N eq
	95.86%	Operating resources, PEM NL 2018b, wind	0.00102	kg N eq
		94.96% comes from electricity production, wind, 1-3MW turbine, offshore		
	04.14%	Cell components, PEM NL 2018b	4.39992E-5	kg N eq
		03.98% comes from the market for platinum		
Mineral, fossil & ren resource depletion				
100.00%		Hydrogen production, PEM NL 2018b	0.00044	kg Sb eq
	97.85%	Operating resources, PEM NL 2018b, wind	0.00043	kg Sb eq
		97.62% comes from electricity production, wind, 1-3MW turbine, offshore		

	02.15%	Cell components, PEM NL 2018b	9.51661E-6	kg Sb eq
		02.07% comes from the market for platinum		
Ozone depletion				
100.00%		Hydrogen production, PEM NL 2018b	9.90177E-8	kg CFC-11 eq
	45.66%	Operating resources, PEM NL 2018b, wind	4.52132E-8	kg CFC-11 eq
		41.68% comes from electricity production, wind, 1-3MW turbine, offshore		
		03.98% comes from market for water, deionised, from tap water, at user		
	54.34%	Cell components, PEM NL 2018b	5.38044E-8	kg CFC-11 eq
		53.49% comes from market for tetrafluoroethylene		
Particulate matter				
100.00%		Hydrogen production, PEM NL 2018b	0.00093	kg PM2.5 eq
	88.03%	Operating resources, PEM NL 2018b, wind	0.00082	kg PM2.5 eq
		87.37% comes from electricity production, wind, 1-3MW turbine, offshore		
	11.97%	Cell components, PEM NL 2018b	0.00011	kg PM2.5 eq
		11.84% comes from the market for platinum		
Photochemical ozone formation				
100.00%		Hydrogen production, PEM NL 2018b	0.00332	kg NMVOC eq
	92.72%	Operating resources, PEM NL 2018b, wind	0.00308	kg NMVOC eq
		91.96% comes from electricity production, wind, 1-3MW turbine, offshore		
	07.28%	Cell components, PEM NL 2018b	0.00024	kg NMVOC eq
		07.14% comes from the market for platinum		
Terrestrial eutrophication				
100.00%		Hydrogen production, PEM NL 2018b	0.00986	molc N eq
	95.56%	Operating resources, PEM NL 2018b, wind	0.00942	molc N eq
		94.41% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.16% comes from market for water, deionised, from tap water, at user		
	04.44%	Cell components, PEM NL 2018b	0.00044	molc N eq
		04.27% comes from the market for platinum		
Water resource depletion				
100.00%		Hydrogen production, PEM NL 2018b	0.00986	m3 water eq
	95.56%	Operating resources, PEM NL 2018b, wind	0.00942	m3 water eq
		94.41% comes from electricity production, wind, 1-3MW turbine, offshore		
		01.16% comes from market for water, deionised, from tap water, at user		
	04.44%	Cell components, PEM NL 2018b	0.00044	m3 water eq
		04.27% comes from the market for platinum		

Table 36. Contribution analysis for the SMR (based on Schmidt et al., 2018) for the different impact categories from ILCD 2011 baseline.

Impact category		Process	Amount	Unit
Acidification				
100.00%		Hydrogen production, SMR NL 2018	0.00917	molc H+ eq
	79.79%	Operating resources, SMR NL 2018	0,00732	molc H+ eq
		88.60% comes from market for steam, in the chemical industry		
		07.32% comes from market for natural gas, unprocessed, at the extraction		
		02.86% comes from the market for electricity, high voltage		
		01.01% comes from market for water, deionised, from tap water, at user		
	20.13%	Direct emissions, SMR NL 2018	0.00184	molc H+ eq
	00.08%	Constructing materials, SMR NL 2018	7.55E-06	molc H+ eq
		00.03% comes from the market for steel, unalloyed		
Climate change				
100.00%		Hydrogen production, SMR NL 2018	11.39466	kg CO2 eq
	75.44%	Direct emissions, SMR NL 2018	8.5961315	kg CO2 eq
	24.55%	Operating resources, SMR NL 2018	2.79794	kg CO2 eq
		14.70% comes from market for steam, in the chemical industry		
		08.71% comes from market for natural gas, unprocessed, at the extraction		
		01.02% comes from the market for electricity, high voltage		
	00.01%	Constructing materials, SMR NL 2018	0.00122	kg CO2 eq
		00.01% comes from the market for steel, unalloyed		
Freshwater ecotoxicity				
100.00%		Hydrogen production, SMR NL 2018	15.09268	CTUe
	99.84%	Operating resources, SMR NL 2018	15.06863	CTUe
		78.11% comes from market for natural gas, unprocessed, at the extraction		
		17.67% comes from market for steam, in the chemical industry		
		02.87% comes from the market for electricity, high voltage		
		01.19% comes from market for water, deionised, from tap water, at user		
	00.16%	Constructing materials, SMR NL 2018	0.02405	CTUe
		00.06% comes from the market for steel, low-alloyed		
Freshwater eutrophication				
100.00%		Hydrogen production, SMR NL 2018	0.00030	kg P eq
	99.78%	Operating resources, SMR NL 2018	0.00030	kg P eq
		64.53% comes from market for steam, in the chemical industry		
		16.08% comes from the market for electricity, high voltage		
		15.66% comes from market for natural gas, unprocessed, at the extraction		
		03.52% comes from market for water, deionised, from tap water, at user		
	00.22%	Constructing materials, SMR NL 2018	6.66958E-7	kg P eq
		00.10% comes from the market for steel, unalloyed		
Human toxicity, cancer effects				

100.00%		Hydrogen production, SMR NL 2018	7.56542E-8	CTUh
	99.32%	Operating resources, SMR NL 2018	7.51391E-8	CTUh
		53.88% comes from market for natural gas, unprocessed, at the extraction		
		35.38% comes from market for steam, in the chemical industry		
		05.64% comes from the market for electricity, high voltage		
		04.42% comes from market for water, deionised, from tap water, at user		
	00.68%	Constructing materials, SMR NL 2018	5.15124E-10	CTUh
		00.36% comes from the market for steel, low-alloyed		
Human toxicity, non-cancer effects				
100.00%		Hydrogen production, SMR NL 2018	6.37920E-7	CTUh
	99.89%	Operating resources, SMR NL 2018	6.37188E-7	CTUh
		72.80% comes from market for natural gas, unprocessed, at the extraction		
		23.38% comes from market for steam, in the chemical industry		
		02.47% comes from the market for electricity, high voltage		
		01.23% comes from market for water, deionised, from tap water, at user		
	00.11%	Constructing materials, SMR NL 2018	7.31628E-10	CTUh
		00.06%comes from the market for steel, low-alloyed		
Ionizing radiation E (interim)				
100.00%		Hydrogen production, SMR NL 2018	3.53205E-7	CTUe
	99.95%	Operating resources, SMR NL 2018	3.53035E-7	CTUe
		75.74% comes from market for steam, in the chemical industry		
		12.01% comes from market for natural gas, unprocessed, at the extraction		
		09.06% comes from the market for electricity, high voltage		
		03.13% comes from market for water, deionised, from tap water, at user		
	00.05%	Constructing materials, SMR NL 2018	1.70343E-10	CTUe
		00.02% comes from the market for steel, unalloyed		
Ionizing radiation HH				
100.00%		Hydrogen production, SMR NL 2018	0.08347	kBq U235 eq
	99.95%	Operating resources, SMR NL 2018	0.08343	kBq U235 eq
		61.63% comes from market for steam, in the chemical industry		
		17.48% comes from the market for electricity, high voltage		
		15.49% comes from market for natural gas, unprocessed, at the extraction		
		05.35% comes from market for water, deionised, from tap water, at user		
	00.05%	Constructing materials, SMR NL 2018	4.05100E-5	kBq U235 eq
		00.02% comes from the market for steel, unalloyed		
Land use				
100.00%		Hydrogen production, SMR NL 2018	2.00972	kg C deficit
	99.91%	Operating resources, SMR NL 2018	2.00786	kg C deficit
		85.29% comes from market for steam, in the chemical industry		
		09.94% comes from market for natural gas, unprocessed, at the extraction		
		03.71% comes from the market for electricity, high voltage		

		00.97% comes from market for water, deionised, from tap water, at user		
	00.09%	Constructing materials, SMR NL 2018	0.00186	kg C deficit
		00.04% comes from the market for steel, unalloyed		
Marine eutrophication				
100.00%		Hydrogen production, SMR NL 2018	0.00198	kg N eq
	54.73%	Operating resources, SMR NL 2018	0,00108	kg N eq
		40.20% comes from market for steam, in the chemical industry		
		11.15% comes from market for natural gas, unprocessed, at the extraction		
		02.66% comes from the market for electricity, high voltage		
	45.21%	Direct emissions, SMR NL 2018	0.00089516	kg N eq
	00.06%	Constructing materials, SMR NL 2018	1.17080E-6	kg N eq
		00.03% comes from the market for steel, unalloyed		
Mineral, fossil & ren resource depletion				
100.00%		Hydrogen production, SMR NL 2018	5.83299E-6	kg Sb eq
	96.94%	Operating resources, SMR NL 2018	5.65463E-6	kg Sb eq
		39.29% comes from market for steam, in the chemical industry		
		26.17% comes from market for natural gas, unprocessed, at the extraction		
		25.96% comes from market for water, deionised, from tap water, at user		
		05.53% comes from the market for electricity, high voltage		
	03.06%	Constructing materials, SMR NL 2018	1.78359E-7	kg Sb eq
		01.63% comes from market for zinc		
Ozone depletion				
100.00%		Hydrogen production, SMR NL 2018	1.91353E-7	kg CFC-11 eq
	99.97%	Operating resources, SMR NL 2018	1.91287E-7	kg CFC-11 eq
		80.20% comes from market for steam, in the chemical industry		
		13.44% comes from market for natural gas, unprocessed, at the extraction		
		03.27% comes from the market for electricity, high voltage		
		03.06% comes from market for water, deionised, from tap water, at user		
	00.03%	Constructing materials, SMR NL 2018	6.67393E-11	kg CFC-11 eq
		00.02% comes from the market for steel, unalloyed		
Particulate matter				
100.00%		Hydrogen production, SMR NL 2018	0.00096	kg PM2.5 eq
	95.10%	Operating resources, SMR NL 2018	0.00091	kg PM2.5 eq
		83.36% comes from market for steam, in the chemical industry		
		09.60% comes from market for natural gas, unprocessed, at the extraction		
		01.19% comes from the market for electricity, high voltage		
	4.78%	Direct emissions, SMR NL 2018	4.59E-05	kg PM2.5 eq
	00.12%	Constructing materials, SMR NL 2018	1.16862E-6	kg PM2.5 eq
		00.06% comes from the market for steel, unalloyed		
Photochemical ozone formation				

100.00%		Hydrogen production, SMR NL 2018	0.00395	kg NMVOC eq
	38.16%	Operating resources, SMR NL 2018	0.00357	kg NMVOC eq
		28.87% comes from market for steam, in the chemical industry		
		07.60% comes from market for natural gas, unprocessed, at the extraction		
		01.28% comes from the market for electricity, high voltage		
	61.79%	Direct emissions, SMR NL 2018	0.00578	kg NMVOC eq
	00.12%	Constructing materials, SMR NL 2018	4.88392E-6	kg NMVOC eq
		00.07% comes from the market for steel, unalloyed		
Terrestrial eutrophication				
100.00%		Hydrogen production, SMR NL 2018	0.02039	molc N eq
	51.88%	Operating resources, SMR NL 2018	0.01058	molc N eq
		41.71% comes from market for steam, in the chemical industry		
		05.17% comes from market for natural gas, unprocessed, at the extraction		
		04.16% comes from the market for electricity, high voltage		
	48.06%	Direct emissions, SMR NL 2018	0.00980	molc N eq
	00.06%	Constructing materials, SMR NL 2018	1.28E-05	molc N eq
		00.03% comes from the market for steel, unalloyed		
Water resource depletion				
100.00%		Hydrogen production, SMR NL 2018	0.35087	m3 water eq
	99.80%	Operating resources, SMR NL 2018	0.35018	m3 water eq
		52.35% comes from market for steam, in the chemical industry		
		33.73% comes from market for natural gas, unprocessed, at the extraction		
		07.38% comes from the market for electricity, high voltage		
		06.35% comes from market for water, deionised, from tap water, at user		
	00.20%	Constructing materials, SMR NL 2018	0.00069	m3 water eq
		00.08% comes from the market for steel, low-alloyed		

Table 37. Contribution analysis for the AE 1-GW NL 2050 ("Scenario A") for the different impact categories from ILCD 2011 baseline.

Impact category		Process	Amount	Unit
Acidification				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00533	molc H+ eq
	91.76%	Operating resources, AE NL 1 GW	0.00489	molc H+ eq
		90.42% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00482	molc H+ eq
		01.09% comes from the market for water, deionised, from tap water, at user	5.81005E-5	molc H+ eq
	08.24%	Constructing materials, AE NL 1 GW	0.00044	molc H+ eq
		05.73% comes from the market for nickel, 99.5%	0.00031	molc H+ eq
		01.19% comes from the market for copper	6.35390E-5	molc H+ eq
Climate change				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.73907	kg CO2 eq

	97.81%	Operating resources, AE NL 1 GW	0.72291	kg CO2 eq
		96.33% comes from the electricity production, wind, 1-3MW turbine, offshore	0.71197	kg CO2 eq
		01.17% comes from the market for water, deionised, from tap water, at user	0.00865	kg CO2 eq
	02.19%	Constructing materials, AE NL 1 GW	0.01617	kg CO2 eq
		01.23% comes from the market for steel, unalloyed	0.00907	kg CO2 eq
Freshwater ecotoxicity				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	48.49526	CTUe
	98.36%	Operating resources, AE NL 1 GW	47.70003	CTUe
		98.09% comes from the electricity production, wind, 1-3MW turbine, offshore	47.56945	CTUe
	01.64%	Constructing materials, AE NL 1 GW	0.79523	CTUe
		01.03% comes from the market for copper	0.50182	CTUe
Freshwater eutrophication				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00052	kg P eq
	95.83%	Operating resources, AE NL 1 GW	0.00049	kg P eq
		94.37% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00049	kg P eq
		01.26% comes from the market for water, deionised, from tap water, at user	6.52849E-6	kg P eq
	04.17%	Constructing materials, AE NL 1 GW	2.15168E-5	kg P eq
		02.43% comes from the market for copper	1.25534E-5	kg P eq
Human toxicity, cancer effects				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	3.62603E-7	CTUh
	97.93%	Operating resources, AE NL 1 GW	3.55111E-7	CTUh
		97.32% comes from the electricity production, wind, 1-3MW turbine, offshore	3.52889E-7	CTUh
	02.07%	Constructing materials, AE NL 1 GW	7.49245E-9	CTUh
		01.20% comes from the market for chromium	4.34351E-9	CTUh
Human toxicity, non-cancer effects				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	8.58683E-7	CTUh
	96.35%	Operating resources, AE NL 1 GW	8.27310E-7	CTUh
		95.70% comes from the electricity production, wind, 1-3MW turbine, offshore	8.21734E-7	CTUh
	03.65%	Constructing materials, AE NL 1 GW	3.13731E-8	CTUh
		02.77% comes from the market for copper	2.38109E-8	CTUh
Ionizing radiation E (interim)				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	1.44178E-7	CTUe
	98.08%	Operating resources, AE NL 1 GW	1.41406E-7	CTUe
		92.75% comes from the electricity production, wind, 1-3MW turbine, offshore	1.33722E-7	CTUe

		04.80% comes from the market for water, deionised, from tap water, at user	6.91704E-9	CTUe
	01.92%	Constructing materials, AE NL 1 GW	2.77162E-9	CTUe
		00.68% comes from the market for steel, unalloyed	9.83797E-10	CTUe
Ionizing radiation HH				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.03872	kBq U235 eq
	97.97%	Operating resources, AE NL 1 GW	0.03793	kBq U235 eq
		90.16% comes from the electricity production, wind, 1-3MW turbine, offshore	0.03491	kBq U235 eq
		07.21% comes from the market for water, deionised, from tap water, at user	0.00279	kBq U235 eq
	02.03%	Constructing materials, AE NL 1 GW	0.00079	kBq U235 eq
		00.60% comes from the market for chromium	0.00023	kBq U235 eq
Land use				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	1.14195	kg C deficit
	98.06%	Operating resources, AE NL 1 GW	1.11980	kg C deficit
		96.71% comes from the electricity production, wind, 1-3MW turbine, offshore	1.10441	kg C deficit
		01.07%comes from the market for water, deionised, from tap water, at user	0.01218	kg C deficit
	01.94%	Constructing materials, AE NL 1 GW	0.02215	kg C deficit
		00.94% comes from the market for steel, unalloyed	0.01071	kg C deficit
Marine eutrophication				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00092	kg N eq
	97.85%	Operating resources, AE NL 1 GW	0.00090	kg N eq
		96.67% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00089	kg N eq
	02.15%	Constructing materials, AE NL 1 GW	1.98165E-5	kg N eq
		00.88% comes from the market for steel, unalloyed	8.09626E-6	kg N eq
Mineral, fossil & ren resource depletion				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00039	kg Sb eq
	99.29%	Operating resources, AE NL 1 GW	0.00038	kg Sb eq
		99.02% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00038	kg Sb eq
	00.71%	Constructing materials, AE NL 1 GW	2.73770E-6	kg Sb eq
		00.30% comes from the market for copper	1.14246E-6	kg Sb eq
Ozone depletion				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	6.59049E-8	kg CFC-11 eq
	61.15%	Operating resources, AE NL 1 GW	4.02985E-8	kg CFC-11 eq
		55.40% comes from the electricity production, wind, 1-3MW turbine, offshore	3.65108E-8	kg CFC-11 eq

		05.55% comes from the market for water, deionised, from tap water, at user	3.65997E-9	kg CFC-11 eq
	38.85%	Constructing materials, AE NL 1 GW	2.56064E-8	kg CFC-11 eq
		37.33% comes from the market for tetrafluoroethylene	2.46039E-8	kg CFC-11 eq
Particulate matter				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00076	kg PM2.5 eq
	95.90%	Operating resources, AE NL 1 GW	0.00072	kg PM2.5 eq
		94.88% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00072	kg PM2.5 eq
	04.10%	Constructing materials, AE NL 1 GW	3.09968E-5	kg PM2.5 eq
		01.99% comes from the market for nickel, 99.5%	1.50497E-5	kg PM2.5 eq
		01.12% comes from the market for steel, unalloyed	8.42459E-6	kg PM2.5 eq
Photochemical ozone formation				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00282	kg NMVOC eq
	96.98%	Operating resources, AE NL 1 GW	0.00273	kg NMVOC eq
		95.93% comes from the electricity's production, wind, 1-3MW turbine, offshore	0.00270	kg NMVOC eq
	03.02%	Constructing materials, AE NL 1 GW	8.51572E-5	kg NMVOC eq
		01.32% comes from the market for steel, unalloyed	3.72251E-5	kg NMVOC eq
Terrestrial eutrophication				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.00856	molc N eq
	97.66%	Operating resources, AE NL 1 GW	0.00836	molc N eq
		96.16% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00823	molc N eq
		01.24% comes from the market for water, deionised, from tap water, at user	0.00011	molc N eq
	02.34%	Constructing materials, AE NL 1 GW	0.00020	molc N eq
		01.02% comes from the market for steel, unalloyed	8.76393E-5	molc N eq
Water resource depletion				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant)	0.87645	m3 water eq
	97.15%	Operating resources, AE NL 1 GW	0.85148	m3 water eq
		95.32% comes from the electricity production, wind, 1-3MW turbine, offshore	0.83542	m3 water eq
		01.59% comes from the market for water, deionised, from tap water, at user	0.01393	m3 water eq
	02.85%	Constructing materials, AE NL 1 GW	0.02497	m3 water eq
		01.73% comes from the market for chromium	0.01513	m3 water eq

Table 38. Contribution analysis for the AE 1-GW NL 2050 (“Scenario B”) for the different impact categories from ILCD 2011 baseline.

Impact category		Process	Amount	Unit
Acidification				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00571	molc H+ eq
	91.39%	Operating resources, AE NL 1 GW	0.00522	molc H+ eq
		89.80% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00513	molc H+ eq
		01.13% comes from the market for water, deionised, from tap water, at user	6.45561E-5	molc H+ eq
	08.61%	Constructing materials, AE NL 1 GW	0.00049	molc H+ eq
		08.02% comes from the market for nickel, 99.5%	0.00046	molc H+ eq
Climate change				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.77814	kg CO2 eq
	99.16%	Operating resources, AE NL 1 GW	0.77160	kg CO2 eq
		97.34% comes from the electricity production, wind, 1-3MW turbine, offshore	0.75742	kg CO2 eq
		01.23% comes from the market for water, deionised, from tap water, at user	0.00961	kg CO2 eq
	00.84%	Constructing materials, AE NL 1 GW	0.00654	kg CO2 eq
		00.52% comes from the market for steel, unalloyed	0.00408	kg CO2 eq
Freshwater ecotoxicity				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	51.06331	CTUe
	99.42%	Operating resources, AE NL 1 GW	50.76701	CTUe
		99.10% comes from the electricity production, wind, 1-3MW turbine, offshore	50.60580	CTUe
	00.58%	Constructing materials, AE NL 1 GW	0.29629	CTUe
		00.35% comes from the market for nickel, 99.5%	0.17860	CTUe
Freshwater eutrophication				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00054	kg P eq
	98.43%	Operating resources, AE NL 1 GW	0.00053	kg P eq
		96.69% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00052	kg P eq
		01.35% comes from the market for water, deionised, from tap water, at user	7.25388E-6	kg P eq
	01.57%	Constructing materials, AE NL 1 GW	8.39264E-6	kg P eq
		00.81% comes from the market for nickel, 99.5%	4.34889E-6	kg P eq
Human toxicity, cancer effects				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	3.80018E-7	CTUh
	99.47%	Operating resources, AE NL 1 GW	3.78001E-7	CTUh
		98.79% comes from the electricity production, wind, 1-3MW turbine, offshore	3.75414E-7	CTUh
	00.53%	Constructing materials, AE NL 1 GW	2.01653E-9	CTUh

		00.24% comes from the market for steel, unalloyed	8.97176E-10	CTUh
Human toxicity, non-cancer effects				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	8.92392E-7	CTUh
	98.72%	Operating resources, AE NL 1 GW	8.80973E-7	CTUh
		97.96% comes from the electricity production, wind, 1-3MW turbine, offshore	8.74185E-7	CTUh
	01.28%	Constructing materials, AE NL 1 GW	1.14184E-8	CTUh
		00.77% comes from the market for nickel, 99.5%	6.83838E-9	CTUh
Ionizing radiation E (interim)				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	1.52576E-7	CTUe
	99.28%	Operating resources, AE NL 1 GW	1.51478E-7	CTUe
		93.24% comes from the electricity production, wind, 1-3MW turbine, offshore	1.42257E-7	CTUe
		05.04% comes from the market for water, deionised, from tap water, at user	7.68560E-9	CTUe
		01.01% comes from the market for potassium hydroxide	1.53481E-9	CTUe
	00.72%	Constructing materials, AE NL 1 GW	1.09789E-9	CTUe
		00.29% comes from the market for steel, unalloyed	4.42709E-10	CTUe
Ionizing radiation HH				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.04099	kBq U235 eq
	99.29%	Operating resources, AE NL 1 GW	0.04070	kBq U235 eq
		90.60% comes from the electricity production, wind, 1-3MW turbine, offshore	0.03714	kBq U235 eq
		07.57% comes from the market for water, deionised, from tap water, at user	0.00310	kBq U235 eq
		01.12% comes from the market for potassium hydroxide	0.00046	kBq U235 eq
	00.71%	Constructing materials, AE NL 1 GW	0.00029	kBq U235 eq
		00.28% comes from the market for nickel, 99.5%	0.00012	kBq U235 eq
Land use				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	1.20545	kg C deficit
	99.12%	Operating resources, AE NL 1 GW	1.19487	kg C deficit
		97.47% comes from the electricity production, wind, 1-3MW turbine, offshore	1.17490	kg C deficit
		01.12% comes from the market for water, deionised, from tap water, at user	0.01353	kg C deficit
	00.88%	Constructing materials, AE NL 1 GW	0.01058	kg C deficit
		00.40% comes from the market for steel, unalloyed	0.00482	kg C deficit
Marine eutrophication				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00097	kg N eq
	99.12%	Operating resources, AE NL 1 GW	0.00096	kg N eq
		97.68% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00095	kg N eq

		01.01% comes from the market for water, deionised, from tap water, at user	9.82729E-6	kg N eq
	00.88%	Constructing materials, AE NL 1 GW	8.53288E-6	kg N eq
		00.37% comes from the market for steel, unalloyed	3.64332E-6	kg N eq
Mineral, fossil & ren resource depletion				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00041	kg Sb eq
	99.73%	Operating resources, AE NL 1 GW	0.00041	kg Sb eq
		99.42% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00041	kg Sb eq
	00.27%	Constructing materials, AE NL 1 GW	1.12083E-6	kg Sb eq
		00.18% comes from the market for nickel, 99.5%	7.41139E-7	kg Sb eq
Ozone depletion				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	4.72348E-8	kg CFC-11 eq
	91.38%	Operating resources, AE NL 1 GW	4.31634E-8	kg CFC-11 eq
		82.23% comes from the electricity production, wind, 1-3MW turbine, offshore	3.88412E-8	kg CFC-11 eq
		08.61% comes from the market for water, deionised, from tap water, at user	4.06663E-9	kg CFC-11 eq
	08.62%	Constructing materials, AE NL 1 GW	4.07136E-9	kg CFC-11 eq
		07.81% comes from the market for tetrafluoroethylene	3.69059E-9	kg CFC-11 eq
Particulate matter				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00080	kg PM2.5 eq
	96.56%	Operating resources, AE NL 1 GW	0.00077	kg PM2.5 eq
		95.28% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00076	kg PM2.5 eq
	03.44%	Constructing materials, AE NL 1 GW	2.74941E-5	kg PM2.5 eq
		02.82% comes from the market for nickel, 99.5%	2.25746E-5	kg PM2.5 eq
Photochemical ozone formation				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00297	kg NMVOC eq
	98.07%	Operating resources, AE NL 1 GW	0.00291	kg NMVOC eq
		96.79% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00288	kg NMVOC eq
	01.93%	Constructing materials, AE NL 1 GW	5.73324E-5	kg NMVOC eq
		01.25% comes from the market for nickel, 99.5%	3.71014E-5	kg NMVOC eq
Terrestrial eutrophication				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.00902	molc N eq
	98.93%	Operating resources, AE NL 1 GW	0.00892	molc N eq
		97.14% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00876	molc N eq
		01.31% comes from the market for water, deionised, from tap water, at user	0.00012	molc N eq
	01.07%	Constructing materials, AE NL 1 GW	9.65721E-5	molc N eq

		00.49% comes from the market for nickel, 99.5%	4.46306E-5	molc N eq
Water resource depletion				
100.00%		AE 1-GW NL, 2050 (Electrolysis plant) - AF	0.91802	m3 water eq
	98.96%	Operating resources, AE NL 1 GW	0.90847	m3 water eq
		96.81% comes from the electricity production, wind, 1-3MW turbine, offshore	0.88875	m3 water eq
		01.69% comes from the market for water, deionised, from tap water, at user	0.01548	m3 water eq
	01.04%	Constructing materials, AE NL 1 GW	0.00955	m3 water eq
		00.60% comes from the market for nickel, 99.5%	0.00548	m3 water eq

Table 39. Contribution analysis for the PEM 1-GW NL 2050 ("Scenario A") for the different impact categories from ILCD 2011 baseline.

Impact category		**Process**	**Amount**	**Unit**
Acidification				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00523	molc H+ eq
	99.09%	Operating resources, PEM NL 1 GW	0.00519	molc H+ eq
		97.98% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00513	molc H+ eq
		01.11% comes from the market for water, deionised, from tap water, at user	5.81005E-5	molc H+ eq
	00.91%	Constructing materials, PEM NL 1 GW	4.76622E-5	molc H+ eq
		00.57% comes from the market for steel, unalloyed	2.96219E-5	molc H+ eq
Climate change				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.77287	kg CO2 eq
	99.12%	Operating resources, PEM NL 1 GW	0.76606	kg CO2 eq
		98.00% comes from the electricity production, wind, 1-3MW turbine, offshore	0.75742	kg CO2 eq
		01.12% comes from the market for water, deionised, from tap water, at user	0.00865	kg CO2 eq
	00.88%	Constructing materials, PEM NL 1 GW	0.00680	kg CO2 eq
		00.76% comes from the market for steel, unalloyed	0.00586	kg CO2 eq
Freshwater ecotoxicity				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	50.91074	CTUe
	99.62%	Operating resources, PEM NL 1 GW	50.71823	CTUe
		99.40% comes from the electricity production, wind, 1-3MW turbine, offshore	50.60580	CTUe
	00.38%	Constructing materials, PEM NL 1 GW	0.19250	CTUe
		00.25% comes from the market for aluminium, cast alloy	0.12606	CTUe
Freshwater eutrophication				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00053	kg P eq
	99.31%	Operating resources, PEM NL 1 GW	0.00052	kg P eq

		98.08% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00052	kg P eq
		01.23% comes from the market for water, deionised, from tap water, at user	6.52849E-6	kg P eq
	00.69%	Constructing materials, PEM NL 1 GW	3.64299E-6	kg P eq
		00.51% comes from the market for steel, unalloyed	2.69470E-6	kg P eq
Human toxicity, cancer effects				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	3.79064E-7	CTUh
	99.59%	Operating resources, PEM NL 1 GW	3.77502E-7	CTUh
		99.04% comes from the electricity production, wind, 1-3MW turbine, offshore	3.75414E-7	CTUh
	00.41%	Constructing materials, PEM NL 1 GW	1.56218E-9	CTUh
		00.34% comes from the market for steel, unalloyed	1.28825E-9	CTUh
Human toxicity, non cancer effects				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	8.81952E-7	CTUh
	99.68%	Operating resources, PEM NL 1 GW	8.79094E-7	CTUh
		99.12% comes from the electricity production, wind, 1-3MW turbine, offshore	8.74185E-7	CTUh
	00.32%	Constructing materials, PEM NL 1 GW	2.85771E-9	CTUh
		00.14% comes from the market for steel, unalloyed	1.20154E-9	CTUh
Ionizing radiation E (interim)				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	1.49940E-7	CTUe
	99.49%	Operating resources, PEM NL 1 GW	1.49174E-7	CTUe
		94.88% comes from the electricity production, wind, 1-3MW turbine, offshore	1.42257E-7	CTUe
		04.61% comes from the market for water, deionised, from tap water, at user	6.91704E-9	CTUe
	00.51%	Constructing materials, PEM NL 1 GW	7.65352E-10	CTUe
		00.42% comes from the market for steel, unalloyed	6.35684E-10	CTUe
Ionizing radiation HH				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.04011	kBq U235 eq
	99.54%	Operating resources, PEM NL 1 GW	0.03993	kBq U235 eq
		92.58% comes from the electricity production, wind, 1-3MW turbine, offshore	0.03714	kBq U235 eq
		06.96% comes from the market for water, deionised, from tap water, at user	0.00279	kBq U235 eq
	00.46%	Constructing materials, PEM NL 1 GW	0.00018	kBq U235 eq
		00.37% comes from the market for steel, unalloyed	0.00015	kBq U235 eq
Land use				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	1.19520	kg C deficit
	99.32%	Operating resources, PEM NL 1 GW	1.18708	kg C deficit

		98.30% comes from the electricity production, wind, 1-3MW turbine, offshore	1.17490	kg C deficit
		01.02% comes from the market for water, deionised, from tap water, at user	0.01218	kg C deficit
	00.68%	Constructing materials, PEM NL 1 GW	0.00813	kg C deficit
		00.58% comes from the market for steel, unalloyed	0.00692	kg C deficit
Marine eutrophication				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00096	kg N eq
	99.35%	Operating resources, PEM NL 1 GW	0.00096	kg N eq
		98.43% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00095	kg N eq
	00.65%	Constructing materials, PEM NL 1 GW	6.26856E-6	kg N eq
		00.54% comes from the market for steel, unalloyed	5.23143E-6	kg N eq
Mineral, fossil & ren resource depletion				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00041	kg Sb eq
	99.69%	Operating resources, PEM NL 1 GW	0.00041	kg Sb eq
		99.46% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00041	kg Sb eq
	00.31%	Constructing materials, PEM NL 1 GW	1.26543E-6	kg Sb eq
		00.24% comes from the market for aluminium, cast alloy	9.97037E-7	kg Sb eq
Ozone depletion				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	4.58390E-8	kg CFC-11 eq
	92.72%	Operating resources, PEM NL 1 GW	4.25012E-8	kg CFC-11 eq
		84.73% comes from the electricity production, wind, 1-3MW turbine, offshore	3.88412E-8	kg CFC-11 eq
		07.98% comes from the market for water, deionised, from tap water, at user	3.65997E-9	kg CFC-11 eq
	07.28%	Constructing materials, PEM NL 1 GW	3.33777E-9	kg CFC-11 eq
		06.48% comes from the Nafion production	2.96995E-9	kg CFC-11 eq
Particulate matter				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00077	kg PM2.5 eq
	99.12%	Operating resources, PEM NL 1 GW	0.00077	kg PM2.5 eq
		98.39% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00076	kg PM2.5 eq
	00.88%	Constructing materials, PEM NL 1 GW	6.78627E-6	kg PM2.5 eq
		00.70% comes from the market for steel, unalloyed	5.44358E-6	kg PM2.5 eq
Photochemical ozone formation				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00293	kg NMVOC eq
	99.06%	Operating resources, PEM NL 1 GW	0.00290	kg NMVOC eq

		98.25% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00288	kg NMVOC eq
	00.94%	Constructing materials, PEM NL 1 GW	2.76467E-5	kg NMVOC eq
		00.82% comes from the market for steel, unalloyed	2.40532E-5	kg NMVOC eq
Terrestrial eutrophication				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00893	molc N eq
	99.25%	Operating resources, PEM NL 1 GW	0.00886	molc N eq
		98.06% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00876	molc N eq
		01.19% comes from the market for water, deionised, from tap water, at user	0.00011	molc N eq
	00.75%	Constructing materials, PEM NL 1 GW	6.70545E-5	molc N eq
		00.63% comes from the market for steel, unalloyed	5.66285E-5	molc N eq
Water resource depletion				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.90520	m3 water eq
	99.72%	Operating resources, PEM NL 1 GW	0.90268	m3 water eq
		98.18% comes from the electricity production, wind, 1-3MW turbine, offshore	0.88875	m3 water eq
		01.54% comes from the market for water, deionised, from tap water, at user	0.01393	m3 water eq
	00.28%	Constructing materials, PEM NL 1 GW	0.00252	m3 water eq
		00.21% comes from the market for steel, unalloyed	0.00187	m3 water eq

Table 40. Contribution analysis for the PEM 1-GW NL 2050 ("Scenario B") for the different impact categories from ILCD 2011 baseline.

Impact category		**Process**	**Amount**	**Unit**
Acidification				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00526	molc H+ eq
	98.71%	Operating resources, PEM NL 1 GW	0.00519	molc H+ eq
		97.48% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00513	molc H+ eq
		01.23% comes from the market for water, deionised, from tap water, at user	6.45561E-5	molc H+ eq
	01.29%	Constructing materials, PEM NL 1 GW	6.79967E-5	molc H+ eq
		01.10% comes from the market for platinum	5.78249E-5	molc H+ eq
Climate change				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.76958	kg CO2 eq
	99.67%	Operating resources, PEM NL 1 GW	0.76702	kg CO2 eq
		98.42% comes from the electricity production, wind, 1-3MW turbine, offshore	0.75742	kg CO2 eq
		01.25% comes from the market for water, deionised, from tap water, at user	0.00961	kg CO2 eq

	00.33%	Constructing materials, PEM NL 1 GW	0.00255	kg CO2 eq
		00.18% comes from the market for steel, unalloyed	0.00136	kg CO2 eq
Freshwater ecotoxicity				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	50.83599	CTUe
	99.79%	Operating resources, PEM NL 1 GW	50.73073	CTUe
		99.55% comes from the electricity production, wind, 1-3MW turbine, offshore	50.60580	CTUe
	00.21%	Constructing materials, PEM NL 1 GW	0.10526	CTUe
		00.14% comes from the market for platinum	0.06890	CTUe
Freshwater eutrophication				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00053	kg P eq
	99.51%	Operating resources, PEM NL 1 GW	0.00053	kg P eq
		98.14% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00052	kg P eq
		01.37% comes from the market for water, deionised, from tap water, at user	7.25388E-6	kg P eq
	00.49%	Constructing materials, PEM NL 1 GW	2.59413E-6	kg P eq
		00.32% comes from the market for platinum	1.68373E-6	kg P eq
Human toxicity, cancer effects				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	3.78221E-7	CTUh
	99.87%	Operating resources, PEM NL 1 GW	3.77734E-7	CTUh
		99.26% comes from the electricity production, wind, 1-3MW turbine, offshore	3.75414E-7	CTUh
	00.13%	Constructing materials, PEM NL 1 GW	4.86818E-10	CTUh
		00.08% comes from the market for steel, unalloyed	2.99059E-10	CTUh
Human toxicity, non cancer effects				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	8.83033E-7	CTUh
	99.62%	Operating resources, PEM NL 1 GW	8.79639E-7	CTUh
		99.00% comes from the electricity production, wind, 1-3MW turbine, offshore	8.74185E-7	CTUh
	00.38%	Constructing materials, PEM NL 1 GW	3.39366E-9	CTUh
		00.32% comes from the market for platinum	2.83190E-9	CTUh
Ionizing radiation E (interim)				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	1.50294E-7	CTUe
	99.77%	Operating resources, PEM NL 1 GW	1.49943E-7	CTUe
		94.65% comes from the electricity production, wind, 1-3MW turbine, offshore	1.42257E-7	CTUe
		05.11% comes from the market for water, deionised, from tap water, at user	7.68560E-9	CTUe
	00.23%	Constructing materials, PEM NL 1 GW	3.51463E-10	CTUe
		00.10% comes from the market for steel, unalloyed	1.47570E-10	CTUe

Ionizing radiation HH				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.04034	kBq U235 eq
	99.76%	Operating resources, PEM NL 1 GW	0.04024	kBq U235 eq
		92.07% comes from the electricity production, wind, 1-3MW turbine, offshore	0.03714	kBq U235 eq
		07.69% comes from the market for water, deionised, from tap water, at user	0.00310	kBq U235 eq
	00.24%	Constructing materials, PEM NL 1 GW	9.66033E-5	kBq U235 eq
		00.08% comes from the market for steel, unalloyed	3.41344E-5	kBq U235 eq
Land use				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	1.19171	kg C deficit
	99.72%	Operating resources, PEM NL 1 GW	1.18843	kg C deficit
		98.59% comes from the electricity production, wind, 1-3MW turbine, offshore	1.17490	kg C deficit
		01.14% comes from the market for water, deionised, from tap water, at user	0.01353	kg C deficit
	00.28%	Constructing materials, PEM NL 1 GW	0.00328	kg C deficit
		00.13% comes from the market for steel, unalloyed	0.00161	kg C deficit
Marine eutrophication				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00096	kg N eq
	99.71%	Operating resources, PEM NL 1 GW	0.00096	kg N eq
		98.69% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00095	kg N eq
		01.02% comes from the market for water, deionised, from tap water, at user	9.82729E-6	kg N eq
	00.29%	Constructing materials, PEM NL 1 GW	2.80016E-6	kg N eq
		00.13% comes from the market for steel, unalloyed	1.21444E-6	kg N eq
Mineral, fossil & ren resource depletion				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00041	kg Sb eq
	99.84%	Operating resources, PEM NL 1 GW	0.00041	kg Sb eq
		99.59% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00041	kg Sb eq
	00.16%	Constructing materials, PEM NL 1 GW	6.40192E-7	kg Sb eq
		00.06% comes from the market for platinum	2.30670E-7	kg Sb eq
Ozone depletion				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	4.69407E-8	kg CFC-11 eq
	91.41%	Operating resources, PEM NL 1 GW	4.29079E-8	kg CFC-11 eq
		82.75% comes from the electricity production, wind, 1-3MW turbine, offshore	3.88412E-8	kg CFC-11 eq
		08.66% comes from the market for water, deionised, from tap water, at user	4.06663E-9	kg CFC-11 eq
	08.59%	Constructing materials, PEM NL 1 GW	4.03289E-9	kg CFC-11 eq

		08.23% comes from the Nafion production	3.86093E-9	kg CFC-11 eq
Particulate matter				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00077	kg PM2.5 eq
	99.42%	Operating resources, PEM NL 1 GW	0.00077	kg PM2.5 eq
		98.61% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00076	kg PM2.5 eq
	00.58%	Constructing materials, PEM NL 1 GW	4.48366E-6	kg PM2.5 eq
		00.36% comes from the market for platinum	2.76682E-6	kg PM2.5 eq
Photochemical ozone formation				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00292	kg NMVOC eq
	99.55%	Operating resources, PEM NL 1 GW	0.00290	kg NMVOC eq
		98.66% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00288	kg NMVOC eq
	00.45%	Constructing materials, PEM NL 1 GW	1.30267E-5	kg NMVOC eq
		00.21% comes from the market for platinum	5.98202E-6	kg NMVOC eq
Terrestrial eutrophication				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.00890	molc N eq
	99.67%	Operating resources, PEM NL 1 GW	0.00888	molc N eq
		98.35% comes from the electricity production, wind, 1-3MW turbine, offshore	0.00876	molc N eq
		01.32% comes from the market for water, deionised, from tap water, at user	0.00012	molc N eq
	00.33%	Constructing materials, PEM NL 1 GW	2.90890E-5	molc N eq
		00.15% comes from the market for steel, unalloyed	1.31459E-5	molc N eq
Water resource depletion				
100.00%		PEM 1-GW NL, 2050 (Electrolysis plant)	0.90510	m3 water eq
	99.90%	Operating resources, PEM NL 1 GW	0.90423	m3 water eq
		98.19% comes from the electricity production, wind, 1-3MW turbine, offshore	0.88875	m3 water eq
		01.71% comes from the market for water, deionised, from tap water, at user	0.01548	m3 water eq
	00.10%	Constructing materials, PEM NL 1 GW	0.00088	m3 water eq
		00.05% comes from the market for steel, unalloyed	0.00043	m3 water eq

4) Flowcharts precision for the ex-ante large-scale LCA models

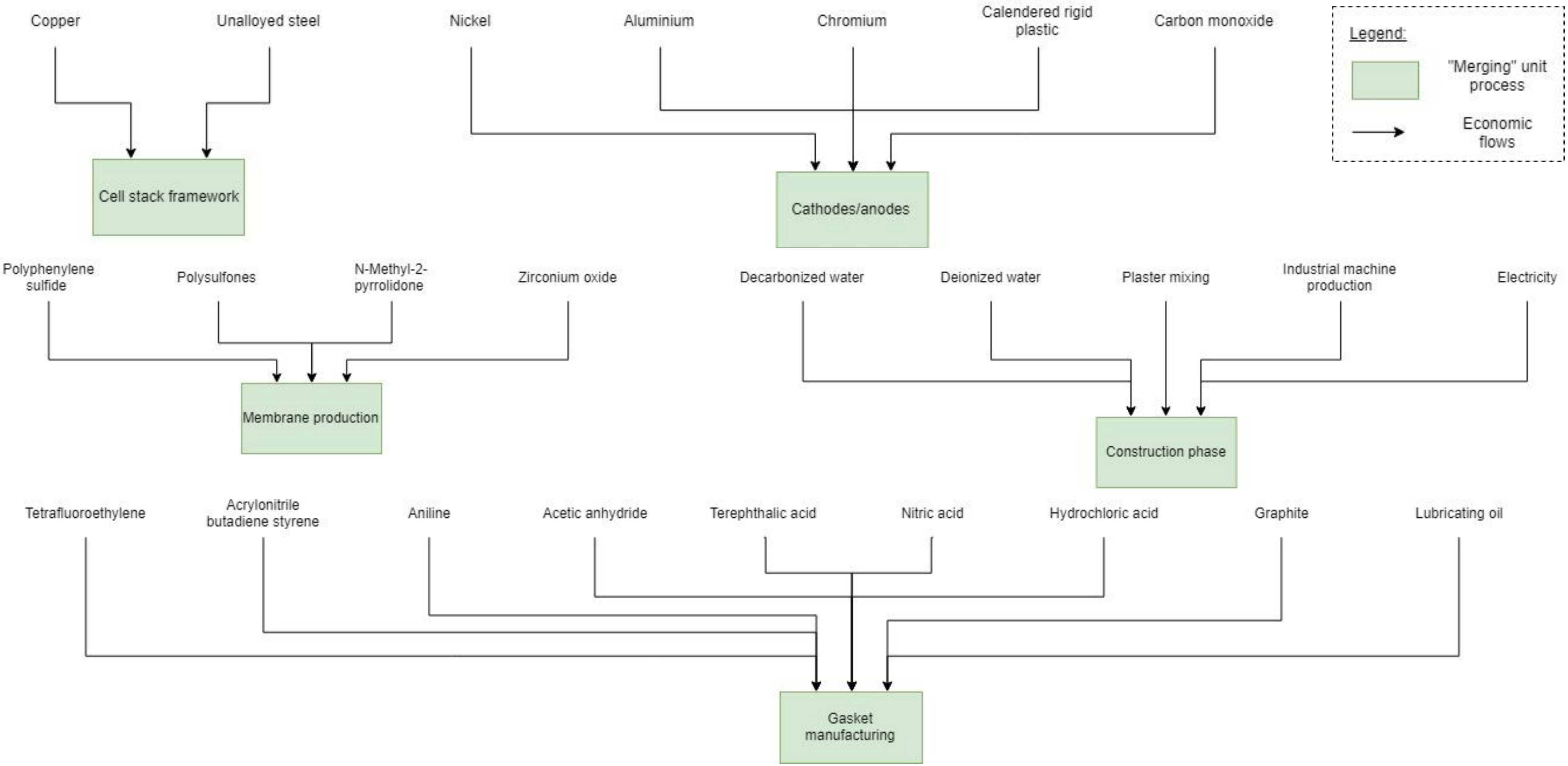


Figure 46. Detailed flows and background processes for the ex-ante large-scale alkaline electrolyser.

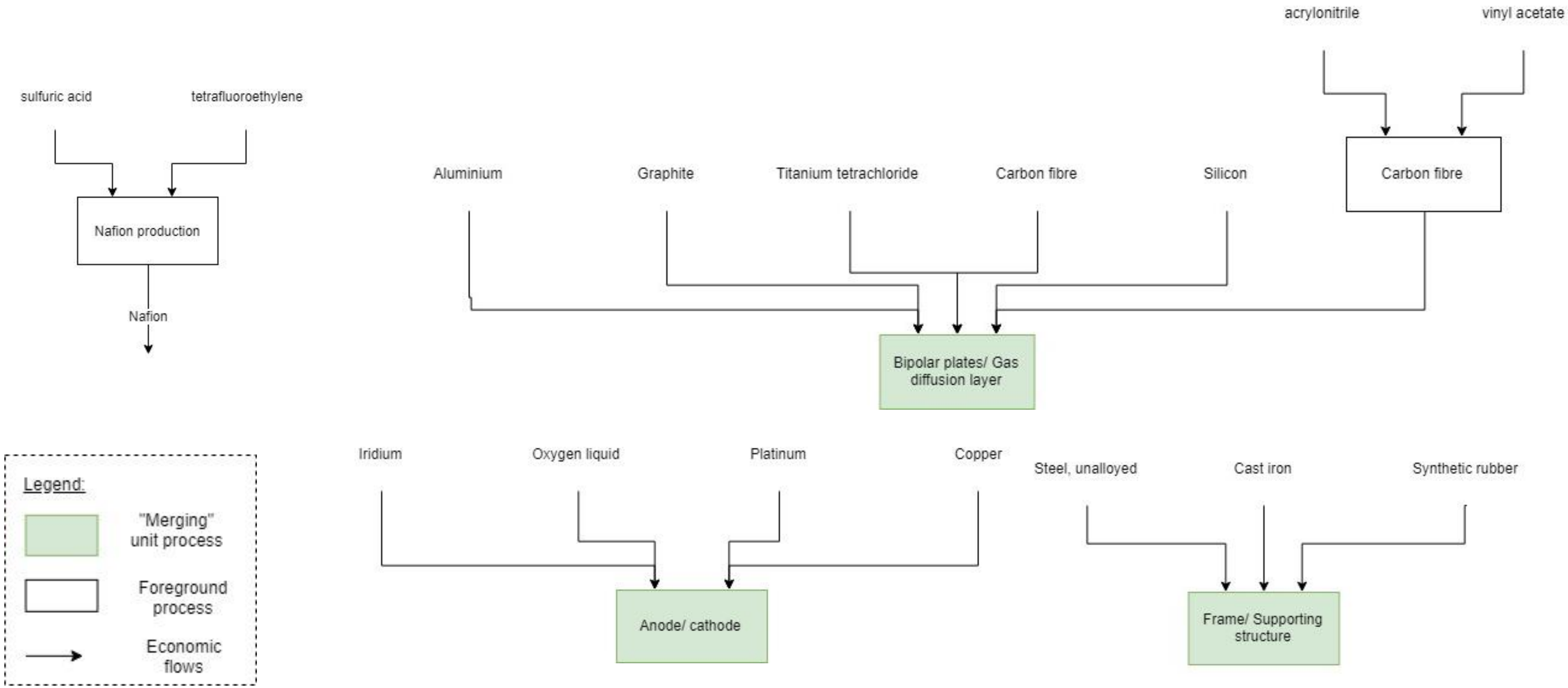


Figure 47. Detailed flows and background processes for the ex-ante large-scale PEM electrolyser.

Note: the "merging" unit process in Figures 46 and 47 are not actual unit processes implemented in OpenLCA. They only disaggregate the simplified version shown in Figures 29 and 30.

5) Interview questions

The interview questions are subdivided into 3 "parts". The first one, used in all interviews, considers broader topics and the general trends or evolutions of the green hydrogen technology, with societal factors (policies, drivers, barriers and competing technologies). The second part considers much more technological aspects and was used only when the interviewees had the knowledge in this (Nouryon and Nel Hydrogen). Finally, the third part considers more open-ending questions and was used through all interviews.

General questions for a broad perspective on the potential futures:

1) Could you tell me more about your position towards the PEM/alkaline electrolysis (position in the company, age in the company, consideration of the technology, research on it)?
2) According to you, what would be the most important developments (4 max) for the technology in the years to come? Example: increase of the current density, a change in the materials to increase the efficiency?
3) Who would be the main actors or kind of stakeholders for the development of green hydrogen in the Netherlands?
4) In your opinion, what would be the most important drivers or potential breakthroughs for the green hydrogen development? (not more than 5, can include stakeholders)
5) In your opinion, what would be the most important barriers or uncertainties for the green hydrogen development? (not more than 5, can include stakeholders)
6) In your opinion, which other alternatives are the most likely to replace the water electrolysis?
7) What is your vision on a large-scale green hydrogen production from the Netherlands by 2050, especially when it concerns its use as a fuel? (order of magnitude for the number of plants, production share, technology used and others)
8) What are the other visions according to you? For example, the previous question concerned more an ideal or desirable vision. What about the *expected* vision?
9) What are the conditions to achieve/fulfil the vision described in question 9?

Below are presented several technical questions, more for scientific experts:

10) What would be the lifespan of?
    a. the electrolyser by 2050? For now, the average value is 20 years. Could we reach 30-40 years? Difference between PEM and alkaline?
    b. the stack or cells? For now, the average is on ca. 10 years. Could we reach 20 years? 30?
11) How would evolve the electrolyser's efficiency between now and 2050?
    a. For alkaline: in theory, the maximum efficiency would be 85% (Ball & Wietschel, 2009, p.290). Currently, it is more around 65-75%. Is it reasonable to consider 85% by 2050?
    b. For PEM electrolysis, it seems to possess more potentials for increased efficiency in the long-term. Now, the efficiency is around 65-82%. Is there a theoretical maximum efficiency? Could we reach 90% by 2050?
12) How would the material/energy requirements evolve between the current state and 2050?
    a. The electricity needs are worth for now around 50 $kWh_e/kg\ H_2$ (or 180 MJ). Which potential decrease could occur in the future with the upscaling effect? A 20% decrease?
    b. The water needs may become a delicate issue, depending on the location. The general value is around 10-15 kg H_2O/kg H_2. Could there be a decrease of 10, 20 or 30%?
    c. The potassium hydroxide used as an electrolyte in the alkaline electrolysis can become a sensitive parameter for the future. For now, the average value is around 1-2 g

KOH/kg H_2. Could we decrease its needs by 20%? More? Less? Does an alternative exist?

   d. The polytetrafluoroethylene seems to be an influencing parameter from my first LCA models. How would you consider its evolution in the future?

13) PEM technology uses some specific materials which can be sensitive, such as Titanium, or Platinum/Platinum group[2]. In your opinion, will there a decrease in their needs (e.g. -20%)? Or which "better" materials could substitute them? With the same equivalences?
14) What would be the average power scale for an electrolyser installation/plant? In MW? Or GW?
15) If I take 100 MW installation, what would be (in order of magnitude) the number of cells and stacks? And the average hydrogen output (in kg/h or kg/year)?

Final/opening questions:

16) Would you have specific data or recommendations concerning the Balance of the Plant (BOP)? For example, storage system, water feed, supporting structures.
17) Are there some crucial elements that I missed or have not been covered in this interview?

6) Activities for the elaboration of the scenarios:

6.1) Workshop "Developing the supply chain for electrolysis", 12/03/2019

This workshop was organised by the Shared Innovation Program VoltaChem. VoltaChem was founded in 2014 by the Dutch Institutes TNO and ECN, in collaboration with industrial and academic partners (VoltaChem, 2014). The workshop was intended to discuss the knowledge of the market, to understand the technical challenges and the infrastructures for testing novel components. To do so, three main questions were addressed during the session:

- What are the technical challenges in the PEM electrolyser?
- What are expectations with respect to the cost level of future electrolysers and their components?
- What are the potential markets, the key drivers and uncertainties?

The workshop was intended for technology and component suppliers. It was held in the ECN research centre in Petten, on the 12th of March 2019. Several presentations were given, including one about the expectations of the hydrogen market in the future, one about the opportunities in the hydrogen value chain and one about the PEM water electrolyser components and their limits.

The main information communicated through this workshop is given below.

ECN has actually stopped hydrogen studies in 2010 but a new trend for hydrogen topic has been noticeable since 2015-2016. Several collaborations between companies have appeared with important stakeholders such as Gasunie or TenneT. The current Dutch gas network net capacity is evaluated at 350 GW in comparison to the net capacity of the Dutch electricity network at 20 GW. Therefore, there is obviously much more potential for hydrogen as a gas than with electricity. The high costs for the PEM electrolysis mostly come from 2 reasons:

- The expensive materials, especially regarding the membrane, the catalyst or the electrodes
- The absence until now of a high-volume market

[2] The platinum group consists in ruthenium, rhodium, palladium, osmium, iridium, and platinum (all noble, precious metallic components)

The lifetime of electrolysers ranges between 40,000 and 80,000 hours. The goal of ECN is to implement a GW-scale installation by 2030. For comparison, most of the PEM electrolysers nowadays reach a maximum of several MW.

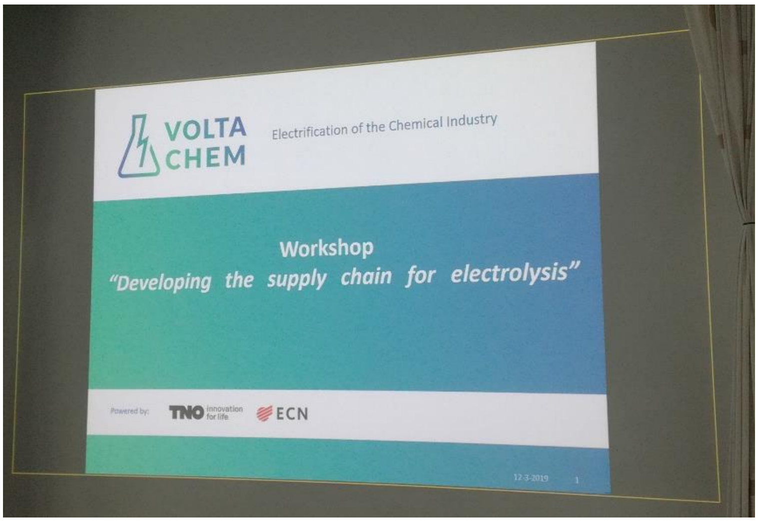
Concerning the scenarios, a projection indicates that only in the South-Holland Province and only from offshore wind turbines, there would be an annual Dutch hydrogen production of 100 to 150 kton. By 2050, 38% of the total Dutch energy production could come from hydrogen.

A presentation highlighted the need to start constructing a consistent and clear supply chain for the PEM electrolysis. This concept is shared by different papers or books such as Ball & Wietschel (2009) who already mentioned that joint collaboration between stakeholders is strongly recommended for a maintained development of the green hydrogen technology. Some models for the supply chain start to be constructed and there is a growing interest from companies, proving that the PEM starts to become economically viable. A SWOT analysis has been conducted and showed that blue and grey hydrogen –coming from fossil fuels-based technologies with and without carbon capture system respectively – may be the potential threats against the green hydrogen development. Furthermore, the adjustment of the gas infrastructure for the hydrogen transport may also hinder the hydrogen economy development. Again, the need to look for cooperation between OEM's is stressed out for the value chain.

Finally, concerning the more technical issues, several recommendations were given such as: using alloy catalysts or doped metal oxide, using protective coatings or alternative materials for the Porous Transparent Layer, using thinner membranes for higher current density and consequently higher production rate. An important message brought by this presentation is that all the elements present in the electrolyser are interconnected. Therefore, an improvement one specific element may turn out to be not so productive. For example, a possibility to increase the electrolyser's efficiency is through increasing the current density. To do so, the membranes should be thinner, but this would lead to more gas cross-over. That is why an improved electrolyser system should consider the system as a whole.

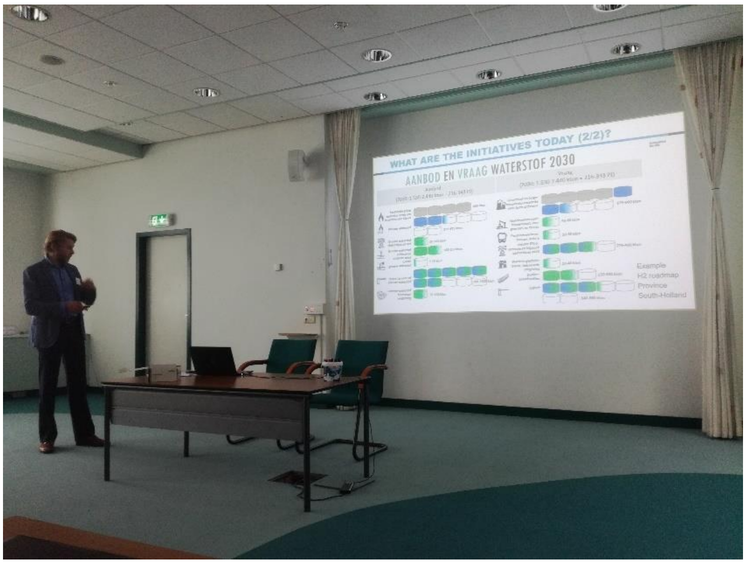
To conclude, different potential direction for development are described in this section. The goal with the plants is to increase their capacities beyond 100 MW. The main improvements to come for the electrolyser are to solve the materials issue, to reduce the CAPEX. Other technical improvements may be achieved in the future such as:

- Increasing the current density
- Increasing the operating temperature
- Increasing the stack area
- More optimal design with less material parts and reduced materials needs



Picture 1: Presentation slide for the workshop

Picture 2: Introduction by Arend de Groot, one of the lecturers and organiser of the workshop.



Picture 3: Lecture by Lennart van der Burg about hydrogen perspectives.

The different presentation slides are available online at https://www.voltachem.com/news/huge-opportunities-for-electrolyzer-technology-in-future-gigawatt-green-hyd

6.2) Interview with Albert van der Molen, Stedin, 18/03/2019

Albert van der Molen is a project leader of a Power-to-Gas installation in Rozenburg, funded by Stedin. Stedin is a system operator for gas and electricity present in South-Holland, Utrecht, Amstelland, Kennermeland and Friesland. One of the main goals of the group and the Rozenburg project is to stimulate the market and proves that the concept is viable. Albert van der Molen kindly accepted to do an interview and provide a visit to the installation. The Power-to-Gas installation seeks to convert electricity into hydrogen and then converts the latter into methane for injection in the gas grid. 8 PEM electrolysers are used, with an individual production rate of 0.5 Nm^3/h (a total of 4 Nm^3/h) with a power range in 15-20 kW. The hydrogen is then mixed with carbon dioxide to produce methane and water, following the equation: $4\ H_2 +\ CO_2 = CH_4 + 2\ H_2O$.

The main information given during the interview is provided below.

Albert van der Molen has previously worked on hydrogen projects in the North of the Netherlands before working in Rozenburg, such as the pilot project for hydrogen injection in the natural gas network on Ameland's island. Rotterdam remains one of the hotspots for hydrogen development in the Netherlands, in parallel with the Northern regions which possess strong goals. Nevertheless, there is no competition atmosphere between the two regions.

The relevance of the technology by 2050 has been discussed: would an electrolysis still make sense by 2050? Other alternatives may be found in the meantime. As potential substitutions for the hydrogen production particularly, the nuclear-based hydrogen production or the different hydrogen studies conducted by DIFFER (Dutch Institute For Fundamental Energy Research) have been mentioned (DIFFER, 2019). However, as the nuclear energy potential is not yet strong in the Netherlands (and would make much more sense in countries such as France), and as the plasma physics are still under research, the focus was put on electrolysis for the Master thesis.

The most important developments for the electrolysis are to increase the overall efficiency which was subdivided into two parts:

- Decrease the electricity input necessary for the production
- Increase the energy content for the hydrogen output

A growing trend has been observed for the last few years, since the efficiency of the electrolysers a decade ago was around 40% and nowadays, it is around 60%. The overall efficiency could also be improved by reusing the oxygen that is produced in the electrolysis. Moreover, a reduction in the amount of platinum or other noble metals needs would also be really valuable, especially for the PEM technology.

According to Albert van der Molen, one of the most important drivers is public opinion. One goal set by the Dutch government is to be natural gas-free by 2050 but the energy demand to warm households will still be present. Therefore, three options are available for house warming:

- District city heating which can have limited potentials depending on the place to consider and can rely on fossil fuels.
- Heat pumps are especially efficient with well-insulated households. There is a project in Hoogeveen which aims to use hydrogen to warm modern houses. This solution may be considered as not optimal since these modern houses are well insulated. In the long term, a heat pump could fit much better.
- Gas with hydrogen as a source.

Studies from Stedin showed that the gas from hydrogen is the most relevant option for 75% of the 3,000 neighbourhoods covered by the company.

The most important barriers mentioned are all the potential risks or accidents in the early phases (early installations, pilot plants, demonstration projects…). One accident in these systems would hinder significantly the technology development and would have much more impacts than in 20 years when the technology may be already well established. Otherwise, the "fake news" is also a potential threat according to Albert van der Molen, as they could spread wrong or unfounded notions among the public.

Concerning the more general development of the green hydrogen technology, Albert van der Molen thinks that the first projects will consider a small scale before reaching large-scale with a backbone structure. Hydrogen produced from wind turbines will probably be produced on-site (so offshore when we consider offshore wind turbines for instance) mainly because the pipelines' costs are 10 to 20 times less expensive than electric cables. Blending gas – i.e. injecting a limited amount (up to 10-20%) of hydrogen in the natural gas network – can be interesting if there is no need to adjust the appliances at the end-of-the-line. However, if gas appliances are considered, for example, adjustments will be necessary. Blending gas has another inconvenient in the fact that it still relies on natural gas or other unsustainable products. That is why Albert van der Molen is in favour of making a full shift to 100% hydrogen transportation through pipelines. Some tests have been achieved with sending hydrogen through PVC pipelines. Although some studies on hydrogen indicate that adjustments of the infrastructures will be necessary to transport hydrogen with less porous metals, such as stainless steel, no leakage has been detected for the small-scale test from Stedin. Albert van der Molen point out that there are already leakages issues or adjustments made for the current gas network. Even though some adjustments will be necessary for some parts of the gas infrastructure, Albert van der Molen does not think that the costs will be so significative, and the situation may be rather similar to a "Business-as-usual" case.

Finally, upscaling the system will most likely reduce the system's cost. The smaller the installation is, the higher the cost is per functional unit. To conclude, Albert van der Molen reminded to temper the hopes put on hydrogen from the stakeholders (scientist, public, municipalities, politicians). Hydrogen may have strong potentials, it should not be considered as *the* solution that is going to solve major issues in the next few years.

Pictures 4 & 5: Power-to-gas installation in Rozenburg. The different elements are installed in the containers.

Picture 6: PEM electrolysers in the installation

Picture 7: System for Methane fabrication from hydrogen and carbon dioxide

6.3) Interview with Thijs de Groot, Nouryon, 02/04/19

Thijs de Groot is an “Innovation technologist” at Nouryon and kindly accepted an interview for the Master thesis. Nouryon is a chemical manufacturer, operating in over 80 countries. This de Groot’s work mainly focuses on “green hydrogen”, in collaboration with suppliers, research centres, universities. According to him, the electrolysis technology is still expensive, but the capital costs will decrease in the years to come, making this technology economically viable. When comparing alkaline and PEM electrolysers, in his opinion, the alkaline will likely remain the most used alternative. Currently, a lot of research institutes and studies promote the PEM technology with significant efforts. This generates some kind of “biased unbalance” in the attention paid on the technology in comparison with alkaline.

One of the biggest issues from the PEM technology remains its use of noble metals, such as Iridium, a rare element on Earth’s crust. Concerning the latter, the current production rate would enable to install 14 GW-PEM electrolysis/year. The figure may sound big; however, it is relatively low compared to the annual primary energy consumption on the planet (around 13,500 TWh/year, equivalent to a power of ca. 18000 GW). At the same time, if the Iridium requirement for the PEM stack decreases, the system’s lifespan would be impacted. A trade-off must be found consequently.

The most important development for the alkaline electrolysis is to increase the current density. Even commercial products such as the ones sold by Nel Hydrogen possess relatively low current densities (around 0.2 A/cm² max). However, some trials and experiments are made in order to reach a current density of 1 A/cm². In this perspective, the PEM technology offers some advantages with current densities reaching 2 A/cm² nowadays, and a possibility to go beyond 3 A/cm² by 2050.

The most important development for the PEM electrolyser is the decrease in material costs/requirements, the improvement of the supply chain framework and of the technical characteristics of the membrane.

The most important drivers/actors are the industries naturally and the presence or implementation of an efficient supply chain model. TenneT and Gasunie are obviously important grid operator actors. ENGIE, Shell, Hydron energy and other smaller companies are important energetic actors. However, to date, there is no strong leader in the electrolyser’s production, at least in the Netherlands. The support from European institutions can also be really helpful with, for example, the Renewable Energy Directive from 2009 which mentions specifically that 10% of European countries’ transport fuels should come from renewable energy sources by 2020 (European Commission, 2019). An example of a political/economic measure that would promote hydrogen technology is to settle the sales price. According to Thijs, there is a need for regulation’s implementation and for the availability of low-cost electricity. Regarding the latter element, wind parks become bigger and bigger and their production shall significantly increase in the coming years in Europe. In this sense, the problem of mismatch between supply and demand can arise, due to the intermittent factor of wind energy production. Consequently, Thijs believes that connections between wind parks and industries should be strengthened. Public opinion is also an important aspect of the good implementation of green hydrogen technology. Nouryon is involved in several projects to promote the technology and to increase public awareness on the hydrogen technology (Nouryon, 2018a, 2018b).

For the wind-based electrolysis, in the near-term future, the electrolyser system will likely be installed inland, since part of the installations is already present. For example, the wind turbines are already built, and the electric cables are already present. Installing the electrolyser system on an offshore platform would likely increase the costs, inducing more delicate maintenance. This second perspective should be considered with a 2030+ vision. Nonetheless, there are still some projects for “offshore electrolysis” in the harbour of Rotterdam and gas pipelines that could be reused already exist in the North Sea (Janssen, 2017; Port of Rotterdam, 2019).

One of the main barriers for the green hydrogen technology comes again with the wind parks capacities which are still increasing. This situation may lead to the issue of the system’s ability to sell its electricity. Therefore, strong relationships between wind parks and industries should be established but to date, there is no proper business case yet available. The political landscape can also have an influence on technology development. As recalled by Thijs, any large upscaling process will require costs and therefore, political support. Thijs used the example of Germany who developed significantly in the 2000s the solar energy with strong political support, with sometimes mixed outcomes. The blue hydrogen can be an alternative preferred to green hydrogen. Yet, this would imply more costs and more installations with Carbon Capture Systems or Storage and equivalent. High-temperature solid oxides may also become a competing technology, but its specific operating conditions would induce lower flexibility than other options. Finally, the Anion Exchange Membrane (AEM) is described by Thijs as a kind of "a mix between PEM and alkaline" which would make it interesting. AEM is rather similar to PEM but avoids the use of noble metals. However, there are still some strong challenges to overcome before reaching a design level ready to be used for installations.

Centralised systems would enable significant costs reductions thanks to the economy of scale. The existing gas network in the Netherlands and its neighbourhood is another element that favours a centralised approach. According to Thijs, decentralised systems do not seem to be the most optimal option, especially in the long-term. Thijs considers that the geographical location is also another important element to consider. Several questions come from it, such as: "Is it preferable to produce hydrogen in the Netherlands or in another country (neighbour)? Should hydrogen be imported?". This recalls a remark made during the ECN/TNO workshop on PEM technology, where a SWOT analysis showed that industrialisation taking place in the US or Asia may be a threat to green hydrogen development in the NL. The interaction between the different countries is then also important.

Looking at the transportation aspect, Thijs has heard from Gasunie members that a significant part of the gas network could be reused "in its current form" for hydrogen transportation. Consequently, a shift to 100% of hydrogen transport would not induce a significant change, except for some specific elements, such as the compressor. In fact, the latter is not adapted for high-pressurised (several hundred bars) hydrogen transports and would need adjustment or replacement.

Considering more technical aspects, Nouryon produces potassium hydroxide (KOH) from potassium chloride (KCl). The former is later used as an electrolyte for alkaline electrolysers. If the potassium chloride process reveals to be unsustainable, an alternative could be the use of sodium hydroxide. Nouryon produces sodium hydroxide (NaOH) from chloride sodium (NaCl) for their chlor-alkali process. This process could be more sustainable than the potassium chloride alternative. If NaOH is used as an electrolyte instead of KOH, the efficiency of the electrolyser will reduce by ca. 10% but the sustainable gain may compensate for the loss. Furthermore, the potassium hydroxide electrolyte can be really delicate to treat or recycle with relatively high environmental impacts.

The Nafion membrane comes from the fluorine industry which possesses relatively dirty emissions. Among the suppliers for this membrane to Nouryon, there are DuPont and 2 Japanese companies.

Electrodes and membranes possess usually a lifespan of 5-10 years. Actually, the lifespan of the stack could be longer than 10 years. The problem arises only because of the loss of efficiency during its use. At some point, the stack is still functioning, but it becomes more financially interesting to replace it with a new model. A lower decay grade could be achievable with technological improvements. However, this improvement would not be so interesting from an industrial point of view. Industrial stakeholders possess specific requirement such as the return on investment in a short time. The other elements being not a part of the stack (Balance of the Plant) could be slightly adjusted to last longer.

The efficiency of the electrolyser must be clearly defined (state clearly whether HHV is considered: High Heating Value or LHV: Lower Heating Value). If HHV is considered, for an AE stack, the efficiency is around 80% nowadays. There should be a possibility to increase it to 90% with a lower current density. For the PEM stack, nowadays, we are around 75%. Normally, 90% should be reachable in

2030+. For improvements, a trade-off always occurs between capital costs and efficiency. The most important factor driven by costs reasons is the decrease in the capital costs (so there is not so much focus on the efficiency).

The water consumption should not become a delicate issue and its impact should be negligible, at least in the Netherlands (where access to water is not a serious issue). However, the water resource aspect may become more delicate to handle in warmer countries (Arabic countries, Africa, Australia…).

If a goal set is to reduce the amount of KOH used as an electrolyte, improvements can be achieved with a design change. Currently, there is a small leakage of KOH that is present in the outflow of the electrolyser, even though it is not considered as an issue for the system. Nevertheless, a potential improvement would be to reduce as much as possible the leakage's amount. It is reasonable to expect that the value of KOH losses will decrease to a few mg/kg of H_2.

Changing materials in the PEM electrolyser is always delicate to handle. There is always the dilemma between "what is possible" and "the level of efficiency that is maintained". A choice must usually be made between cost efficiency and lifespan.

Currently, the largest stack has a capacity of 6 MW. Being optimistic, a single stack may reach a maximum of 20 MW if all parameters are aligned. Nevertheless, the 20 MW should be considered as a chemical/physical limit to the upscaling process. So, for example, when one considers a 1 GW plant, fifty 20-MW stacks would be necessary then. A current example from Nouryon is a 200 MW plant which possesses 32 stacks (so each stack has a capacity of 6.25 MW). The goal of the Netherlands is to possess an electrolysis production capacity of 3-4 GW by 2030 and 20 GW by 2050.

Looking at the Balance of the Plant (BOP), many scaling-up effects may be applied to the pumps, storage systems. Therefore, the impacts of these specific elements, in general, will be reduced.

The number of operating hours for the electrolyser is also another important aspect that can influence the results. Batteries can be an option to increase this value and therefore the efficiency of the system. If the wind park is considered as an electrical supplier, a typical value of system use could be around 5,000 h/year. Estimations can be made by looking at future plant installations.

6.4) Interview with Steve Szymanski, Nel Hydrogen, 03/04/19

As a note for the context, Steve Szymanski possesses much more background connected to the PEM technology than for the alkaline one.

Concerning the development of the PEM technology, a strong focus is made on the CAPEX and cost reduction through a combination of upscaling effects and reduction of the material's needs. The efficiency of the stack could be increased through material innovation. As an example, Nel Hydrogen possesses now a plant in Norway with the goal to scale-up the alkaline electrolyser's production capacity. As a matter of fact, a decrease in stack costs can be achieved with new process equipment. Despite the presence of the alkaline technology, the PEM technology is expected by Nel Hydrogen to become the most used electrolysis alternative in the future. In fact, it is expected that the CAPEX from PEM electrolysers will reach the same level (and even go below) as the ones from alkaline electrolysers. Furthermore, the PEM technology fits better for systems dealing with renewable energy resources. Even though the alkaline technology would be able to deal with large-scale wind parks, PEM still performs better when it comes to dynamic behaviour and loading factors. The alkaline electrolyser can achieve some ramping but not as fast as PEM. Naturally, in baseload applications, both technologies could fit.

The political support is relatively important at a large scale, through incentives or carbon prices for example. Currently, hydrogen from gas (SMR and equivalent) is still really cheap in comparison to electrolysis, so it is particularly hard to compete. An interesting example is the State of California who possesses a “low-carbon” fuel standards. Companies can get credits for their sustainable technologies and sell them afterwards. This is an example of a political measure that promotes the development of more sustainable fuels. Otherwise, there is no real technological barrier for the electrolyser’s implementation. Yet there is a tough competition with based-battery electric cars. The latter possess a non-negligible momentum. Nevertheless, vehicle transport remains the main field where hydrogen could achieve an important breakthrough. There are strong initial barriers for such a vision to be achieved, mainly the costs for the infrastructure. Therefore, there is a high initial cost. However, once this barrier has been overcome, the implementation path should be much easier afterwards.

7) Supporting elements and figures for the scenario development

Below are presented several documents that were useful for the scenario’s development, subdivided into different topics.

7.1) Market penetration

Some supporting documents about the market’s penetration are provided below.

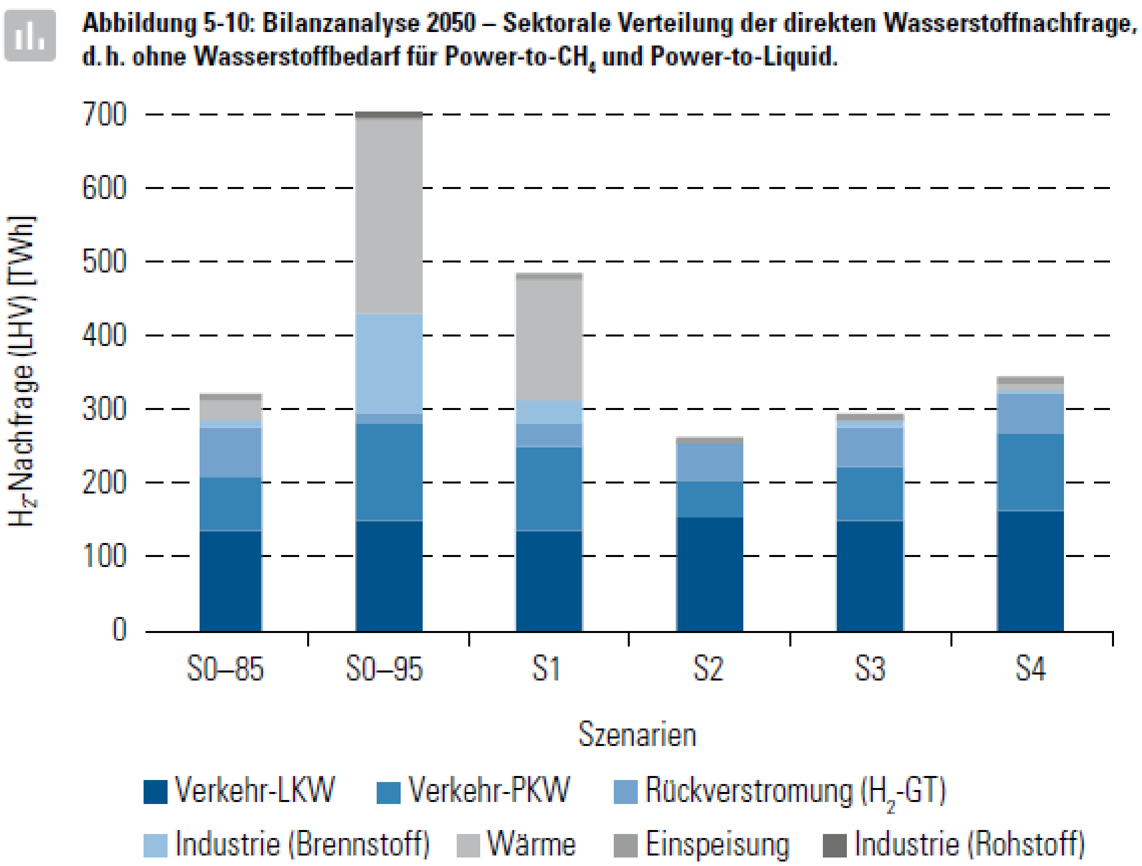


Figure 48. Projections for the hydrogen market penetration, by sectors, by 2050, in Germany (extracted from Smolinka et al. (2018, p.73)).

Figure 48 mainly shows transport is likely to become the market’s sector with the largest potential in Germany, in the future (Verkher = “transport”, PKW = “individual car”, LKW= “heavy truck transport”).

The figures below provide examples of hydrogen applications' development and scales:

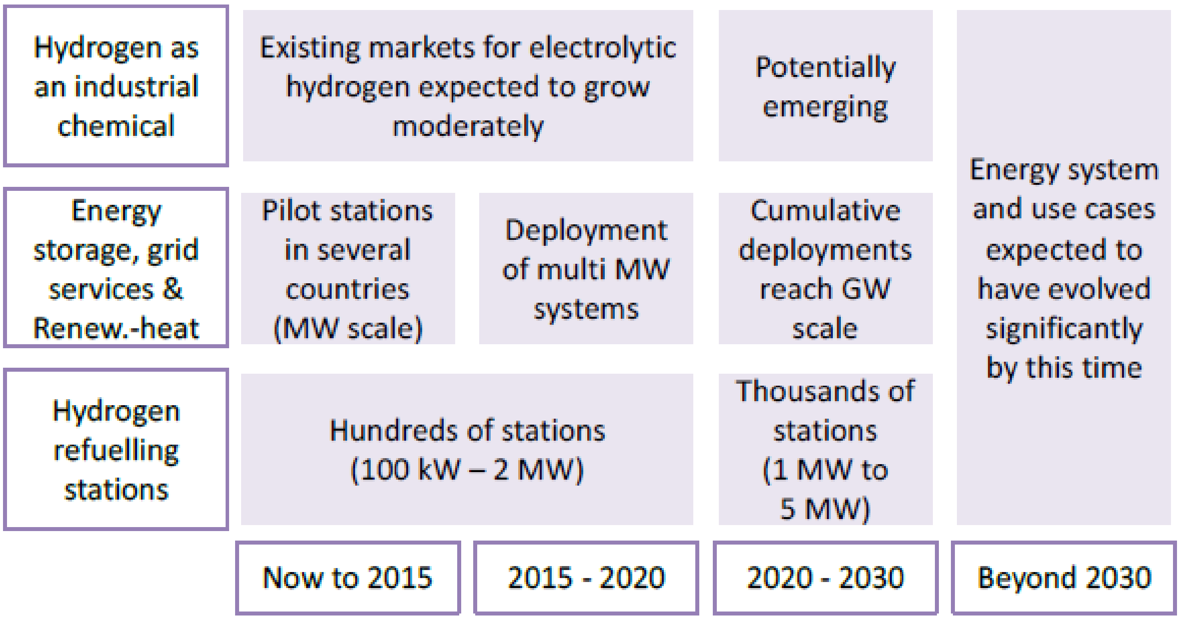


Figure 49. Projections for the hydrogen breakthrough in the market (extracted from Bertuccioli et al. (2014, p.5))

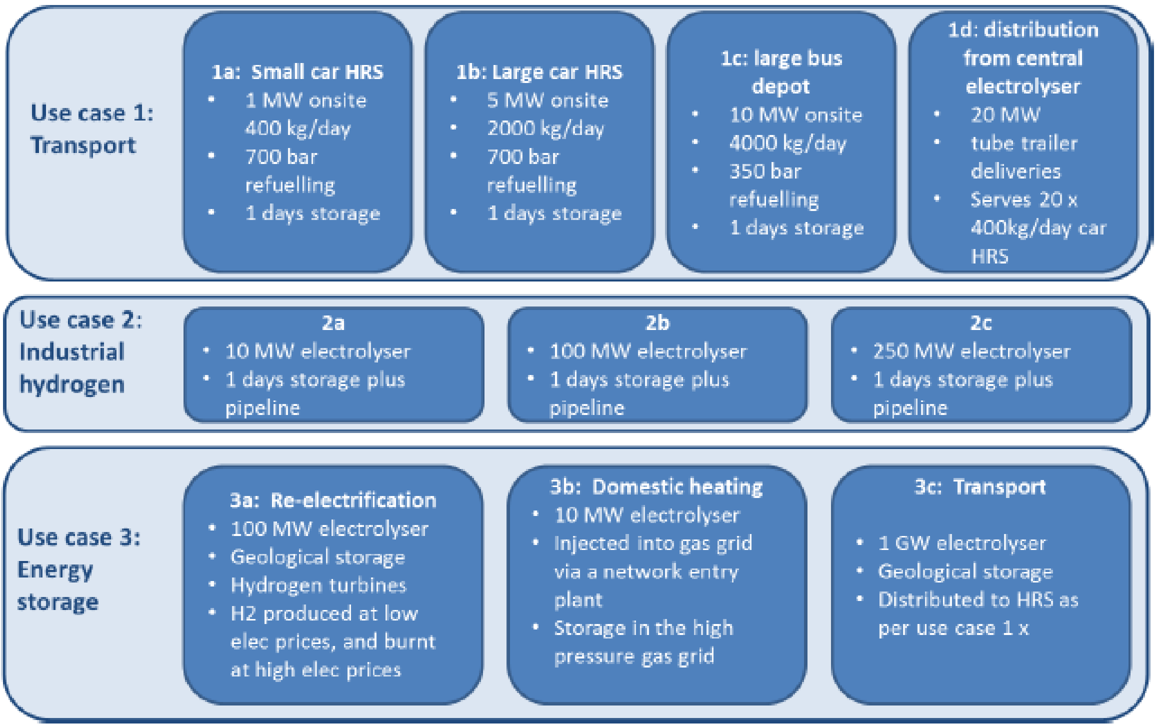


Figure 50. Summary of application and use cases (extracted from Bertuccioli et al. (2014, p.20))

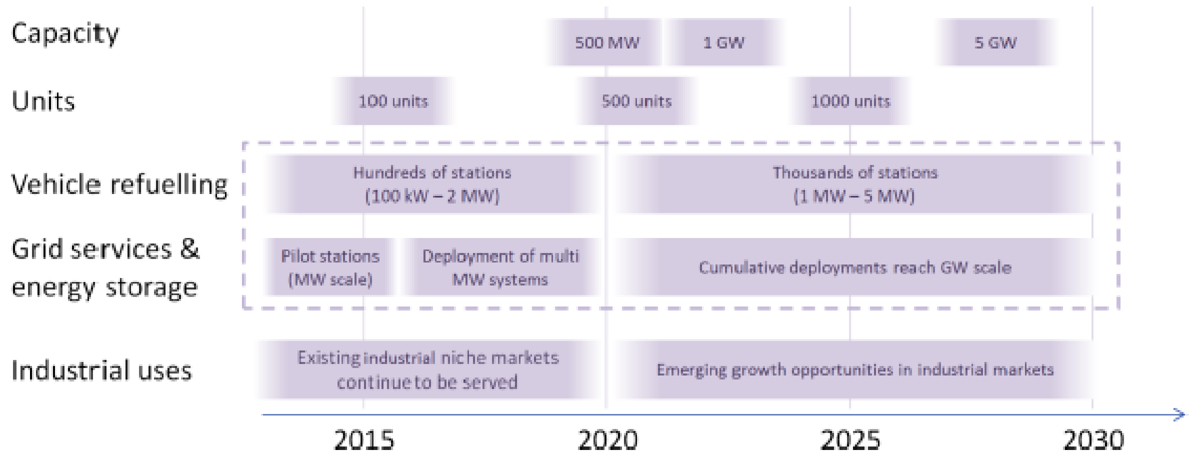


Figure 51. Projections for the expected development of the electrolyser's applications (extracted from Bertuccioli et al. (2014, p.47))

Evaluation of the Dutch car fleet in the North of the NL: ("Scenario B")

In "Scenario B", most of the hydrogen is produced in the North of the NL and used for the Dutch car fleet in this region. Therefore, to estimate the hydrogen cars' penetration, some order of magnitudes were necessary. CBS (2014) indicates on a Netherlands' map that on average, 1,000 Dutch residents in the Northern regions possess 500 cars. Statista (2019) provides the Dutch population per region in 2018. As the Dutch population is not expected to increase significantly in the future (CBS, 2017; CBS StatLine, 2017; PopulationPyramid.net, 2017; World population review, 2019; Worldometers, 2019), these numbers are taken as a reference for the 2050's scenario. Furthermore, the goal for 2050 is to get an order of magnitude and not a precise number. The regions considered for the "North of the NL" are the following (arbitrary choice):

- Groningen: 582,944 inhabitants in 2018

- Drenthe: 492,100 inhabitants in 2018

- Friesland: 647,268 inhabitants in 2018

- Overijssel: 1,151,501 inhabitants in 2018

- Flevoland: 411,670 inhabitants in 2018

- North-Holland: 2,831,182 inhabitants in 2018

Based on the numbers above, the total Dutch population in the North of the NL is worth 6,116,665 inhabitants in 2018, equivalent to 3,058,333 cars. The Dutch population is evaluated in 2018 at 17.2 million inhabitants (Statista, 2019b), equivalent to 8.5 million cars. So, the North of the NL (as defined above) would share 35.60% of the Dutch fleet car. As the thesis considers a future state (in 2050) and there can be discussions on which regions to consider for the "North of the NL" geographical definition, an average value of 30% of the Dutch fleet car has been chosen for "Scenario B" (with H_2-cars being located in the North of the NL).

7.2) Lifespan of the electrolyser

Some additional documents about the electrolyser's lifespan are provided below.

System lifetime (1)			Today	2015	2020	2025	2030
years	Alkaline	Central	**25**	**26**	**28**	**29**	**30**
		Range (2)	20 - 30	22 - 30	25 - 30	28 - 30	30 - 30
	PEM	Central	**20**	**22**	**25**	**28**	**30**
		Range	10 - 30	14 - 30	20 - 30	25 - 30	30 - 30

(1) Typically includes several stack replacements or overhauls under continuous operation.

(2) Range excl. outlier with 50 years lifetime

Figure 52. Projections by 2030 for the system's lifespan (extracted from Bertuccioli et al. (2014, p.65))

Some projections are available concerning the stack's lifetime (**Figure 53**).

Stack lifetime (1)			Today	2015	2020	2025	2030
hours	Alkaline	Central	**75,000**	**80,000**	**95,000**	**95,000**	**95,000**
		Range	60,000 - 90,000	70,000 - 90,000	90,000 - 100,000	90,000 - 100,000	90,000 - 100,000
	PEM	Central	**62,000**	**67,000**	**74,000**	**76,000**	**78,000**
		Range	20,000 - 90,000	30,000 - 90,000	50,000 - 90,000	55,000 - 90,000	60,000 - 90,000

(1) Available data is representative of continuous operation. Stack lifetime under dynamic operation may vary.

Figure 53. Projections for the stack's lifetime (extracted from Bertuccioli et al. (2014, p.65))

Voltage degradation:

Concerning the electrolyser itself, the main factor that influences its lifespan is the voltage degradation.

The voltage degradation of an electrolyser is the overpotential that is required for the electrolysis to maintain its hydrogen production rate constant. This type of degradation is one of the main factors influencing an electrolyser's lifespan. Due to decay processes, the overpotential increases through the lifespan of the electrolyser with the increased cell resistance in different electrolyser's components (electrolyte, catalyst…). Values accepted for the state-of-the-art system under continuous operation are in the range 0.4 to 0.5 µV/h for alkaline and PEM electrolysers, even though some literature indicate a value as high as 15 µV/h for PEM (Bertuccioli et al., 2014; Smolinka et al., 2018). If the value of 0.5 µV/h is taken as an average reference, an electrolyser system would lose 10% of its efficiency after 60,000 hours of operation (Bertuccioli et al., 2014). As mentioned by Thijs de Groot (Nouryon, Appendix 6.3), an electrolyser rarely fails catastrophically, and a replacement is achieved only because it is more economically beneficial to do so, not because the system is inoperable.

Smolinka et al. (2018) made projections on the voltage degradation for different electrolysers technologies through the years (cf. Appendix 7.3). By 2050, the degradation process is the lowest with the alkaline technology with a voltage degradation value of ca. 1 µV/h. The PEM technology has a higher value at 2 µV/h, even though it has had the best improvement in the voltage degradation. In this sense, alkaline may provide a longer lifespan than alkaline.

The projections on voltage degradation through time are shown in **Figure 54**.

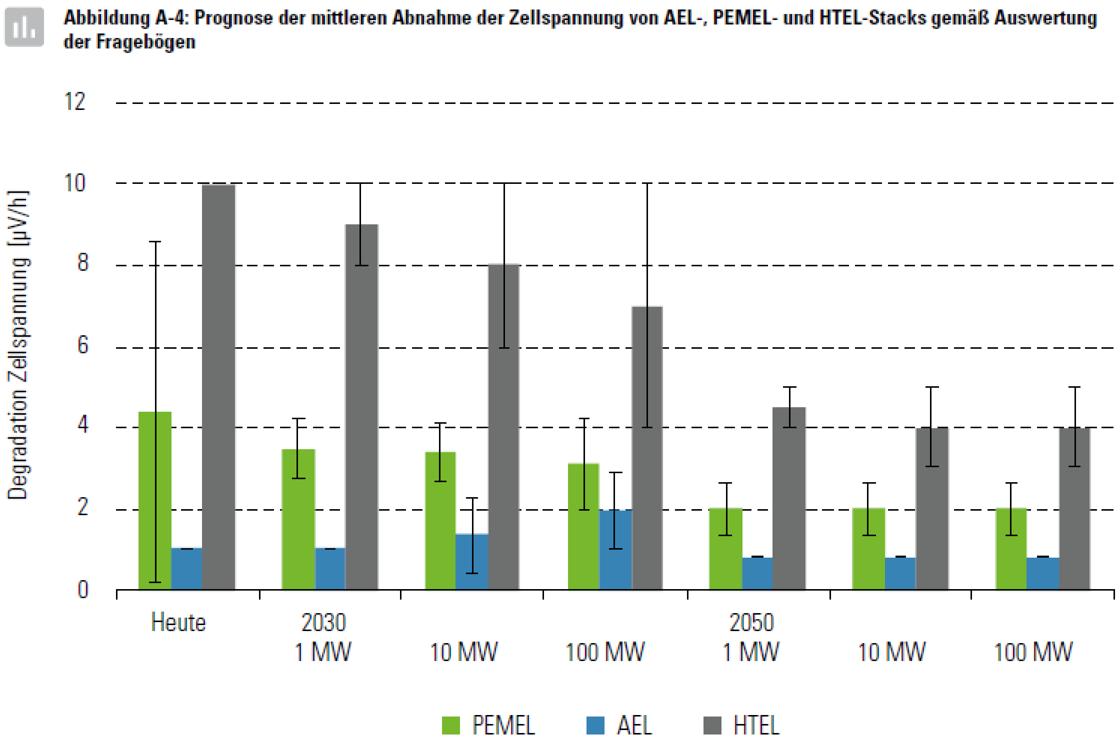


Figure 54. Projections for the voltage degradation of three electrolyser technologies (extracted from Smolinka et al. (2018, p.175)).

7.3) System and stack capacities

Below are provided with some additional documents about the electrolysers' system and stacks capacities.

		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm^3_{H2}/h	0.25 – 760	0.01 – 240	0.1 – 1
	kW	1.8 – 5,300	0.2 - 1,150	0.7 – 4.5
Hydrogen purity [6]		99.5% – 99.9998%	99.9% – 99.9999%	99.4%
Indicative system cost	€/kW	1,000-1,200	1,900 – 2,300	N/A

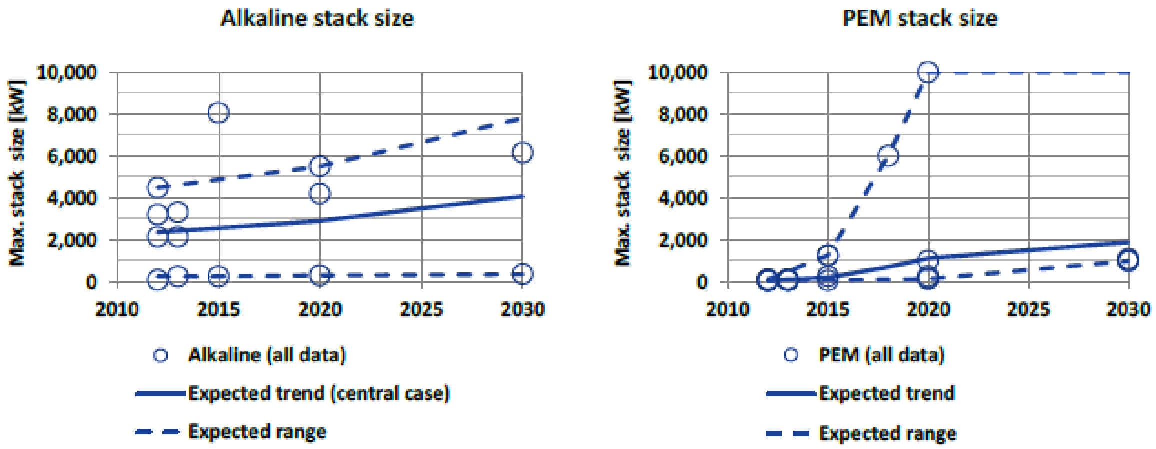
Figure 55. Technical characteristics comparison between PEM, alkaline and AEM (extracted from Bertuccioli et al. (2014, p.15)).

What is interesting with **Figure 55** is that the PEM technology is considered in 2014 to applications with a capacity reaching the kW ranger (maximum value: 1,150 kW), whereas nowadays (2018-2019), PEM is used in installation with capacities of several MW. For instance, a 3.5 MW PEM electrolyser is available commercially by 2017 (Koj et al., 2017). This fact shows the improvements achieved by PEM electrolysers.

System size			Today	2015	2020	2025	2030
kW	Alkaline	Central	**3,200**	**3,600**	**5,500**	**6,100**	**6,700**
		Range [(1)]	1,100 - 5,300	1,600 - 5,600	5,000 - 6,000	5,000 - 7,300	4,900 - 8,600
	PEM	Central	**180**	**2,100**	**5,400**	**5,900**	**6,400**
		Range [(1)]	100 - 1,200	1,300 - 10,000	1,600 - 90,000	1,800 - 90,000	2,100 - 90,000

[(1)] range indicates the largest systems offered for use in energy related applications. Smaller systems do exist.

Figure 56. Expectations for the system size by 2030 (extracted from Bertuccioli et al. (2014, p.61))



Stack size			Today	2015	2020	2025	2030
kW	Alkaline	Central	**2,400**	**2,600**	**2,900**	**3,500**	**4,100**
		Range [(1)]	200 - 4,500	200 - 4,900	300 - 5,500	300 - 6,700	400 - 7,800
	PEM	Central	**50**	**200**	**1,100**	**1,500**	**1,900**
		Range [(1)]	40 - 100	100 - 1,300	100 - 10,000	500 - 10,000	1,000 - 10,000

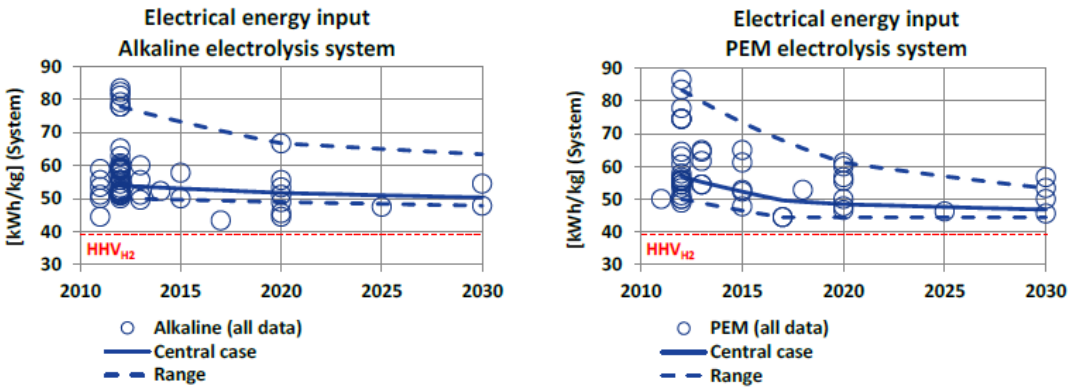
[(1)] range indicates the largest stacks offered for use in energy related applications. Smaller stacks do exist.

Figure 57. Projections for the stack size by 2030 (extracted from Bertuccioli et al. (2014, p.61)).

At the stack level, the alkaline technology is expected to possess a higher potential on average (4.1 MW) than PEM by 2030 (1.9 MW). However, the range of values is higher for PEM than alkaline stacks. This element is probably due to the higher uncertainty linked to PEM's development.

7.4) Efficiency of the electrolyser

Some additional documents are provided concerning the electrolyser's efficiency.



Electricity input [1]			Today	2015	2020	2025	2030
kWh_{el}/kg_{H2}	Alkaline	Central	**54**	**53**	**52**	**51**	**50**
		Range [2]	50 - 78	50 - 73	49 - 67	48 - 65	48 - 63
	PEM	Central	**57**	**52**	**48**	**48**	**47**
		Range [2]	50 - 83	47 - 73	44 - 61	44 - 57	44 - 53

[1] at system level, incl. power supply, system control, gas drying (purity at least 99.4%). Excl. external compression, external purification and hydrogen storage

[2] some outliers excluded from range

Figure 58. Projections for the electrical input (extracted from Bertuccioli et al. (2014, p.11)).

Availability			Today	2015	2020	2025	2030
hours/year	Alkaline	Central	**8,585**	**8,585**	**8,585**	**8,585**	**8,585**
		Range [1]	8,585 - 8,585	8,585 - 8,585	8,585 - 8,585	8,585 - 8,585	8,585 - 8,585
	PEM	Central	**8,443**	**8,459**	**8,586**	**8,586**	**8,586**
		Range [2]	8,585 - 8,300	8,618 - 8,300	8,672 - 8,500	8,672 - 8,500	8,672 - 8,500

[1] Only one alkaline manufacturer provided availability data

[2] Only two PEM manufacturer provided availability data

Figure 59. Projections for the availability of the two electrolyser technologies (extracted from Bertuccioli et al. (2014, p.62))

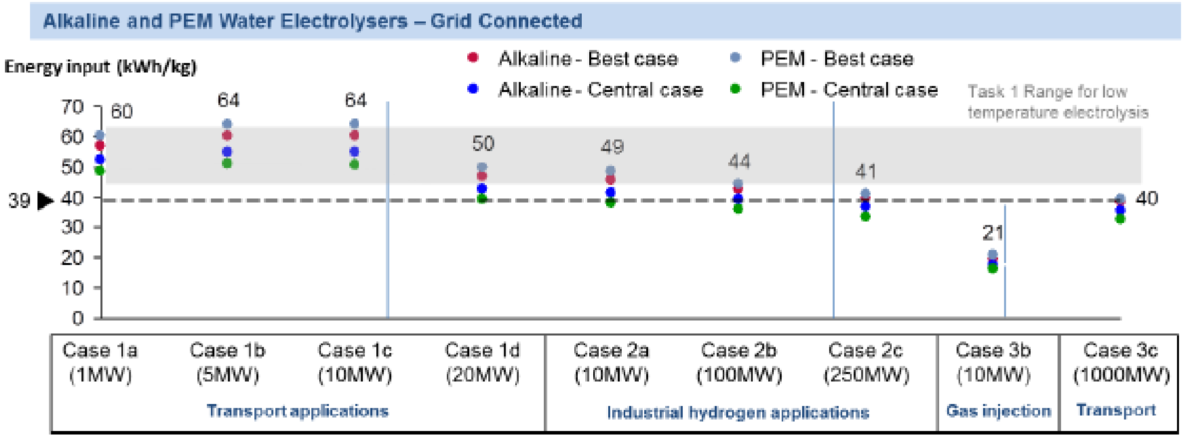


Figure 17: Energy input targets for Alkaline and PEM technologies required to compete with counterfactual in Germany, 2030.

Figure 60. Projections for the electricity input needs for electrolyser, in Germany (extracted from Bertuccioli et al. (2014, p.24)) (An energy input lower than 39.4 kWh is possible when other heating sources are present).

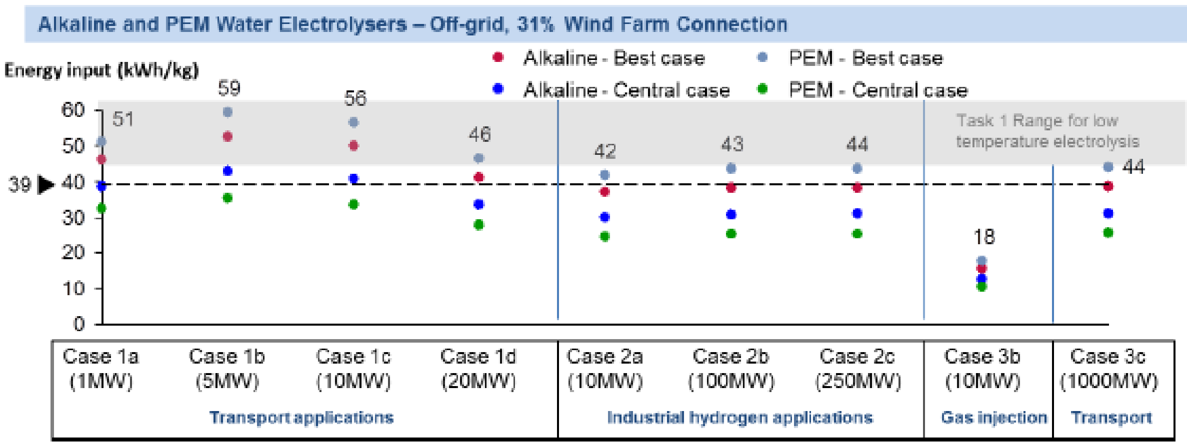
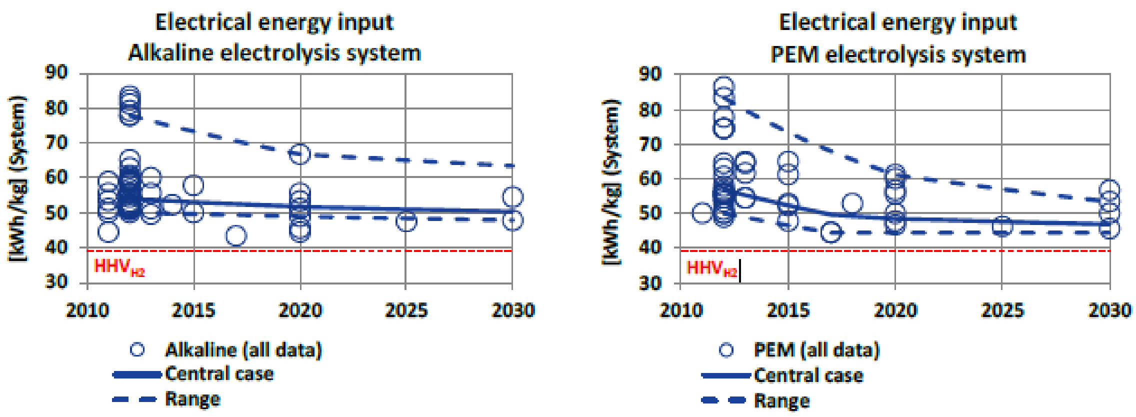


Figure 20: Energy input targets for Alkaline and PEM technologies required to compete with counterfactual in the UK, 2030.

Figure 61. Projections for the electricity input needs for electrolysers in the UK (extracted from Bertuccioli et al. (2014, p.25))

If the focus is more on the LHV values, the graphs below give some data.



Electricity input [(1)]			Today	2015	2020	2025	2030
kWh_{el}/kg_{H2}	Alkaline	Central	**54**	**53**	**52**	**51**	**50**
		Range [(2)]	50 - 78	50 - 73	49 - 67	48 - 65	48 - 63
	PEM	Central	**57**	**52**	**48**	**48**	**47**
		Range [(2)]	50 - 83	47 - 73	44 - 61	44 - 57	44 - 53

[(1)] at system level, incl. power supply, system control, gas drying (purity at least 99.4%). Excl. external compression, external purification and hydrogen storage

[(2)] some outliers excluded from range

LHV efficiency (electrical) [(1)]			Today	2015	2020	2025	2030
% $_{(LHV, el)}$	Alkaline	Central	**62%**	**63%**	**64%**	**65%**	**66%**
		Range [(2)]	43% - 67%	45% - 67%	50% - 68%	51% - 69%	53% - 70%
	PEM	Central	**59%**	**63%**	**68%**	**69%**	**71%**
		Range [(2)]	40% - 67%	45% - 71%	54% - 74%	58% - 74%	62% - 74%

[(1)] at system level, incl. power supply, system control, gas drying (purity at least 99.4%). Excl. external compression, external purification and hydrogen storage.

Figure 62. Projections for the electrical input need for the electrolysers (LHV based-definition) (extracted from Bertuccioli et al. (2014, p.62))

The "availability of the system" is defined as the time per year when the system can be used and is another parameter that can influence the efficiency of an electrolyser. As a matter of fact, if an electrolyser is extremely efficient but often needs maintenance, its general output and interest will decrease. **Table 41** indicates the availability expected for both technologies (Alkaline and PEM) by Bertuccioli et al. (2014).

Table 41. Projections for the availability of the two electrolyser technologies (adapted from Bertuccioli et al. (2014, p.62))

Year	2019	2030	**Unit**
Alkaline system availability	8,585	8,585	hours
PEM system availability	8,585 - 8,300	8,586	hours

Table 41 shows an availability of 98% for the two electrolyser technologies by 2050 when the operating resources are available anytime. When electricity comes from wind turbines only, this availability is expected to reach reasonably around 40-50% in most optimistic cases, due to wind intermittency. The baseline case is considered at 30% of availability. The "technical" availability of the electrolyser is

therefore not a problem to consider, only the wind turbines energy defines the actual use of the electrolysers.

7.5) Material use

The sections below provide more details on material use, supply and future for electrolysers.

For both electrolysers' technologies (PEM and alkaline), a market study conducted by ekinetix and Stratelligence indicate that many components, parts and subsystems of the electrolyser are also part of other non-hydrogen systems. Therefore, the market potentials for the materials' supply is increased since part of the supply chain is already present (see Appendix 6.1). Nevertheless, some innovation and progress are still necessary for some specific materials, as described in the following paragraphs.

On the one hand, the alkaline technology is known for more than a century and is considered as mature. For this reason, much less R&D is conducted on this alternative than PEM electrolysers for example. Nonetheless, on the cell level, an increase in current density will induce a decrease in costs. Bertuccioli et al. (2014) state that it is reasonable to go from 0.5 A/cm² (2015) to 1 A/cm² by 2030 for alkaline cells. To do so, new catalyst materials are necessary. Researches considered RuO_2 and IrO_2 for the OER (anode side) but the materials have shown limited stability until now. More research in the membranes is also recommended to limit the gas crossover and increase the lifetime.

On the other hand, the PEM technology usually requires expensive or rare materials to reach comparable performances or lifespans to alkaline electrolysers. As a consequence, most of the research focuses on the reduction of material needs.

On the cell level, the replacement of the bipolar plates would be a key improvement. These bipolar plates consume noble metal, such as titanium (Ti), since the plates need to sustain in highly acidic environments. Advanced coatings or plate manufacturing techniques are potential options to solve this issue. Increasing the cell area would also limit the materials wasted in plate edges and manifolds. Bertuccioli et al. (2014) estimate that a large cell area would decrease by 20-50% the material amount needed than small cells, with equivalent current density.

Noble metals are used in catalysts for the OER since they can resist high corrosion and enhance the catalytic activity. "Advanced catalyst support structures, mixed metal oxides and nanostructured catalysts" are among the potential solutions mentioned by Bertuccioli et al. (2014).

Noble metals are used for the same reasons on the HER with palladium (Pd) and platinum (Pt). The same strategies used for the OER to reduce the related costs can be applied in the HER case. However, as the HER metal load is lower, Bertuccioli et al. (2014) expect that this specific aspect will not be the most important ones in the years to come.

Graphs concerning the material use's projections are provided below.

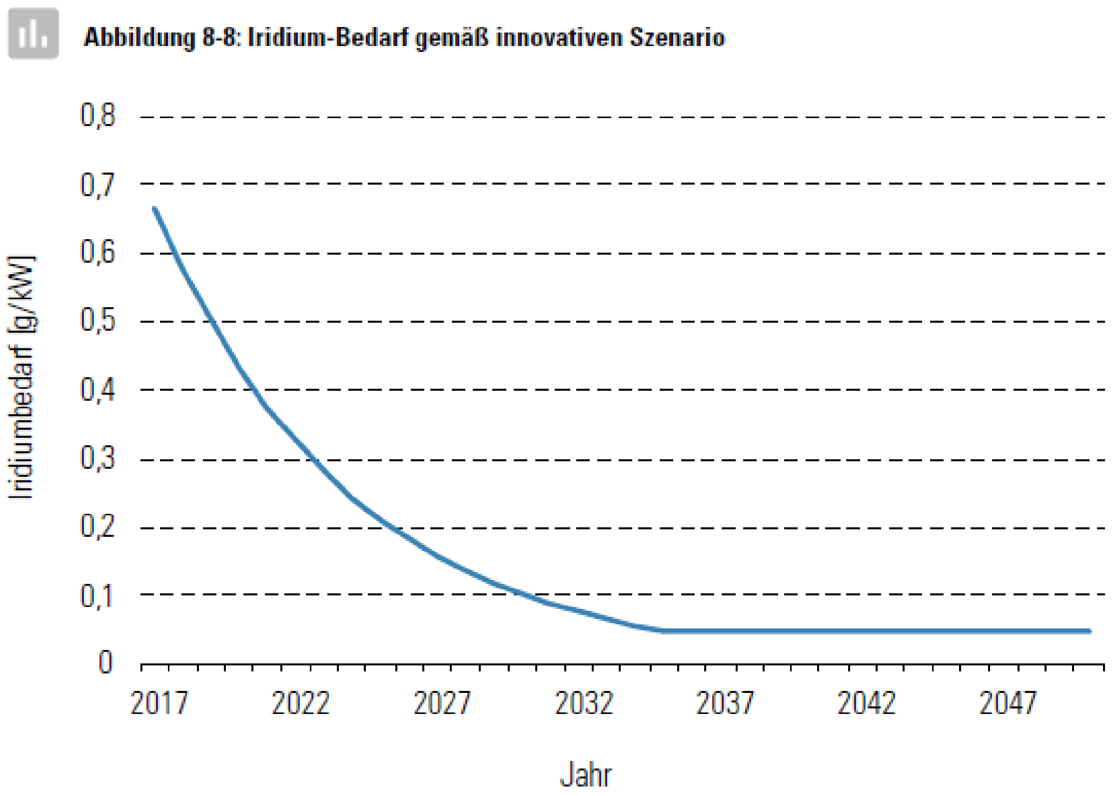


Figure 63. Projections for the iridium load for the PEM alternative (extracted from Smolinka et al. (2018, p.128)).

The Iridium load decreases from 2018 to 2034 and then remains stable at a value of 0.05 g/kW, resulting in a reduction of more than 90%.

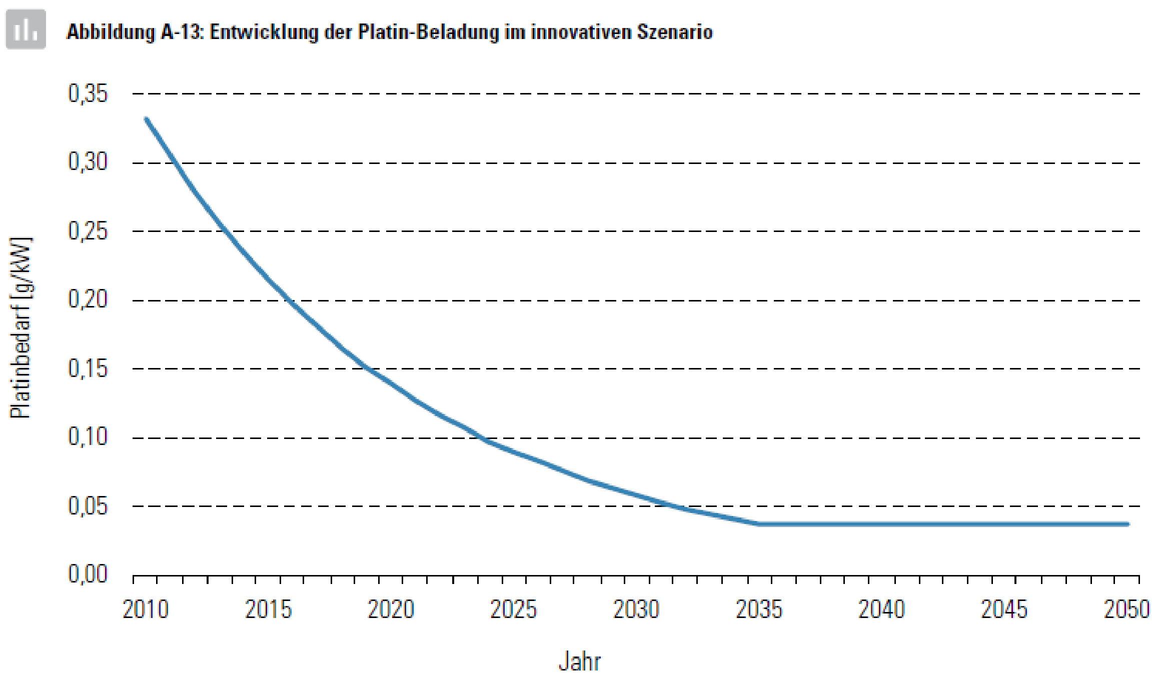


Figure 64. Projections for the platinum load for the PEM alternative (extracted from Smolinka et al. (2018, p.195)).

The decrease of Platinum load occurs from the 2010s until 2035. Further on, a limit is expected to be reached at ca. 0.04 g/kW, resulting in a decrease of around 88%.

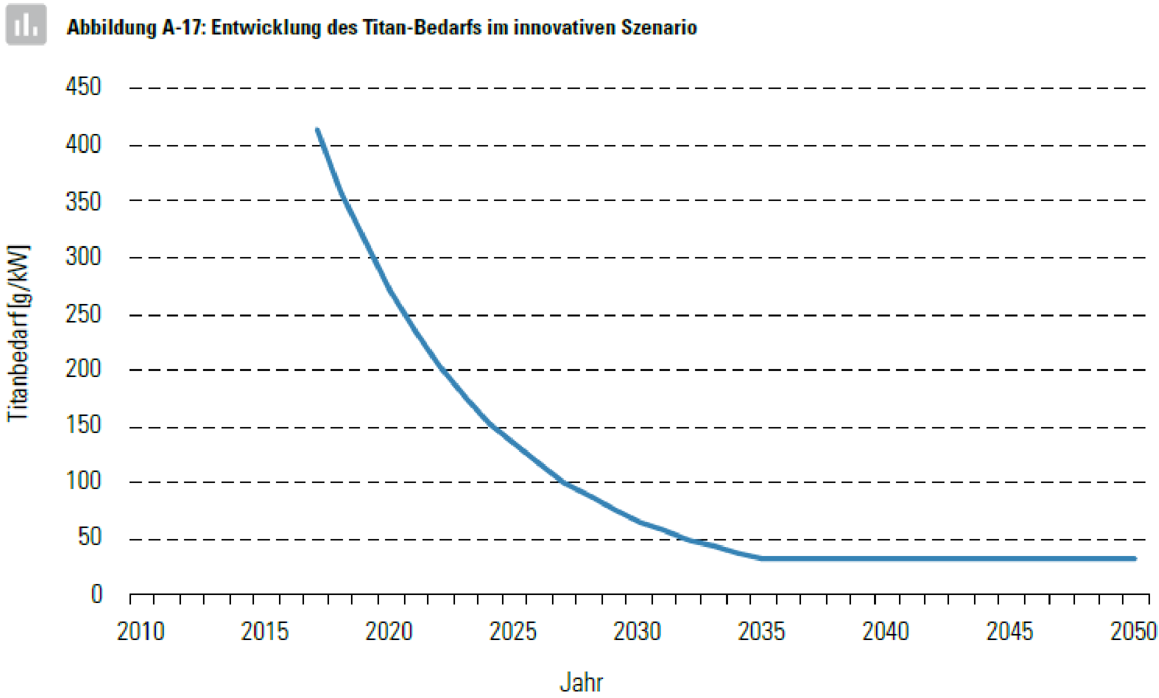


Figure 65. Projections for the titanium load for the PEM alternative (extracted from Smolinka et al. (2018, p.197)).

Once again, the decrease in the load requirement occurs until 2035 before reaching a limit at 32 g/kW, resulting in a reduction of more than 90%.

7.6) Roadmap from TKI Gas

The scale reachable for the technology and the roadmaps' descriptions are necessary to develop coherent scenarios. Bertuccioli et al. (2014) consider different "use cases" by 2030 with different scales and functions, as shown in Appendix 7.7.

TKI Gas presented "Outlines of a Hydrogen Roadmap" at the Ministry of Economic Affairs and Climate Policy's demand. This document is further described to provide indications on a potential roadmap developed specifically for the Netherlands. First, several elements are reviewed (technical, social, legislative aspects…) and then the "action plan" from TKI Gas is briefly described. The following elements were partly a basis and inspiration to construct the final scenarios for the thesis. The roadmap described by TKI Gas is an interesting example of combination of different elements (societal, technical, political…). Furthermore, the roadmap describes the general state of hydrogen's technology in the Netherlands.

In 2018, the hydrogen production technologies are already present (sustainable and unsustainable). The main barrier remains their costs, but massive production and standardisation may reduce these. Despite the good predictions (reduced capital costs) and the potentials in the NL (wind and a bit of solar), hydrogen imports may still be necessary with liquefied hydrogen or ammonia.

Thanks to the diversity of hydrogen origin and production ways, it is most likely that the energy carrier will play an important role in the future energy system. Gigler & Weeda (2018) claim that hydrogen should not be limited to transport alone, but also for a much more extended supply of energy and raw materials.

Distribution and transportation of hydrogen also raise relevant questions with the options of gradually shifting towards hydrogen gas transport or gas blending. Fuel cells and fuel cells systems remain the major innovation challenges for the end-use of hydrogen in various applications, such as in hydrogen cars. The manufacturability and standardisation remain key aspects from the hydrogen technology to consider early, in order to implement it massively afterwards.

Gigler & Weeda, (2018) also recall that non-technical aspects are also relevant since they can play a significant role in a technology development's pace. These factors can delay or halt technological development since no clear legislation framework takes hydrogen production into account. The same goes for all the safety regulations: the existing ones are based on hydrogen use for the industries and not in public systems (gas network, transports…). The project conducted by Gasunie and some other stakeholders in Zeeland Flanders over hydrogen transmission in pipelines is private and cannot be extended to the national gas transmission system since hydrogen is not included in the Dutch Gas Act. The project conducted by Stedin about hydrogen injection in the gas network in Rozenburg is only a demonstration installation (see Appendix 6.2). There are some studies conducted on safety issues, especially for hydrogen use in vehicles. However, for other hydrogen use, there is a lack of research.

The trading system for hydrogen is also another important aspect to consider. Several questions raise such as: What kind of approach should be adopted for hydrogen trades? An open platform system? A closer system? Agreements and discussions need to be conducted in this sense.

Finally, Gigler & Weeda (2018) combine all the elements mentioned in the previous paragraphs in their "action plan". The authors point out the fact that the transport sector and industry are likely the most urgent and promising sectors for hydrogen's technology to achieve a breakthrough. A focus on wind turbine/energy development is one of the main points mentioned (Gigler & Weeda, 2018). Another focus should be put on the evolution of the Fuel Cell Electric vehicle (FCEV) demand and its potential competing technologies (such as the "traditional" electric cars with batteries). The infrastructure questions are also important aspects, such as the potential reuse of the Dutch gas network or the connections between hydrogen and the offshore wind turbines. Concerning the latter aspect, should hydrogen be produced offshore and transported to the land with gas pipelines? Or should electricity be transported to the land through electric cables and *then* converted to hydrogen? The answers to these questions imply design change. All these elements require further investigation. The main output of the first step in the "action plan" is to develop a clear Master plan for hydrogen development, with detailed steps described and planned.

The second step of the "action plan" will be to implement actual hydrogen production and consumption (pilot) installations to provide compelling results for larger development. These first results may be the trigger to promote long-term perspectives with the hydrogen economy. Coordination between the projects, stakeholders and cities is important at this stage. Some small scales "experiments" can be conducted in urban areas, cities, etc. Some plans are being prepared in Rotterdam and other cities for industries to use Carbon Capture System to decrease their environmental impacts. Again, the authors prioritise applications of hydrogen in industries and mobility instead of the built environment (for example heating/cooling) and energy generation, for a question of potential and emergency.

In parallel, for the third step of the "Action plan", R&D should continue to improve the efficiency of the system, to develop the most sustainable alternatives (with for example a lower consumption of noble metals for PEM electrolysers), reduce the costs, etc.

Overall, proper management must be used within and between all relevant stakeholders to ensure a steady and maintained hydrogen development in the NL for the years to come. The TKI Gas report provides much information about hydrogen development in the Netherlands and gives an "action plan". These elements are used as inspirations to describe in a more consistent way the scenarios in the next chapters.

Some graphs developed by the roadmap by TKI Gas for hydrogen's implementation in the NL are provided below. They give an idea of potential orientation to adopt for hydrogen technology's implementation.

Functionality	Hydrogen demand		Offshore wind energy Electrolysis		Natural gas/ CCS Reforming	
	PJ/j	Mton/j	TWh/j	GW	PJ/j	Mton CO_2/j
High-Temperature Heat:						
- Non-energy use	50	0,4	21	4,8	67	3,8
- Process heat	100	0,8	42	9,6	133	7,5
- Sustainable chemistry	480	4,0	202	46,1	640	46,2
- Sustainable fuels	700	5,8	295	67,3	933	52,8
- Steel production	20	0,2	8	1,9	27	1,5
Mobility and Transport	125	1,0	53	12,0	167	9,4
Power and Light	115	1,0	48	11,1	153	8,7
Low-Temperature Heat	100	0,8	42	9,6	133	7,5

Figure 66. Projection for the hydrogen production in the NL (extracted from Gigler & Weeda, 2018, p. 43)

Figure 67 gives an overview of the technology shift and use.

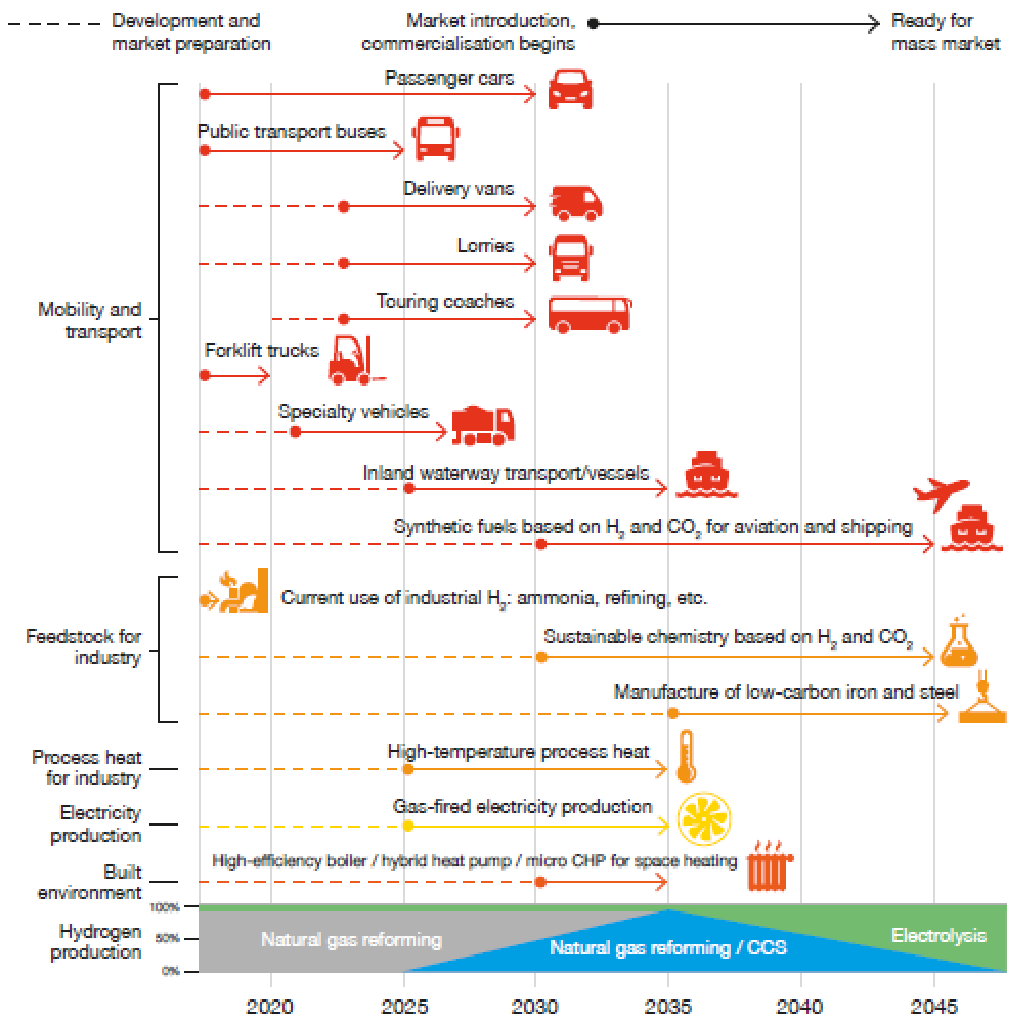


Figure 67. Planning for the hydrogen implementation in a range of applications (extracted from Gigler & Weeda, 2018, p.87)

7.7) Other factors

This section gives information that could be useful in further different research programs but was not deemed helpful in the thesis development. The scope of the section is rather large and encompasses different topics.

A few more information is provided concerning the potential stakeholders. Bertuccioli et al. (2014) provide a list of stakeholders who responded to contact requests for a European study on electrolysers: 14 industries and 8 academic institutes, such as Areva, E. ON, Hydrogenics, ITM Power, Siemens and Proton OnSite.

Bertuccioli et al. (2014) make an analysis of Key Performance Indicators (KPI) for the electrolyser in the years to come, through a techno-economic analysis. **Figure 66** shows their outputs and give an idea of the different factors that can be considered for the electrolyser's technology.

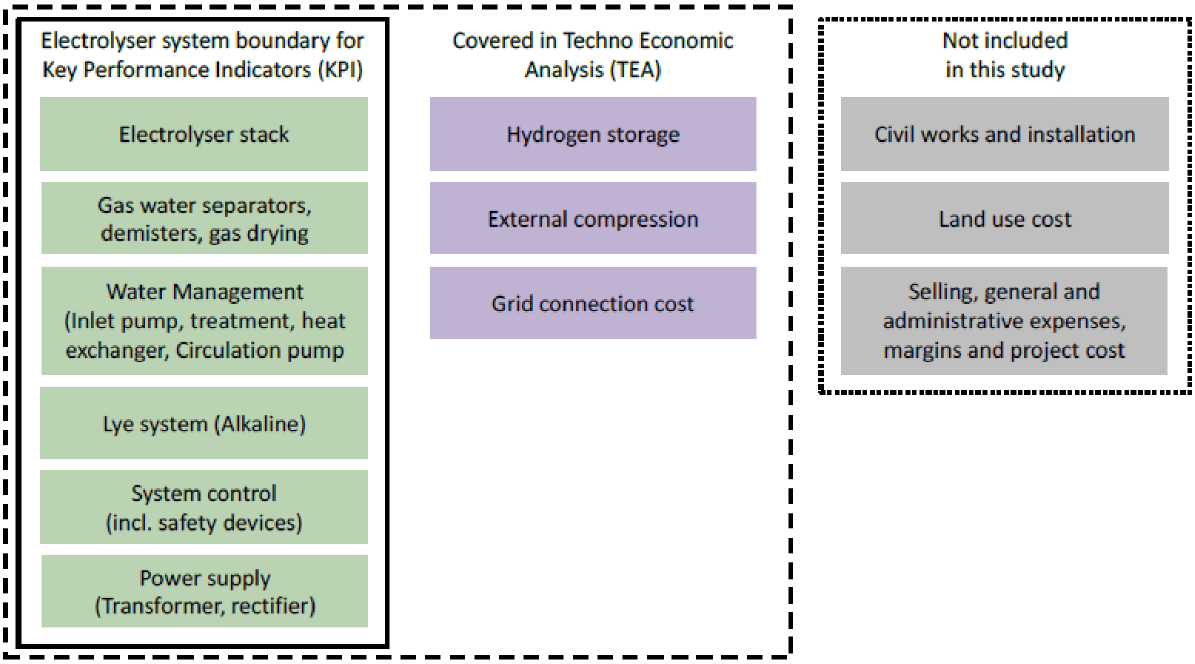


Figure 68. Key Performance Indicators developed by Bertuccioli et al. (2014, pp.9-10).

	2015	2020	2025	2030
System cost (€/kW)	950–1,600	600–1,000	600–900	600–800
Indicative stack size (MW)		1-3 MW		2-4 MW
Indicative large system size (MW)	≈3	≈5	≈6	≈7
Electrical input (kWh/kg$_{H2}$)	≈56	≈52	≈51	≈50
Stack life (khr)	65–80	75–95	75–95	80–95

Figure 69. Expected evolution of some key performance indicators (cf. **Figure 68**) for the electrolyser (extracted from Bertuccioli et al. (2014, p.48))

The LCA conducted by Bareiß et al. (2019) estimated the lifespan of the BOP at 20 years. According to the authors, the most critical parts exposed to degradation are the MEA and the anodic PTL.
In general, Bareiß et al. (2019) gave a general overview of the material change expected in the "near-term" for 1 MW PEM stack. They did the same table for the Balance of the Plant (1 MW scale). The information is provided in figures 68 and 69.

Material (kg)	2017	Near future
Titanium	528	37
Aluminum	27	54
Stainless steel	100	40
Copper	4.5	9
Nafion®	16	2
Activated carbon	9	4.5
Iridium	0.75	0.037
Platinum	0.075	0.010

Figure 70. Projections for the materials need at the stack level, for the PEM electrolyser (extracted from Bareiß et al. (2019, p.867))

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

Figure 71. Projections for the materials' needs for the Balance of the Plant, for the PEM electrolyser (extracted from Bareiß et al. (2019, p.867))

Bareiß et al. (2019) assume that a system solely fed by renewable energy sources would have a full load hour value of 3,000h (availability of 34% of the year). The authors also point out the fact that the stack and the Balance of the Plant account for a few percent of the total GHG emissions. The electricity supply alone accounts for 96%. The high-power density of the PEM electrolyser should enable it to possess a lower global warming impact than alkaline technology. The electricity mix is really an important factor in the environmental profile of the technology.

Output pressure for hydrogen:

A pilot installation in Hamburg develops hydrogen at 55 bars to send it to the gas network. Significant cost reductions are expected with an output pressure of 60 bars. High output pressure can be relevant and save costs for some specific demand, such as for fuel cars. Some models under development nowadays aim to produce higher pressurised hydrogen than commercial models available, with internal electrochemical compression. The main difference between internal (electrochemical compression) and external (pumps) compression lies in the electricity input requirement. Any internal compression step would require a higher electricity need. The conclusions from Bertuccioli et al. (2014) is that internal compression achieves more cost reductions than external systems.

Hydrogen output pressure			Today	2015	2020	2025	2030
bar(g)	Alkaline	Central	**15**	**20**	**30**	**30**	**30**
		Range [1]	0.05 - 30	0.05 - 40	0.05 - 60	0.05 - 60	0.05 - 60
	PEM	Central	**20**	**30**	**30**	**30**	**30**
		Range [1]	10 - 30	20 - 80	30 - 100	30 - 100	30 - 100

[1] some outliers are excluded from the range (pressures up to 450 bar have been reported for a tubular design)

Figure 72. Projections for the hydrogen output pressure from an electrolyser (extracted from Bertuccioli et al. (2014, p.68))

The LCA conducted by Bareiß et al. (2019) considered an output hydrogen at 30 bar.

Dynamical behaviour of electrolysers:

The tables below can give some ideas on how the electrolyser's technologies can be compared for their dynamical behaviours:

Minimum part load operation			Today	2015	2020	2025	2030
%$_{(full\ load)}$	Alkaline	Central	**30%**	**24%**	**15%**	**15%**	**15%**
		Range	20% - 40%	16% - 33%	10% - 20%	10% - 20%	10% - 20%
	PEM	Central	**9%**	**7%**	**4%**	**4%**	**4%**
		Range	5% - 10%	3% - 8%	0% - 5%	0% - 5%	0% - 5%

Startup time - from cold[1] to minimum part load (Hydrogen production)			Today	2015	2020	2025	2030
minutes	Alkaline [2]	Central	**20**	**20**	**20**	**20**	**20**
		Range	20min - several hours	20min - several hours	20min - several hours	20min - several hours	20min - several hours
	PEM [3]	Central	**5**	**5**	**5**	**5**	**5**
		Range	5 - 15	5 - 15	5 - 15	5 - 15	5 - 15

[1] pressurised if applicable

[2] Start-up times depend on system design (pressurised/unpressurised) and system optimisation. Start-up time in terms of electrical load typically quicker, while efficiecny during start-up phase reduced.

[3] Start-up times from power conservation mode can be <1min

Figure 73. Projections for the minimum part-load operation and the start-up time for AE and PEM electrolysers (extracted from Bertuccioli et al. (2014, p.66)).

Ramp up from minimum part load point to full load			Today	2015	2020	2025	2030
$\%_{(full\ load)}$ /second	Alkaline	Central	**7%**	**13%**	**17%**	**17%**	**17%**
		Range [1]	0.13% - 10%	0.13% - 20%	0.13% - 25%	0.13% - 25%	0.13% - 25%
	PEM	Central	**40%**	**40%**	**40%**	**40%**	**40%**
		Range [2]	10% - 100%	10% - 100%	10% - 100%	10% - 100%	10% - 100%

[1] Based on data from three alkaline manufacturers

[2] Based on data from three PEM manufacturers

Ramp down from full load point to minimum part load			Today	2015	2020	2025	2030
$\%_{(full\ load)}$ /second	Alkaline	Central	**10%**	**20%**	**25%**	**25%**	**25%**
		Range [1]	10% - 10%	20% - 20%	25% - 25%	25% - 25%	25% - 25%
	PEM	Central	**40%**	**40%**	**40%**	**40%**	**40%**
		Range [2]	10% - 100%	10% - 100%	10% - 100%	10% - 100%	10% - 100%

[1] Based on data from two alkaline manufacturers

[2] Based on data from three PEM manufacturers

Figure 74. Projections for the ramp-up and the ramp down for AE and PEM electrolysers (extracted from Bertuccioli et al. (2014, p.66)).

Current density:

On the one hand, the alkaline technology supports lower current densities than PEM. This is due to the bubble formation in the electrolyte that limits the effective active electrode area. Some research is being conducted to reduce the bubble formation but its impact on the system design and cost is still uncertain.

Current density			Today	2015	2020	2025	2030
A/cm^2	Alkaline	Central	**0.3**	**0.4**	**0.7**	**0.7**	**0.8**
		Range	0.2 - 0.4	0.2 - 0.7	0.3 - 1.0	0.5 - 1.0	0.6 - 1.0
	PEM	Central	**1.7**	**1.9**	**2.2**	**2.4**	**2.5**
		Range	1.0 - 2.0	1.2 - 2.2	1.6 - 2.5	1.6 - 2.8	1.6 - 3.0

Figure 75. Projections for the current density for AE and PEM electrolysers (extracted from Bertuccioli et al. (2014, p.67))

On the other hand, Smolinka et al. (2018) also considered and made some projections concerning the current density for PEM and alkaline in the decades to come. **Figure 76** shows their projections.

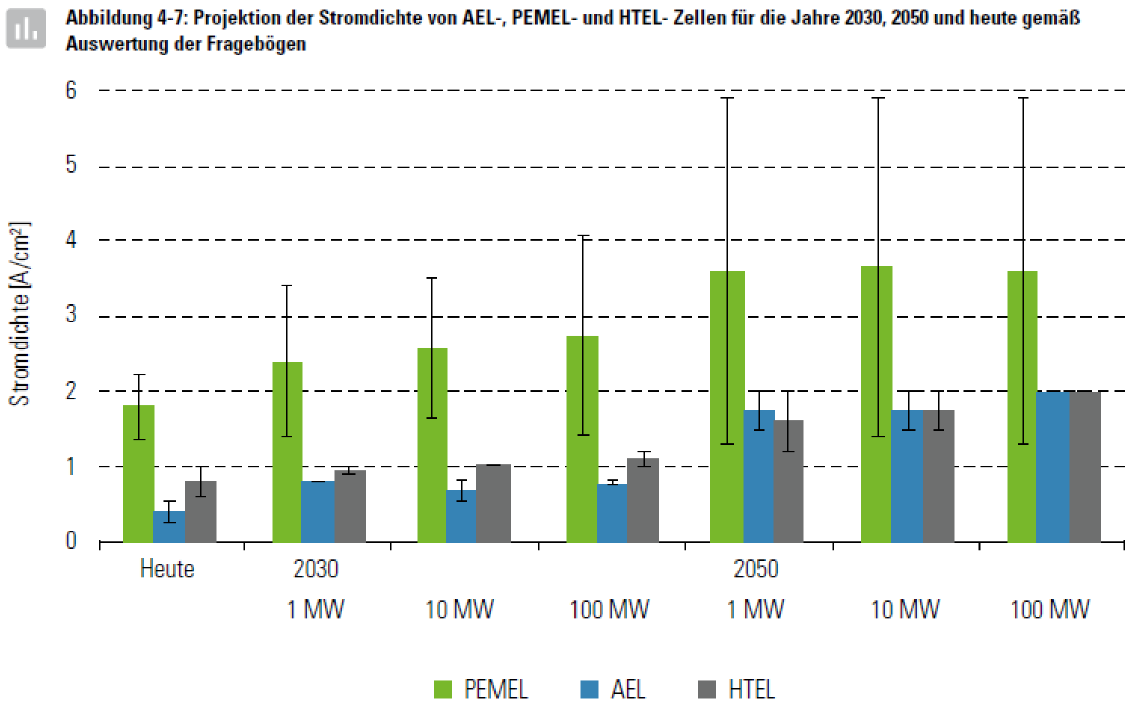


Figure 76. Projections for the current density for three electrolyser technologies. (extracted from Smolinka et al. (2018, p.39)).

Figure 76 shows that PEM will gain the highest increase in the current density, reaching a value of 3 A/cm^2 by 2050. On the contrary, alkaline and solid oxides will remain at 1.5-2 A/cm^2, depending on the scale. Bareiß et al. (2019) estimated a current density of ca. 1.5 A/cm² for the current PEM electrolyser system.

Operating temperature of the electrolyser:

The operating temperature of the electrolyser is another parameter that has not been implemented in the LCAs from the thesis/ this parameter may have an influence on energetic consumptions but expected to be negligible in comparison to other factors (electricity origin, etc.). Some projections are still available to get an idea of the operating system temperature's evolution in the future.

Operating temperature			Today	2015	2020	2025	2030
°C	Alkaline	Central	**70**	**70**	**70**	**73**	**75**
		Range [1]	60 - 80	60 - 80	60 - 80	60 - 85	60 - 90
	PEM	Central	**60**	**64**	**70**	**70**	**70**
		Range [2]	50 - 80	54 - 84	60 - 90	60 - 90	60 - 90

[1] excludes outliers of up to 150°C (pressurised)
[2] excludes outliers of up to 200°C (pressurised)

Figure 77. projections for the operating temperature for AE and PEM electrolyser (extracted from Bertuccioli et al. (2014, p.68))

The LCA conducted by Bareiß et al. (2019) considered an output hydrogen at 60°C.

Production framework:

Smolinka et al. (2018) study the distribution of the different hydrogen products in Germany for the coming decades. **Figure 56** shows the expected trend, according to one type of scenario, where PEM, AE and Solid oxide share 40%, 40% and 20% of the total electrolysis production respectively by 2050.

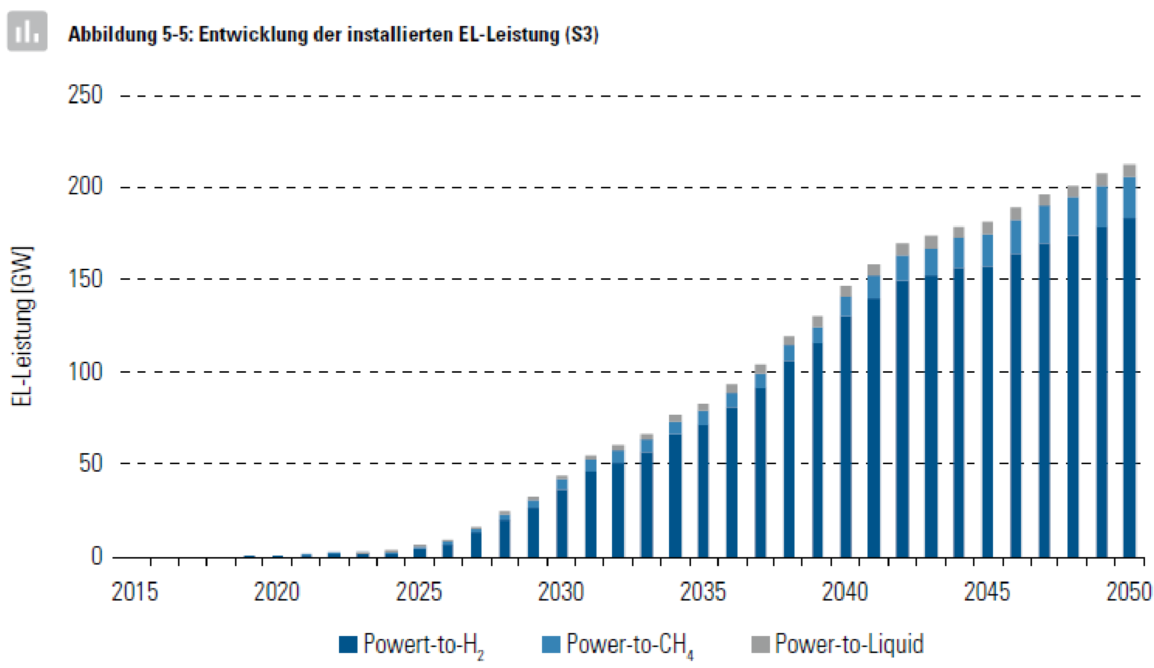


Figure 78. Projections for the installed capacity of electrolyser in Germany (extracted from Smolinka et al. (2018, p.69))

An obvious result is that direct hydrogen production is the most privileged path in this scenario (ca. 80%). The intermediary step to convert hydrogen into methane does not seem to be so attractive.

A factor that has been mentioned on a few occasions is the industrialisation and standardisation processes. A comparison can be made with the wind energy technology to show how the costs decreased massively with the implementation of standard models for wind turbines. The study market conducted by ekinetix and Stratelligence also indicated the industrialisation effect as an opportunity for green hydrogen development in their SWOT analysis (see Appendix 6.1).

The report from (TenneT & Gasunie, 2019) considers three kinds of scenarios: local, national and international levels. The difference is the level at which most of the steering processes occur. The report indicates that at the local, a focus will be put mostly on solar with limited use of wind. However, on the national level, the focus would be much more put on wind for centralised production. On the international level, the imports would become much more massive.

8) Collaboration with ENGIE and sensitivity analyses

In parallel to the development of scenarios for the future, a collaboration has been conducted with the laboratory CRIGEN, located in Seine-Saint-Denis, in the North of Paris. There, discussions and meetings with experts on hydrogen and LCA were made, in order to discuss the model development and gain some perspective on the results. During the exchanges, three main problematics were mentioned, as described in the three next sections.

This section describes the main outcomes from the collaboration that occurred with ENGIE.

8.1) The water origin issue

An electrolyser normally consumes “demineralised water” which is slightly different than “deionised water”. In order to refine the models and conduct some kind of sensitivity analysis, ENGIE transmitted data from a thesis from 2008/2009, from KU Leuven, about demineralisation water processes (Van der Bruggen, 2009).

There are 3 important steps in water demineralization:

1) Pre-treatment: “membrane techniques (filtration, microfiltration: 0,1 –1 µm and ultrafiltration: up to 0,1 µm), rough filtration or coagulation, flocculation, or decantation.” (Van der Bruggen, 2009, p.8). As the Ion-exchangers (IX) are not developed to “filter out suspended solids, colloids or oily emulsions” (Van der Bruggen, 2009, p.18), these elements must be removed before the IX treatment.
2) Treatment/demineralisation: “distillation, ion-exchange beds (IX) and reverse osmosis (RO), where RO and IX are the most current methods” (Van der Bruggen, 2009, p.8).
3) Post-treatment/polishing: “a polishing step to guarantee the required concentration of some specific ions. Generally, IX resins are used for this step in Belgian power plants. Electro deionization (EDI) is another option.” (Van der Bruggen, 2009, p.8).

Depending on the quality of the water used as a source, different processes can be considered. The membrane seems to play a significant role in purifying the water. Depending on the type and quality of the membrane, the final water’s quality can vary. It must be recalled that it is not necessary to remove all the components from water, but just to meet the requirements of the system used.

Example of the different processes that can be used:

For Ion-exchangers, they are made of organic compounds called resins. The latter is made of a backbone with active sites. Mainly two types of backbones exist: polystyrene and acrylic. In order to produce acids and bases, cationic and anionic sites are connected to the resin. Therefore, a resin containing an anionic site is called a cationic exchanger and vice-versa.

In the example of the polystyrene, there can be reticulations (connections between different chains of polystyrene) with an agent, such as divinylbenzene (DVB). However, too many reticulations make the resin too stiff and the efficiency will start decreasing after reaching a maximum value. “Generally, a maximum of 8 % DVB is taken for sulphuric resins.” (Van der Bruggen, 2009, p.10)

Two types of resin structures are used:

1) Gel: homogeneous structure
2) Macroporous: heterogeneous structure

Cationic resins can endure temperatures up to 120°C, anionic resins: not higher than 60°C (sometimes even not higher than 35°C). Anionic and cationic exchangers can be divided into two categories each time: strong and weak (acids/bases).

“The capacity of an ion exchanger is “the quantity of ions likely to be fixed per unit of volume or per unit of weight (...) expressed as the equivalent per unit of weight or of volume of compacted resin” (Degrémont, 2007).” (Van der Bruggen, 2009, p.11)

“The ion leakage can therefore be defined as the remaining concentration of the ions that have to be removed in the treated liquid” (Van der Bruggen, 2009, p.12)

Different combinations of strong and weak resins (acid/base) can be made. These combinations are more or less like a line of different resins along which the water needs to flow through. The option “2 strong” enable to remove all the ions, including silica. You can have for example this kind of “line”: “WAR + SAR + degasser + WBR + SBR” (Van der Bruggen, 2009, p.15). Apparently, with this line, really pure water is obtained eventually.

“It is not evident to choose between IX and RO/IX for the production of demineralised water in power plants. However, in general, one can state that when the amount of organic matter in the raw water is higher than 1000 mg/l, RO is always the preferred option” (Van der Bruggen, 2009, p.32). If the value is lower, there is no universal rule on how to make the choice and it only depends on several parameters.

The LCA from the KU Leuven’s thesis looks only at the production of demineralised and not on further use. Except on the production of the IX system, all the other systems are out of the scope. The functional unit of the study is “is 1 m^3 of demineralised water that meets the specifications for the production of electricity in a thermal power plant in Belgium” (Van der Bruggen, 2009, p.40). So, there may potentially be a difference between what is required in a Belgian plant and what is required for an electrolyser. However, I may probably consider that the difference is negligible. All the data consider a system lifespan of 1 year, even though the resins considered in the study should only be changed once every 8 years. Losses by Joules’ law are neglected.

Three LCA models were modelled for the production of demineralised water. The names of the plants are not communicated, based on a common agreement with ENGIE France. Instead, code names are used.

- Model A1. The main treatment steps from the plant are based on rough filtration, an IX and a neutralisation process.
- Model A2 2005. The main treatment steps are based on pre-treatment, an IX and a neutralisation process.
- Model A3 2008. The main treatment steps are based on rough filtration, ultra-filtration, Reverse Osmosis, an IX and a neutralisation process. It is the same plant than in the model “A2 2005”, with an update operated in 2008 with the integration of an ultra-filtration and reverses osmosis steps. The addition of these steps enables to reduce the amount of chemicals (NaOH and HCl) used in the resins and reach higher purity of water.

As the KU Leuven’s thesis is to be treated as confidential, no specific numbers are provided concerning the processes from the models and no flowchart is communicated.

Results:

The results of the contribution analyses showed that, regardless of the impact assessment method, the electricity production, HCl production, NaOH production and the production of anionic resin beads remain the highest process contributor to the environmental impacts of the system.

The 4 main process contributors are “pre-treated water”, “HCl production”, “NaOH production”, “electricity production”. But especially NaOH and HCl productions.

If 1 m^3 of demineralised water is considered as an output, the three systems (Model A1, Model A2 2005 and Model A3 2008) have comparable performances. "Model A1" possess the lowest environmental impacts in all impact categories, "Model A2 2005" possesses the highest valuers in all impact categories (confirming the fact the updated system is "better/more sustainable").

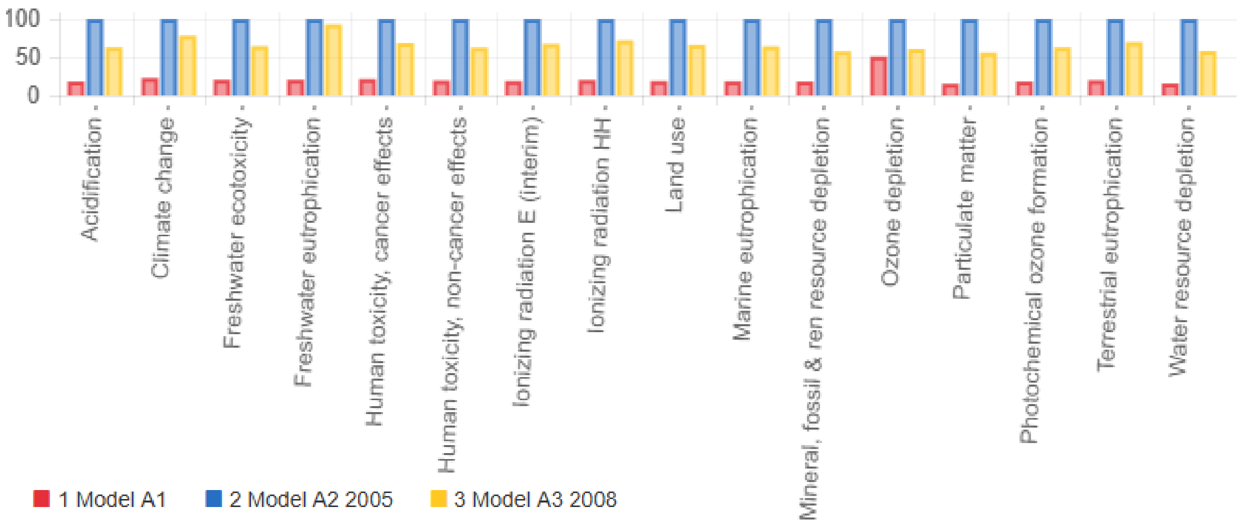


Figure 79. Relative results for the production of demineralised water from the 3 models of demineralisation water plants. (ILCD 2011 baseline)

In **Figure 79**, comparisons were conducted between alternatives with different water origins. The first case, called "ecoinvent", considers the deionised water from ecoinvent. The second case, called "A1", considers the water supply from the "Model A1" installation. This alternative had the profile with the lowest environmental impacts in all categories. Consequently, it can be considered as the most "best-case scenario". The third case, called "A2 2005" considers the water supply from the "Model A2" installation in 2005. This alternative had the profile with the biggest environmental impact values for all categories, hence it can be considered as a "worst-case scenario". This way, a comparison is made between the "standard" alternative (ecoinvent) and the two most extreme cases ("A1" and "A2 2005").

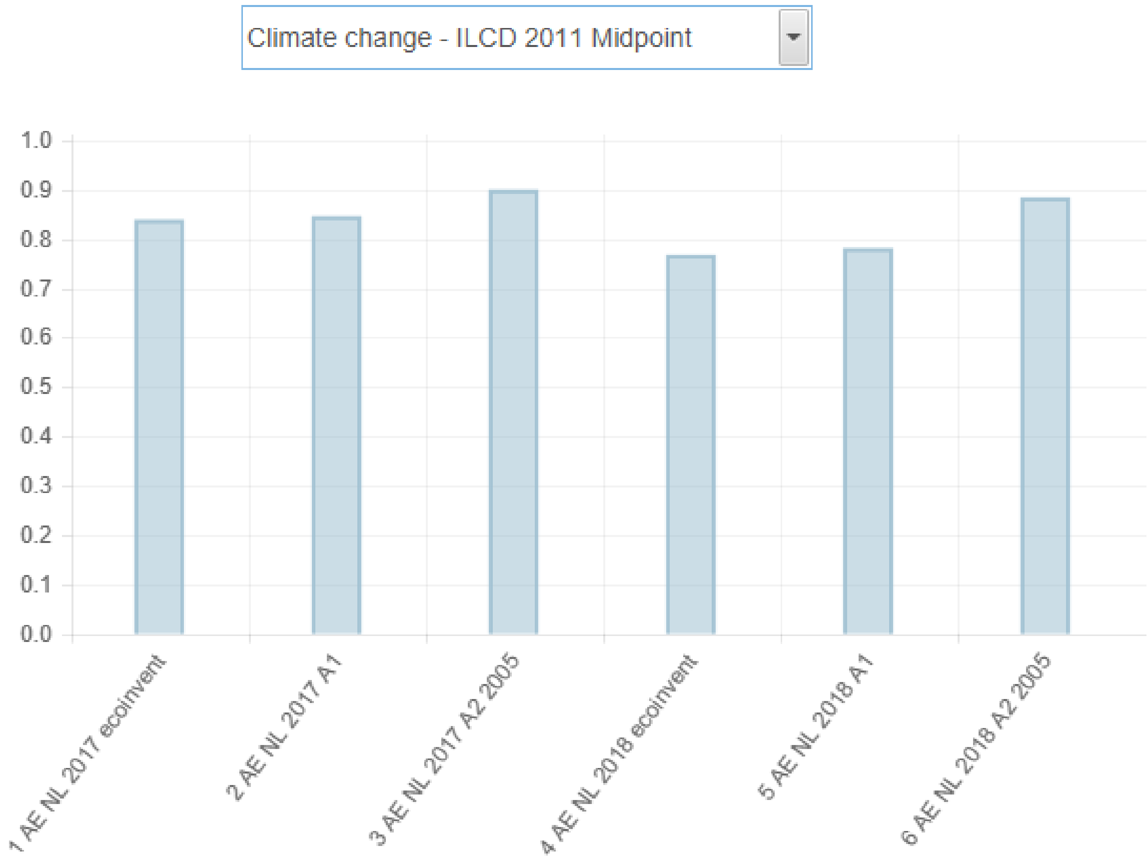


Figure 80. Relative results for the Hydrogen production with the models AE NL 2017 and AE NL 2018. The difference between the alternatives occurs at the origin of the water used for the electrolyser's operation (water from ecoinvent, or water from "Model A1" or water from "Model A2 2005").

The same trend than in **Figure 80** is observed for all impact categories. Only the "Ionising radiation" shows slightly larger differences and "ozone depletion" shows significant differences. These differences are mainly due to the Ion-exchange step and all the production processes linked to it.

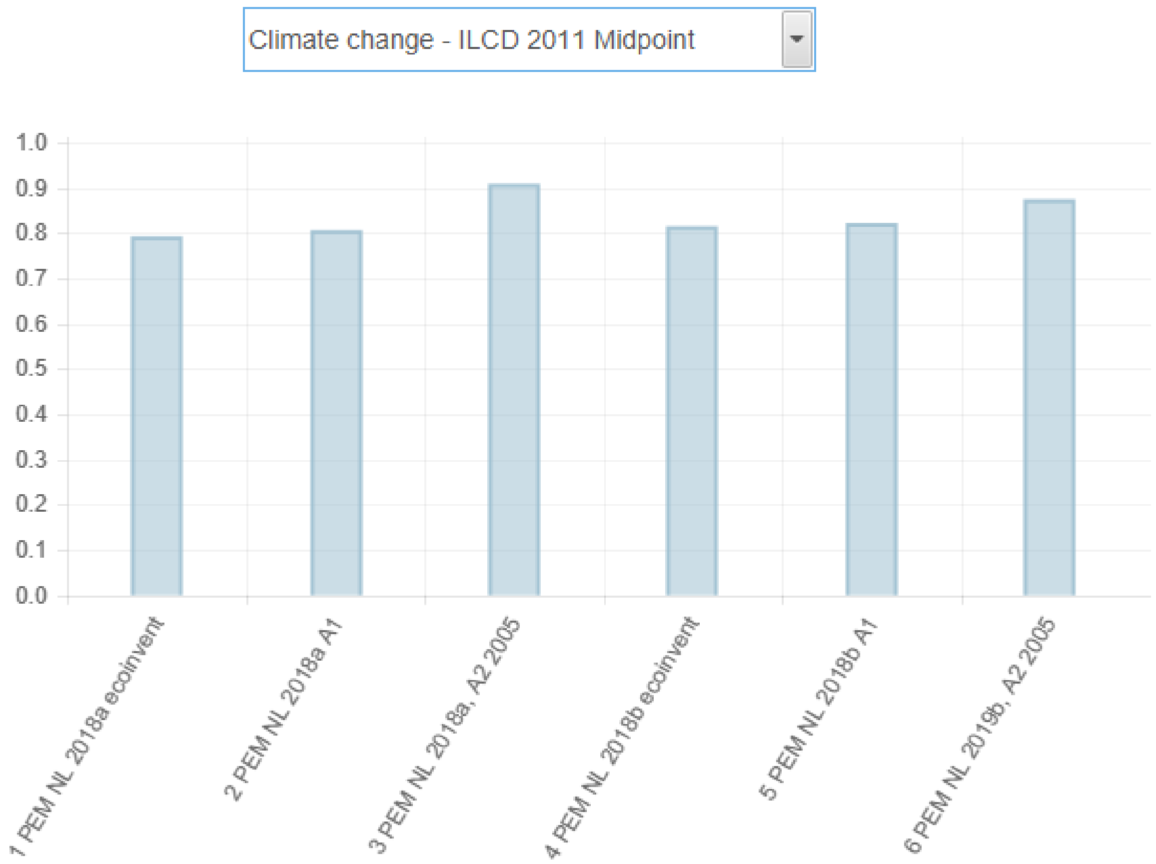


Figure 81. Relative results for the hydrogen production with the models PEM NL 20178a and PEM NL 2018b. The difference between the alternatives occurs at the origin of the water used for the electrolyser's operation (water from ecoinvent, or water from the "Model A1" or water from "Model A2 2008").

Similar conclusions than for **Figure 80** are drawn. The variations in environmental impacts' values do not exceed 10% for AE and PEM technologies. Consequently, the water origin does not seem to influence so much the results.

The overall results show that a change of water's origin does not influence significantly the environmental profile for all electrolyser technologies. Overall the "ecoinvent" alternative possesses the lowest environmental impact, except in a few impact categories. Differences with the "A1" alternative are minimal, in the range of -1 to 2%. Differences with the "Model A2 2005" are more significant and remain in the range of 1 to 15%. There are a few exceptions to these conclusions, they will be discussed now. The two "ionizing radiations" impact categories show significant higher variations, reaching 42% in the PEM case. This is mainly due to the chemical components connected to the "Ion-exchanger line" which possess a more prominent impact (hydrochloric acid, potassium hydroxide. A deeper contribution analysis would conduct to the origin of electricity. In this case, France is usually a major supplier of electricity. As around 75-80% of the French electricity is produced by nuclear, there are ionising radiations due to nuclear waste. The "ozone depletion" is also an impact category that shows significant variations, reaching 304% in the PEM case. This change is mainly due to the market for hydroxide potassium which is tenfold higher in the "Model A2 2005" installation than in the "Model A1" installation.

Discussion with members from ENGIE France led to the conclusion that using “deionised water” from ecoinvent is an accepted assumption. The purity of the “deionised water” should be high enough to be assimilated to “demineralised water” that is normally used by electrolysers. Furthermore, access to data from ENGIE and ecoinvent showed that both waters are produced in a similar way with ion-exchangers. According to Stephane, only in real specific cases, better modelling would be relevant, such as medical issues where the water quality is of high importance. This is confirmed by the ecoinvent process description claiming that “the quality of water needed in the different applications varies considerably”. The process modelled in ecoinvent produces water with a conductivity of 1 µS/cm and a silica content (as SiO_2) of 25 µg/L. Uncertainties remain on the quality of the raw water quality and the electricity used. The ecoinvent model considers only the ion-exchange process and no others, such as reverse osmosis, electrodialysis or distillation. The data originate from 2002 but have been extrapolated to 2018 with all the required adjustments (Wernet, 2018).

8.2) The Rare metals issue

All models calculate identically the materials consumptions. The “objective” value of rare metals consumed for one kg of hydrogen remains the same. The question is whether how the metals are embedded in impact assessment methods. The case of Iridium was especially considered, as it is one of the metals frequently mentioned by the stakeholders’ interviews and is one of the rarest elements on Earth.

The ILCD 2011 impact assessment does not classify Iridium in one impact category particularly. However, the families “CML 2001 (all impact categories)” and “ReCiPe midpoint (E)” do consider this metal, in the “abiotic depletion” and “metal depletion” impact category, respectively. However, as the “Iridium” is an environmental flow (not an economic one), it is not connected to a specific process (such as, for example, “market for iridium” or “iridium extraction”). Therefore, the use of iridium in PEM’s cell production stage implies that the iridium is directly extracted from the environment which is unlikely the case. This is one limitation of the modelling. Furthermore, as it is an environmental flow, the software OpenLCA does not its presence in the contribution process, it is implicit and calculated but not shown. Its contribution factor can be calculated manually but the results are always particularly low (around 0.002% for the ReCiPe family and 0.08% for the CML 2001 family). Therefore, the consumption of rare metals for the electrolyser system is considered as negligible at the state-of-the-art of the technologies. The impacts are not shown as especially sensitive for the resource’s depletion. The same conclusion occurs for the other rare metals considered (Titanium and Platinum). For these elements, they are modelled as economic flows, hence they are connected to some processes (market, production, etc.) and were shown on the contribution trees by the LCA software. Each time, their impacts were below 1%.

8.3) The recycling issue

A topic that was mentioned several times by employees in ENGIE was the recycling perspective. An expert of LCA especially thought that considering recycling processes would be valuable in the electrolyser case. Currently, most of the studies/LCA on electrolysers do not really consider the EoL stage, usually due to a lack of data. As a matter of fact, a few processes or installations are present due to the scale of the electrolyser plants (especially for PEM). Therefore, this stage is still hypothetical and under research, as the demand is not yet strong demand to justify its presence. Nevertheless, some studies have been conducted on the recycling potentials for critical metals, such as Titanium. Furthermore, a European project in collaboration with FCH, “HyTechCycling” was conducted to study more the recycling perspectives for the fuel cells and hydrogen technology.

8.5) Elements for the scenario's development and technological parameters:

In this section, several various notes are written that came along the ENGIE's collaboration. AE and PEM should probably not be considered as being in competition, but rather as parallel or combining technologies. It is rather unlikely that only one technology will be used, even if a preference may be found.

The current R&D trends for PEM focus on rising the Iridium stability, rather than finding an alternative for it. Finding an alternative has been proved really difficult and no ideal solution has been discovered. Consequently, increasing Iridium stability would enable longer lifespan and higher efficiency?

Concerning the output pressure, Stephane mentioned the fact that 2 kinds of electrolysers may be considered for the alkaline technology. The first one is depressurised and produces hydrogen at a relay low pressure (around 200 mbars) and the second one is pressurised with an output pressure going up to 34 bars. Therefore, the induced range is quite large. The PEM technology can produce hydrogen with an output pressure between 10 and 100 bars.

9) Platinum/Iridium/Nafion recovery

Below is presented the flowchart for the Iridium recovery. The process and concepts are exactly the same as the ones described in section 5.2.2. Only the role of Pt has been replaced by Ir.

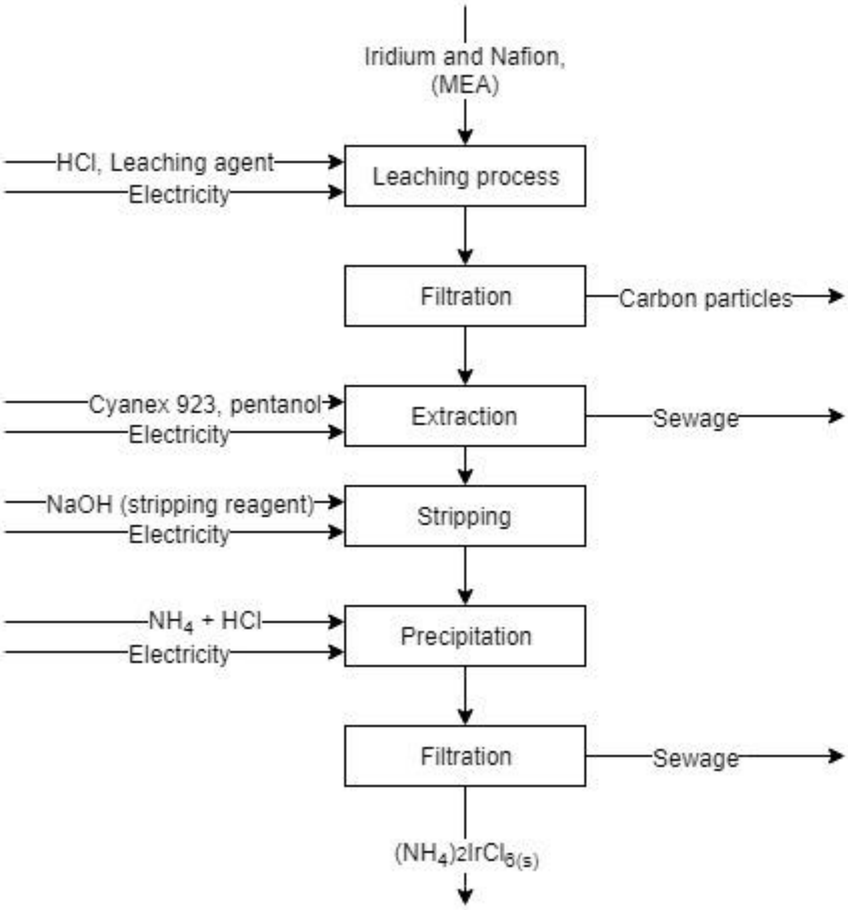


Figure 82. Iridium recovery process based on Duclos et al. (2016); Laforest et al. (2016) and Valente et al. (2017).

The numerical values for each flow are extracted (or adjusted linearly when necessary) from the work from Laforest et al. (2016).

In the Platinum recovery process described by Laforest et al. (2016), 1 kg of Pt is defined as an input, embedded with 0.7 kg of Nafion. Consequently, in 1.7 kg of input from the MEA, the platinum share is worth 58.82%. The same logic applied for the Ir/Nafion couple. However, the calculations for the ex-ante large-scale LCA model show that there is more Nafion that can be handled by the two recycling processes (Ir and Pt), probably due to some trade-off in the upscaling processes. In the end, there is an "extra" amount of Nafion that is left. This extra amount is automatically sent to the unit process "Service treating Nafion". More research could solve this issue.

10) Nickel recovery

The two main resources that have been used to develop the Nickel recovery process are the works from Valente et al. (2017) and Lee et al. (2010). The original flowcharts for the process are provided below:

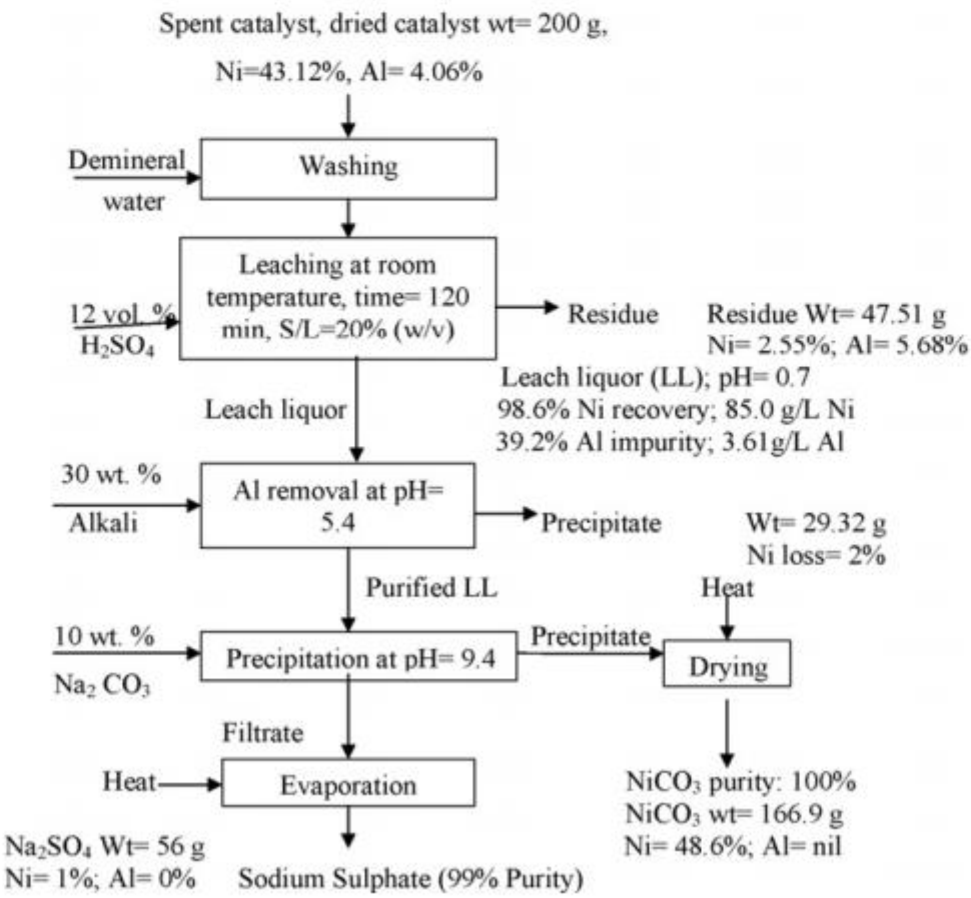


Figure 83. Process flow for Nickel recovery (extracted from Lee et al., 2010, p.1125)

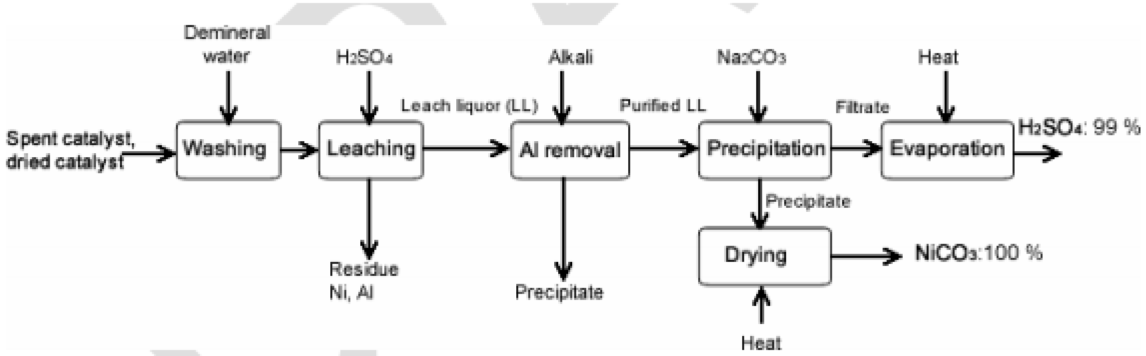


Figure 84. Simplified flowchart for Nickel recovery (extracted from Valente et al., 2017, p.28).

All calculation shown below were made for the specific thesis' context. Otherwise, numerical values for the flows were extracted (or linearly adjusted) from the works of Valente et al. (2017) and Lee et al. (2010). **Figure 83** clearly indicates that 200 g of dried catalyst is injected in the "washing" process. The amount of Nickel and Aluminium were calculated based on the percentages:

$$m_{Ni\ input}(dried\ catalyts) = 0.4312 \times 200\ g = 86.24\ g\ (Eq. 24)$$

$$m_{Al\ input}(dried\ catalyst) = 0.0406 \times 200\ g = 8.12\ g\ (Eq. 25)$$

Lee et al. (2010) indicate that in the experiment's conditions described in **Figure 83**, 100 mL of sulfuric acid (H_2SO_4) was necessary for the "leaching" process. The density of H_2SO_4 is worth 1.83 g/ml. All the chemical values (molar mass, density…) were extracted from PubChem (U.S. National Library of Medicine, 2019). As the sulfuric acid's concentration is worth 12% vol, its amount has been calculated with the following equation:

$$m_{H_2SO_4\ input} = 0.12 \times 100\ ml \times 1.83 \frac{g}{ml} = 21.96\ g\ (Eq. 26)$$

The mass of Ni and Al in the residue from the "leaching" process has been calculated with the following equations:

$$m_{Ni\ in\ residue\ from\ leaching} = 0.0255 \times 47.51\ g = 1.21\ g\ (Eq. 27)$$

$$m_{Al\ in\ residue\ from\ leaching} = 0.0568 \times 47.51\ g = 2.70\ g\ (Eq. 28)$$

The mass of Ni's losses in the precipitate from the "Al removal" process has been calculated with the following equation:

$$m_{Ni\ loss\ in\ precipitatre} = 0.02 \times 29.32\ g = 0.59\ g\ (Eq. 29)$$

The goal of the "Al removal" process is to extract all the aluminium present in the solution. This is confirmed by the fact that all the other outflow possesses no aluminium. Therefore, the mass of aluminium in the precipitate from the "Al removal" process has been calculated with the following equation:

$$m_{Al\ in\ precipitate} = m_{Al\ input}(dried\ catalyst) - m_{Al\ in\ residue\ from\ leaching}$$
$$= 8.12 - 2.70\ g = 5.42\ g\ (Eq. 30)$$

It is assumed that the alkali used in the "Al removal" process has been entirely used to extract the aluminium. Therefore, the mass of alkali has been calculated with the following equation:

$$m_{alkali\ in\ precipitate} = m_{alkali\ input} = m_{precipitate} - m_{Al\ in\ precipitate} - m_{Ni\ loss\ in\ precipitatre}$$
$$= 29.32 - 5.42 - 0.59\ g = 23.31\ g\ (Eq. 31)$$

Lee et al. (2010) indicate that the alkali's type used is sodium hydroxide (NaOH). From the previous equation, is it assumed that 23.31 g of NaOH was used in the "Al removal" process. The amounts of Nickel and of carbonate (CO_3) in nickel (II) carbonate ($NiCO_3$) were calculated with the following equations:

$$m_{Ni\ in\ NiCO_3} = 0.486 \times 166.9\ g = 81.11\ g\ (Eq. 32)$$

$$m_{CO_3\ in\ NiCO_3} = 166.6 - 81.11\ g = 85.79\ g\ (Eq. 33)$$

The amount of sodium sulphate was calculated with the following equation:

$$m_{Na_2SO_4} = 0.99 \times 56\ g = 55.44\ g\ (Eq. 34)$$

The amount of Nickel in the sodium sulphate outflow, which is impure, has been calculated with the following equation:

$$m_{Ni\ in\ Na_2SO_4} = 0.01 \times 56\ g = 0.56\ g\ (Eq. 35)$$

Finally, the number of moles has been calculated for Na_2 and CO_3 with the following equations. With these numbers of moles, the mass for the sodium carbonate (Na_2CO_3) input can be deduced.

$$n_{Na_2SO_4} = n_{Na_2} = \frac{m_{Na_2SO_4}}{M_{Na_2SO_4}} = \frac{55.4\ g}{142.036\ g/mol} = 0.39\ mol\ (Eq. 36)$$

$$n_{NiCO_3} = n_{CO_3} = \frac{m_{NiCO_3}}{M_{NiCO_3}} = \frac{166.9\ g}{118.701\ g/mol} = 1.41\ mol\ (Eq. 37)$$

In theory, an equality must be found between n_{Na_2} and n_{CO_3} to respect the equivalence implied by the formula Na_2SO_4. This is not the case ($n_{Na_2} < n_{CO_3}$). The most likely explanation of the number's mismatch is the lack of data on secondary flows, such as potential losses or heat flows. Consequently, the "worst-case" scenario has been adopted: the highest value is expected. With this assumption, it is certain that the precipitation's reaction will be efficient. If the environmental impacts connected to the whole Nickel recovery process is finally found to be negligible despite the worst-case scenario, then it can be concluded that Nickel's recovery is not a significant contributor to look at. On the contrary, if the environmental impacts due to Nickel's recovery is particularly high, then, further research would be required and recommended in order to develop a better model. That is why the number of moles for Na_2CO_3 is assumed to be worth 1.41 mol. Based on this, the mass of Na_2CO_3 has been calculated with the following equation:

$$m_{Na_2CO_3\ input} = n_{Na_2CO_3} \times M_{Na_2CO_3} = 1.41 \times 105.988\ g = 149.44\ g\ (Eq. 38)$$

When a total evaluation of the inputs and outputs is made, a difference can be found:

$$\begin{aligned} IN - OUT = {} & m_{dried\ catalyt} + m_{H_2SO_4\ input} + m_{alkali\ input} + m_{Na_2CO_3\ input} - m_{residue} \\ & - m_{Al\ precipitate} - m_{NiCO_3\ output} - m_{Na_2SO_4\ output} \\ & = 200 + 21.96 + 23.31 + 149.44 - 47.51 - 29.32 - 166.9 - 56\ g \\ & = 94.98\ (Eq. 39) \end{aligned}$$

Due to a lack of data, several assumptions were taken. No information was available on the amount of water needed for the "washing" process. As the water is used only to clean the catalyst and leaves the process, it is considered that a balance is respected between the input and the output (the water that goes in goes out). For these reasons, the water flow has been neglected in this process.

Similarly, no information was available on the heat needed for the "evaporation" and "drying process". No detailed research could have been conducted on these numbers and they were neglected as well. The lack of data for heat is one room for improvement since the need for heat may have significant influences on the technology's environmental performance.

The mass balance is not respected (IN>OUT). The assumptions previously adopted, such as the value adopted for the Na_2CO_3's mass inflow or the lack of numbers for the heat flows, probably explain this imbalance. As no clear indication was found on how to refine the model, a new outflow was defined as "losses" with a value of 94.98 g, to respect the mass balance. The "losses" flow is most likely a mix of water that is used as a diluent and other chemicals that were lost. For a lack of time and data, no further study was conducted on to describe in more details the composition of the "losses" flow.

11) Recycling processes for common elements

This appendix details the processes selected in OpenLCA with the ecoinvent 3.4 database to treat common elements such as steel, aluminium, etc.

Ex-ante large-scale alkaline's electrolyser:

- Aluminium cast alloy sent as "treatment of scrap aluminium, municipal incineration | scrap aluminium | Cutoff, U - Europe without Switzerland" ➔ only treatment process found. The other options would require more research to clearly understand its functioning.
- Copper sent to "treatment of non-Fe-Co-metals, from used Li-ion battery, pyrometallurgical processing | copper | Cutoff, U – GLO" because of the similitude of the process used for noble metals (it would probably optimize the infrastructure).
- Steel sent to "treatment of scrap steel, municipal incineration | scrap steel | Cutoff, U - Europe without Switzerland". It is either this or landfill. At least from incineration, you can get some energy.
- Plastic waste sent to "treatment of waste plastic, industrial electronics, municipal incineration | waste plastic, industrial electronics | Cutoff, U – RoW". Seems the most adapted and available option.
- Some chemicals are specific and do not possess a recycling system modelled in ecoinvent. In the list, there are: acetic anhydride, acrylonitrile-butadiene-styrene copolymer, aniline, carbon monoxide, chromium, graphite, hydrochloric acid, industrial machine, lubricating oil, N-methyl-2-pyrrolidone, nitric acid, plaster mixing, polyphenylene sulphide, polysulfone, purified terephthalic acid, tetrafluoroethylene, potassium hydroxide and zirconium oxide ➔ no treatment available. Would need a modelling
- Water is sent to "market for wastewater, average | wastewater, average | Cutoff, U - Europe without Switzerland" (I don't have so many data on water consumption so the average is taken). Addition of decarbonized and deionized water and translation from kg to m^3. It is assumed for simplicity that wastewater has a density of 1000 kg/m^3.

Ex-ante large-scale PEM electrolyser:

- Activated carbon modelled as "spent activated carbon, granular": EoL flow with cut-off ➔ no model in ecoinvent. The other processes were not considering the activated carbon as a "waste".
- Aluminium, cast alloy sent as "treatment of scrap aluminium, municipal incineration | scrap aluminium | Cutoff, U - Europe without Switzerland" ➔ only treatment process found. The other options would require more research to clearly understand its functioning.

- Some chemicals are specific and do not possess a recycling system modelled in ecoinvent. In the list, there are: Carbon fibre, cast iron, graphite, silicon, metallurgical grade and titanium tetrachloride
- Rubber to “treatment of waste rubber, unspecified, municipal incineration | waste rubber, unspecified | Cutoff, U - Europe without Switzerland” as waste rubber. Only process available.

The flowcharts for ex-ante large-scale AE and PEM electrolysers with recycling processes are shown in **Figure 85** and **Figure 86**. For readability, the recycling processes have not been extended. The “Nickel recovery process possesses an extended flowchart in **Figure 28** and the “Pt + Ir + Nafion treatment” process possesses an extended flowchart in **Figure 27**.

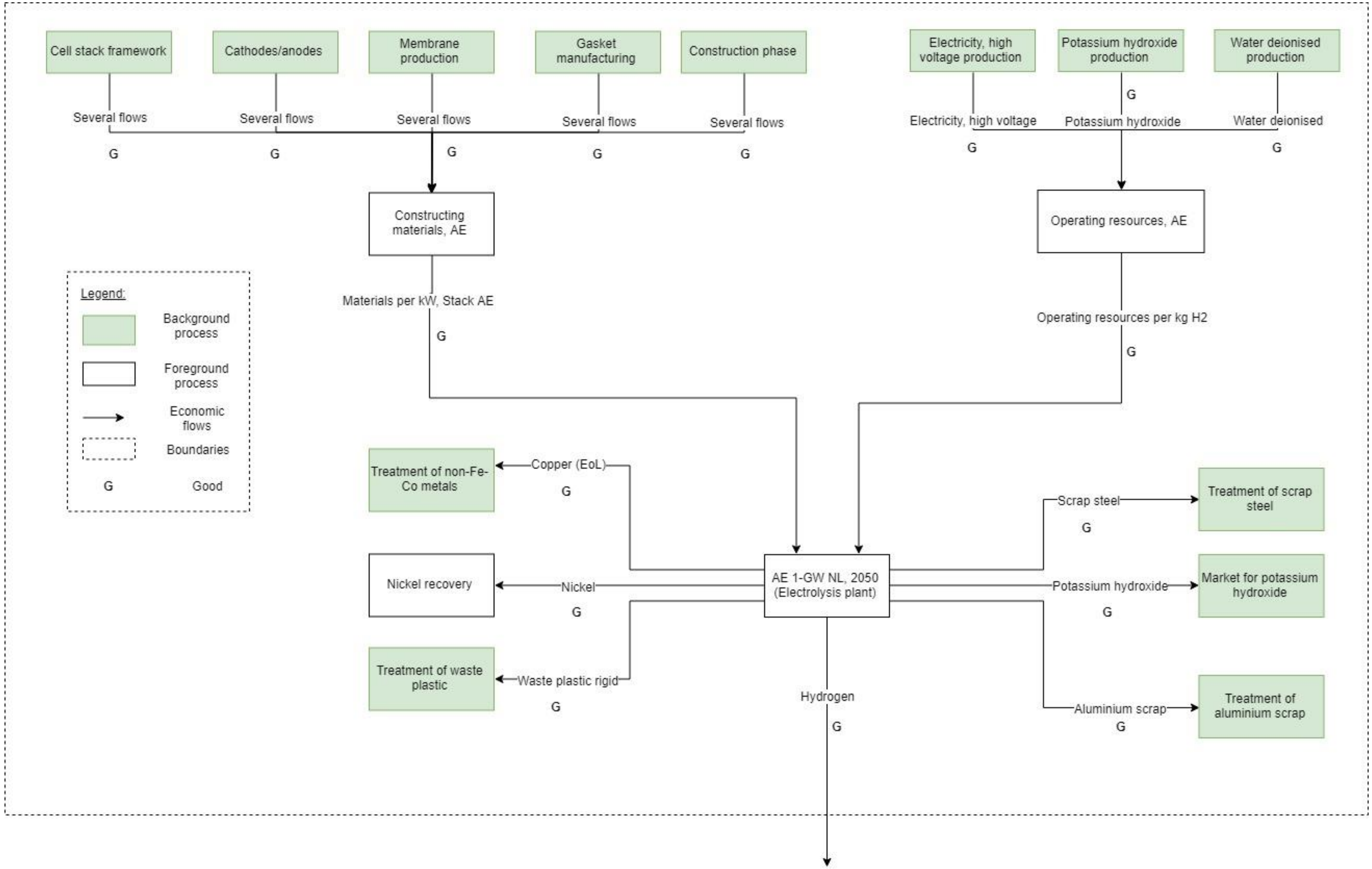


Figure 85. Flowchart for the ex-ante large-scale LCA model of alkaline electrolyser with recycling systems.

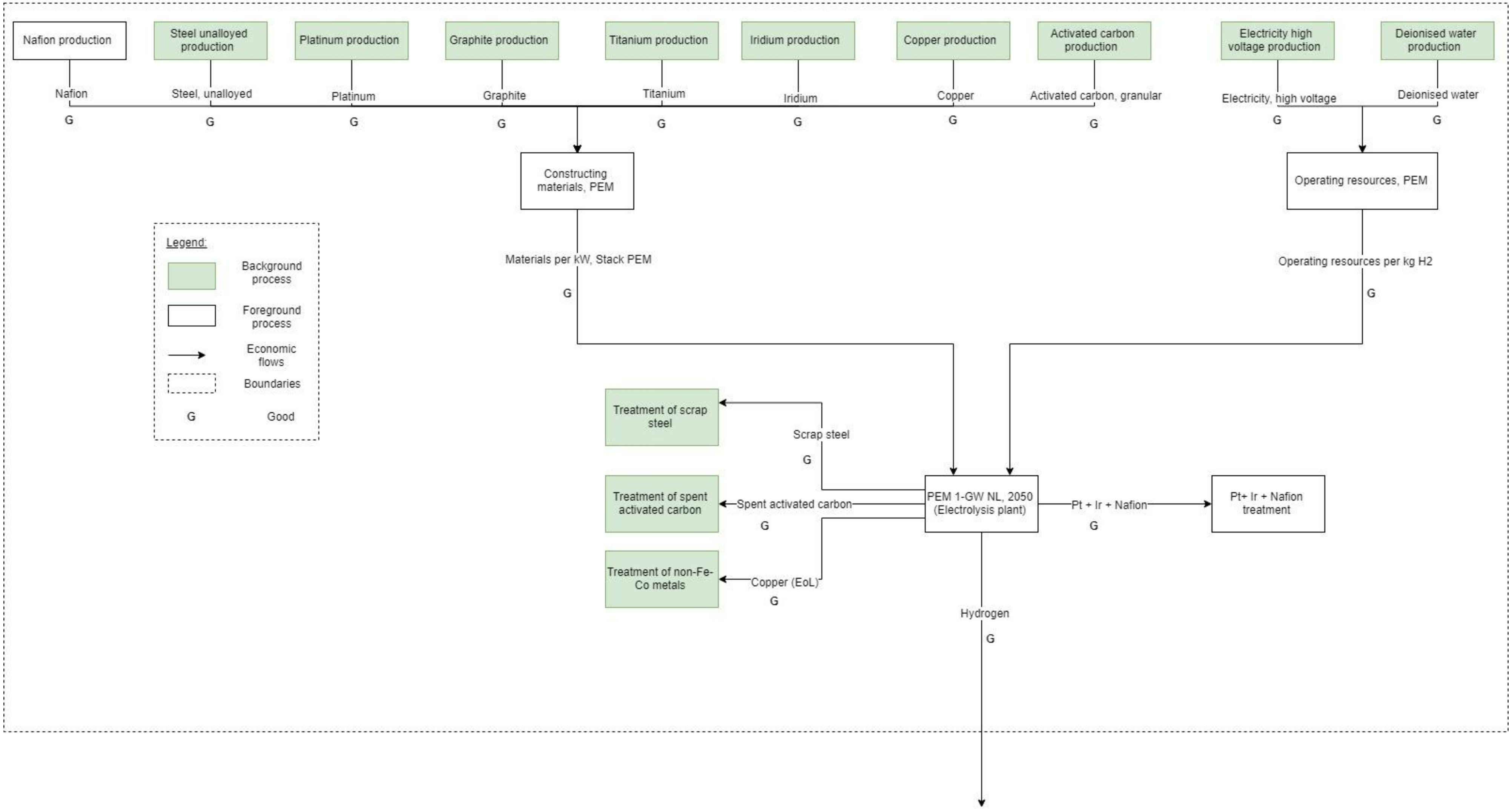


Figure 86. Flowchart for the ex-ante large-scale LCA model of PEM electrolyser with recycling systems.

12) Data inventories for the ex-ante large-scale LCA model

The boundaries definition was one issue raised during the development of the ex-ante large-scale LCA models. The pilot-scale LCA models (AE NL 2017, AE NL 2018, PEM NL 2018a and PEM NL 2018b) possess different levels of precision and details. Common elements can be found between the models but also differences. Hence the question arises about which elements to consider because they are essential and possess a clearly defined role and which elements can be skipped because they are too specific to the case study. After discussions with the first supervisor, it has been decided that the more detailed Life Cycle Inventory is, the better it is. The flows were removed only when they possessed an unclear role or when they were irrelevant. The list of flows that were deleted are indicated below:

- For the ex-ante large-scale alkaline electrolyser's model: the heat flow from "Constructing materials" (AE NL 2017) was not considered since it is likely connected to a BOP element (heat exchanger). The "steam" flow from "Constructing materials" (AE NL 2017) was also deleted for the same reason. The "Polyethylene granulate" flow was deleted since there was no clear indication on its use. Several possibilities were found but without a clear answer. The "steam" and "nitrogen" flows from "Operating resources" were also deleted. No other source was found to support the two mentioned flows' use and provide a fair idea on the requirements for them. Furthermore, the pilot-scale LCA's environmental profiles showed negligible contributions from these flows in the system's environmental performances.
- For the ex-ante large-scale PEM electrolyser's model: the "solvent" flow from "Constructing materials" (PEM NL 2018a) was not considered, as no specific or quantified details were found for modelling.

The inflows/outflows for the ex-ante large-scale LCA models can be found in the file "Appendix, Life Cycle Inventories, Pilot-scale LCA and ex-ante large-scale LCA models".

13) List of parameters

Tables 42 and 43 provide the list of parameters implemented in the models AE 1-GW NL 2050 and PEM 1-GW NL 2050 respectively.

Table 42. List of parameters implemented in OpenLCA for the model AE 1-GW NL 2050

Model	**AE 1-GW NL 2050**		
Process	*Constructing materials, AE NL 1 GW*		
	Name	**Uncertainty**	**Description**
	Acetic_anhydride_rate_AE	none	in kg/kW
	Acrylonitrile_butadiene_styrene_rate_AE	none	in kg/kW
	Aluminium_rate_AE	none	in kg/kW
	Aniline_rate_AE	none	in kg/kW
	Carbon_monoxide_rate_AE	none	in kg/kW
	Chrome_rate_AE	none	in kg/kW
	Copper_rate_AE	none	in kg/kW
	Decarbonized_water_rate_AE	none	in kg/kW
	Deionized_water_rate_AE	none	in kg/kW
	Electricity_rate_AE	none	in MJ/kW
	Graphite_rate_AE	none	in kg/kW
	Hydrochloric_acid_rate_AE	none	in kg/kW

	Industrial_machine_production_rate_AE	none	in kg/kW
	Lubricating_oil_rate_AE	none	in kg/kW
	N_Methyl_2_pyrrolidone_rate_AE	none	in kg/kW
	Nickel_rate_AE	uniform: min=0.200000 max=2.00000	in kg/kW
	Nitric_acid_rate_AE	none	in kg/kW
	Plaster_mixing_rate_AE	none	in kg/kW
	Polyphenylene_sulfide_rate_AE	none	in kg/kW
	Polysulfone_rate_AE	none	in kg/kW
	Polytetrafluoroethylen_rate_AE	none	in kg/kW
	Rigid_plastic_rate_AE	none	in kg/kW
	Steel_rate_AE	uniform: min=10.0000 max=30.0000	in kg/kW
	Terephthalic_acid_rate_AE	none	in kg/kW
	Zirconium_oxide_rate_AE	none	in kg/kW
Process	*Operating conditions, AE NL 1 GW*		
	Name	**Uncertainty**	**Description**
	Electricity_per_kg_H2	none	in kWh
	Potassium_hydroxide_per_kg_H2	none	in kg
	Water_per_kg_H2	none	in kg
Process	*AE 1-GW NL, 2050 (Electrolysis plant)*		
	Name	**Uncertainty**	**Description**
	Plant_capacity_AE	uniform: min=100000 max=1.00000E+06	in kW
	Plant_H2_production_rate_AE	none	in kg H2/h
	Plant_lifetime_AE	uniform: min=175320 max=262980	in hours
	Stack_capacity_AE	uniform: min=5000.00 max=20000.0	in kW
	Stack_lifetime_AE	uniform: min=80000.0 max=120000	in hours
	Wind_coverage	none	in %
	Dependent parameters		
	Name	**Formula**	**Description**
	Hydrogen_prod_total_AE	Plant_H2_production_rate_AE *Plant_lifetime_AE *Wind_coverage	in kg
	Materials_needed	(plant_capacity_AE *plant_lifetime_AE *wind_coverage)/(stack_lifetime_AE)	in kg

Table 43. List of parameters implemented in OpenLCA for the model PEM 1-GW NL 2050

	PEM 1-GW NL 2050		
Process	*Constructing materials, AE NL 1 GW*		
	Name	**Uncertainty**	**Description**
	Activated_carbon_rate_PEM	none	in kg/kW
	Aluminium_rate_PEM	none	in kg/kW
	Carbon_fibre_rate_PEM	none	in kg/kW
	Cast_iron_rate_PEM	none	in kg/kW

	Copper_rate_PEM	none	in kg/kW
	Graphite_rate_PEM	none	in kg/kW
	Iridium_rate_PEM	uniform: min=1.00000E-05 max=0.000700000	in kg/kW
	Nafion_rate_PEM	uniform: min=0.00200000 max=0.0160000	in kg/kW
	Platinum_rate_PEM	uniform: min=1.00000E-05 max=0.000300000	in kg/kW
	rubber_rate_PEM	none	in kg/kW
	Silicon_rate_PEM	none	in kg/kW
	Steel_rate_PEM	uniform: min=7.00000 max=10.0000	in kg/kW
	Titanium_rate_PEM	uniform: min=0.0350000 max=0.500000	in kg/kW
	Dependent parameters		
	Name	**Formula**	**Description**
	Oxygen_rate_PEM	Plant_H2_production_rate_PEM *Plant_lifetime_PEM *Wind_coverage	in kg/kW
	Titanium_tetrachloride_rate_PEM	(plant_capacity_PEM *Plant_lifetime_PEM *Wind_coverage)/(Stack_lifetime_PEM)	in kg/kW
Process	*Operating resources, PEM NL 1 GW*		
	Name	**Uncertainty**	**Description**
	Electricty_per_kg_H2	none	in kWh
	Water_per_kg_H2	uniform: min=9.00000 max=10.0000	in kg
Process	*PEM 1-GW NL, 2050 (Electrolysis plant)*		
	Name	**Uncertainty**	**Description**
	Plant_capacity_PEM	uniform: min=100000 max=1.00000E+06	in kW
	Plant_H2_production_rate_PEM	none	in kg H2/h
	Plant_lifetime_PEM	uniform: min=175320 max=262980	in hours (30 years)
	Stack_capacity_PEM	uniform: min=5000.00 max=20000.0	in kW
	Stack_lifetime_PEM	uniform: min=80000.0 max=130000	in hours
	Wind_coverage	none	in %

14) Economic and fuelling stations aspects

Even though the economic aspects are not the main focus of this Master thesis, information is provided below on these. Most of the data come from the literature review.

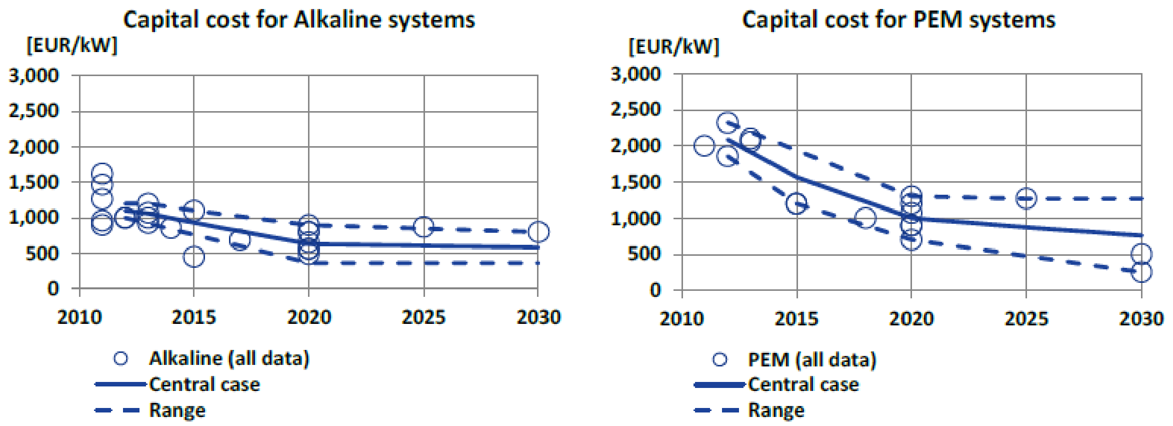
The costs of the electrolysers remain one of the most important barriers to overcome, as stated by Ball & Wietschel: “for hydrogen from renewable electricity to be economically viable, the cost of electrolyser must come down sharply” (Ball & Wietschel, 2009, p.628). the authors make an estimation of a worldwide investment of a hydrogen-fuel system of 1,200-2,700 billion $ by 2050. This amount of money is considered as considerable but should be seen as an insurmountable barrier to overcome, especially in comparison with other investment programs.

There is a high need for clean H_2 in fuel cells since even the “the slightest trace of carbon monoxide impedes the functioning of the precious metal catalyst in the fuel cell” (Ball & Wietschel, 2009, p.296).

In the option of adaptation, to avoid any hydrogen-related issue, investments are estimated to be up to twice that of comparable natural gas pipelines.

Wind parks may increase distribution costs because of their inherent locations. However, these same costs may decrease since it can be connected directly to the electricity grid, leading to higher transmission efficiency and savings.

According to Bertuccioli et al. (2014), currently, the system costs for PEM is around twice higher than for alkaline (1,000 to 1,500 €/kW). The report expects that the costs will decrease to reach 370 €/kW for alkaline and 700 €/kW as best cases. The report recalls that despite the more mature state of the alkaline technology, sales and production remain low and there are still potentials for technological innovation. The development of strong supply chains is an important aspect of both technologies.



System cost [1]			Today	2015	2020	2025	2030
EUR/kW	Alkaline	Central	**1,100**	**930**	**630**	**610**	**580**
		Range	1,000 - 1,200	760 - 1,100	370 - 900	370 - 850	370 - 800
	PEM	Central	**2,090**	**1,570**	**1,000**	**870**	**760**
		Range	1,860 - 2,320	1,200 - 1,940	700 - 1,300	480 - 1,270	250 - 1,270

[1] incl. power supply, system control, gas drying (purity above 99.4%). Excl. grid connection, external compression, external purification and hydrogen storage

Figure 87. Projections for the CAPEX and system costs for AE and PEM technologies (extracted from Bertuccioli et al. (2014, p.13))

Bertuccioli et al. (2014) state that the SMR technology is still cheaper than electrolysis nowadays. Nevertheless, the electrolysis costs are expected to decrease by 2030 to become almost competitive with SMR, though remaining a bit higher than SMR. Based on the German country case study, the authors claim that the most efficient strategies to develop significantly the hydrogen production is through low electricity prices and reductions in transmission/distribution costs. In general, the lowest cost for hydrogen production by 2030 is achieved through a combination of CAPEX/OPEX reductions and an increase in the electrolyser efficiency.

Some projections were made by Bertuccioli et al. (2014) in Germany. In potential future large-scale applications of hydrogen production, it will be difficult for the electrolysis to compete with other existing technologies without a carbon payment. However, on on-site systems (with the electrolyser located at the station), some scenarios make the electrolysis competitive with SMR or other competing technologies. The higher the plant capacity is, the lower the hydrogen cost is. Other projections made in the UK show that hydrogen costs become competitive with SMR only for transport end-use. For other use, further payments (like carbon) are necessary. Bertuccioli et al. (2014) conclude that despite all the improvements expected, in the German and UK case studies, the production costs of hydrogen from electrolysis will still remain higher than SMR by 2030. The cost is projected at 2.3–5.0 €/kg H_2 from the electrolysis and 2.2–2.5 €/kg H_2 from the SMR in 2030. The electricity is the biggest cost contributor to electrolysis whereas the gas cost is the biggest contributor to SMR. The report recalls that political support can help to implement the electrolysers and that the costs are dependent on the situation considered with the decentralised or centralised distribution. In the UK case study, an off-grid production coupled with a wind turbine avoids all the grid-related costs/fees. For car refuelling stations, distributed on-site electrolysers can reach commercial competitiveness with SMR by 2030, in most of the case studies.

Bertuccioli et al. (2014) made an overview of the different elements that can contribute the most to costs reductions. The main results are shown below.

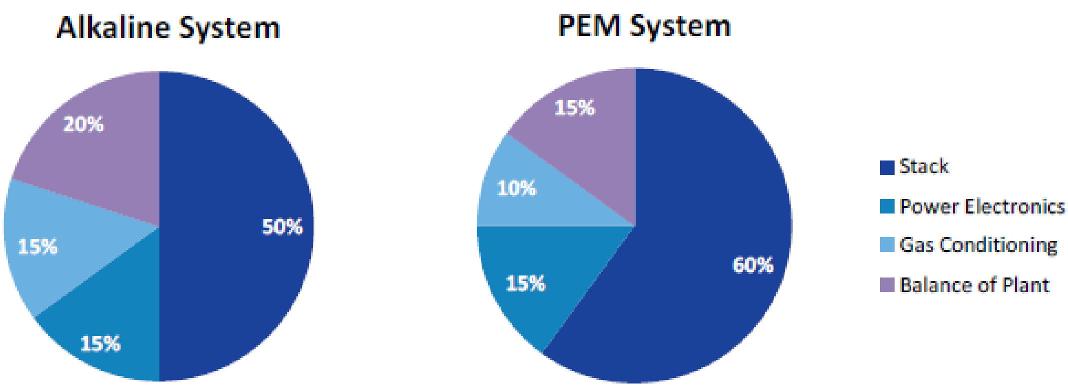


Figure 88. System costs breakdown for the alkaline and PEM system (extracted from Bertuccioli et al. (2014, p.25))

A similar study has been conducted by Smolinka et al. (2018). The results are shown below.

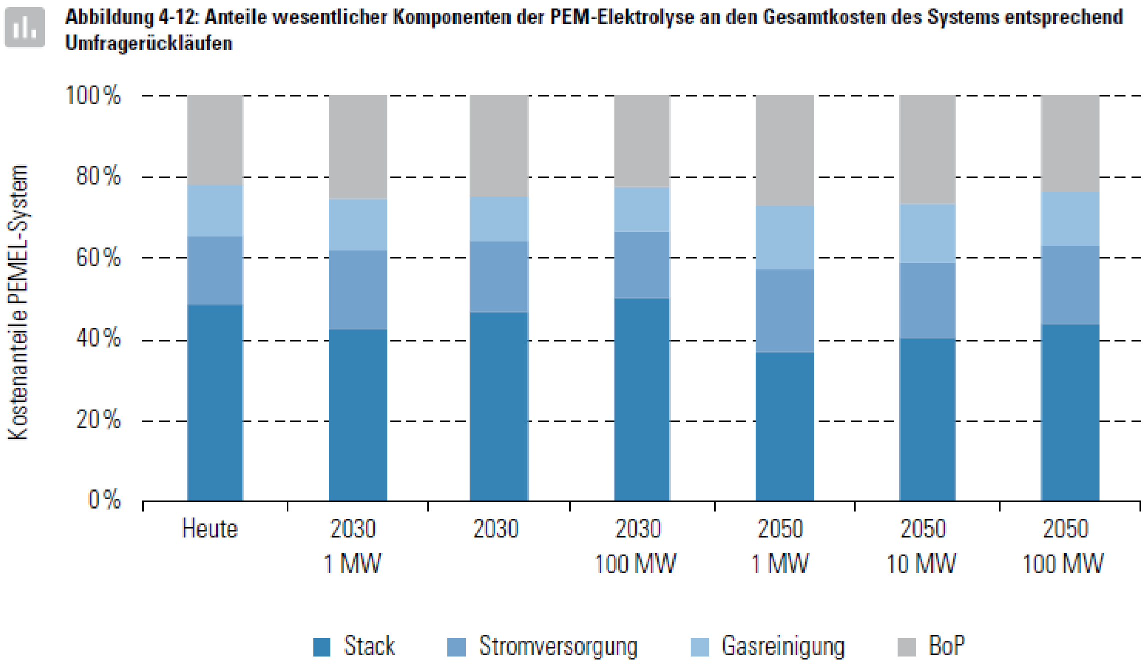


Figure 89. Projections of the system costs breakdown for the PEM technology. “Stromversorgung” = electricity supply, “Gasreinigung” = gas-cleaning, BoP = Balance of the Plant (extracted from Smolinka et al. (2018, p.45)).

The costs related to stacks share also a non-negligible part around 40%. The two previous studies prove that focusing on stacks can be a relevant strategy to decrease the system costs.

Concerning the alkaline technology, no major cost reductions linked to technological innovation is expected in the years to come. Therefore, the development of the technology should focus on incremental and design aspects.

Nowadays, the PEM technology is more expensive than alkaline. However, the study conducted by Smolinka et al. (2018) expects that the cost of hydrogen production (in €/kW) will decrease in the next decades. Their projections are shown in **Figure 90**:

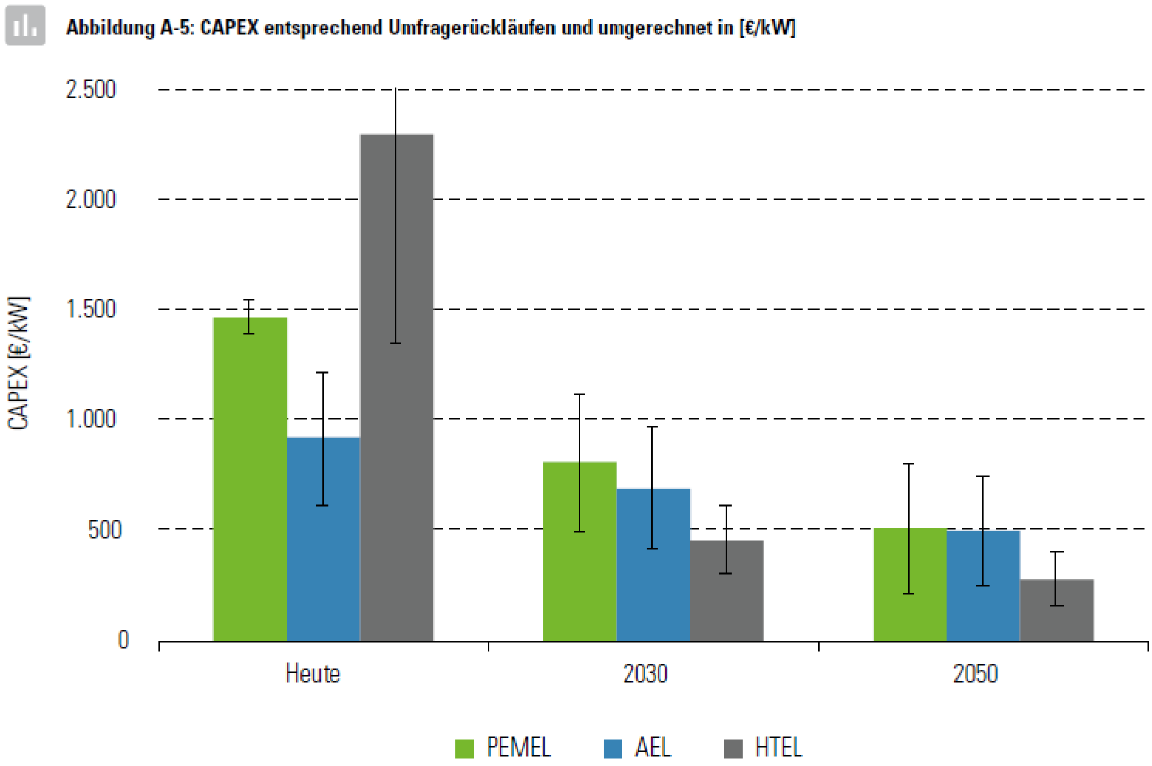


Figure 90. Projections for the CAPEX for three electrolysers technologies. (extracted from Smolinka et al. (2018, p.175))

By 2050, it is shown that the PEM costs will be extremely similar to alkaline technology, making both of them competitive. Therefore, in the future, the cost considerations should not be a relevant criterion to choose one technology from another one.

Balance of the Plants element: Larger systems will likely enable to decrease the costs from the balance of the plant (inverter, gas drying, system control, etc.). These costs seem to be especially present when going from kW capacity up to 500 kW. At higher levels, the effect flattens according to Bertuccioli et al. (2014).