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Technological scope and potential cost reductions Early Phase Scale up

Final report

Ministerie van Economische Zaken en Klimaat

Rotterdam, 15 February 2023

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Management Summary

The coalition agreement of the Dutch government acknowledges that new technologies are needed to meet the 2050 climate targets and thus proposes financial support to bridge the gap between support mechanisms for established technologies and support for (applied) research. The subsidy instruments that will be developed for this purpose are part of a package of policy instruments aimed at energy innovation and the targets for 2030 and later.

Main research aim

The goal of this study is threefold: first to identify technologies used for the production of high-quality energy carriers and to assess their potential for scale-up[1]. Second, to review and evaluate the assessment framework. Third, to estimate the cost reduction potential of the selected technologies.

Methodology

The study is divided into four phases:

1. An initial scoping exercise to identify innovative technologies that could contribute to reaching the climate objectives of the Dutch government.
2. Application of an assessment framework developed by the Ministry for selecting the technologies that are most eligible for a subsidy.
3. Review of the assessment framework.
4. Qualitative deep dive into the cost reduction potential of the technologies selected in phase 2.

The study team used a combination of desk research, expert input, and industry interviews.

Result of phase 1: Identification of technologies eligible for assessment for phase 2

This step casts a net wide of technologies that produce energy carriers using four main criteria that potential technologies have to meet in order to fall within the scope of the subsidy as outlined in the Coalition Agreement:

1. the technology must produce an energy carrier;
2. the energy carrier must be of high quality;
3. the energy carrier must be renewable;
4. the energy carrier must be able to result in cost-effective CO_2 emission reduction when scaled up substantially.

This analysis resulted in ten technologies that produce a high- quality renewable energy carrier and are in scope for phase 2, namely: Gasification, Biomass pyrolysis, Methane pyrolysis, Alkaline electrolysis, Proton exchange membrane (PEM) electrolysis, Hydrogenation-based chemical methanation, Hydrogenation-based biological methanation, Mobil Process (Methanol-to-X), Hydrocarbon production based on the Fischer-Tropsch process, Electrolytic Haber-Bosch ammonia production. These processes are based on two key processes, electrolysis and thermochemical conversion, complemented with a group of technologies to produce tertiary energy carriers.

1 using an assessment framework as developed by the Ministry of Economic Affairs and Climate Policy.

The technologies that did not meet the four main criteria were mainly due to them not meeting the fourth criterion. Many technologies that were considered, were not ready for scale up or were already scaled up successfully to some degree. These technologies could not scale up substantially and thus could not result in cost-effective CO_2 emission reduction.

Result of phase 2: selection of technologies eligible for a subsidy

We then applied the assessment framework of the Ministry to further assess which technologies could fall within the initial scope. The assessment framework was developed by the Ministry of Economic Affairs and Climate Policy. It consisted of the following criteria/indicators:

1. the technology is necessary for a climate-neutral society,
2. the technology is ready for scale-up but needs government help to do so,
3. government intervention at this stage of the technology's development is effective,
4. government intervention will have deep and broad impact.

Three technology groups (containing four individual technologies) meet the requirements of the assessment framework: electrolysis (alkaline and PEM), gasification, and biomass pyrolysis.

The four technologies that meet all criteria of the assessment framework are technologically sufficiently developed, but require support to scale up to play a major role in a climate-neutral society. Notable about these technologies is that they are all processes that are the starting point of a chain of upgrading processes. The resulting hydrogen, syngas and bio-oil are feedstocks for other technologies. This makes them a foundation for other processes and possibly a bottleneck in the energy system if their supply is insufficient.

There is a need for hydrogen and carbon atoms in a climate-neutral society, either as separate matter or to create complex molecules. For hydrogen, the technologies that are viable and ready for scale-up are alkaline and PEM electrolysis. For processing biomass, two technologies are viable and ready for scale-up: gasification and pyrolysis. These four technologies can become the foundation of other technologies to build on. If hydrogen and carbon are scarce, this forms a bottleneck for all other technologies that are needed in a climate-neutral society. These technologies provide renewable hydrogen and carbon, which can subsequently be used in tertiary (Power-to-X) technologies.

Six technology groups do not meet the requirements: methane pyrolysis, hydrogenation-based chemical methanation, hydrogenation-based biological methanation, Mobil Process (Methanol-to-X), Fischer-Tropsch synthetic hydrocarbon fuel production, and electrolytic Haber-Bosch ammonia production.

The technologies that did not meet the criteria of the framework are all mature advanced upgrading processes which were developed with fossil fuels as feedstock. They are employed globally on a large scale and are generally commercially viable; thus these processes do not need to be scaled up. However, these technologies can still be important in a climate-neutral society. As tertiary technologies, they are further down the production chain and therefore require more energy input; but they have added value in specific use-cases. They should be further developed and supported to iron out technicalities that hinder their application in a green energy system.

Result of phase 3: recommendations for improving the assessment framework

In phase three, a review of the assessment framework of the Ministry was conducted to offer recommendations on how the framework could be improved. The assessment framework in its current form has already been applied successfully to the selection of eligible technologies. However, four points of improvement were identified:

1. a production chain perspective is crucial in the assessment;
2. the timespan under assessment is unclear;
3. the scope of ‘a climate neutral society’ is very broad;
4. technologies under assessment have distinct needs.

Recommendations to further improve the framework include:

1. Broadening the scope of the assessment framework to include other technologies and processes that are required for the production of high-quality energy carriers. Focusing on individual technology groups might result in the scale-up of intermediate products only.
2. Defining the timeline of the scale-up and, more notably, clarifying the approach towards transitional technologies.
3. Elaborating on the definition of a climate-neutral society and, where relevant, including relevant indicators in the assessment framework (such as energy intensity of the production process and estimated reduction in GHG emissions).
4. Add a portfolio perspective to the assessment framework, by assessing the mix of technologies in scope. As a result, technologies with lower individual scores may be selected for subsidy on the grounds of their complementarity with other technologies.

Result of phase 4: cost reduction potential of pyrolysis, gasification and electrolysis

In phase four, we dive into the cost reduction potential for the technologies that meet the criteria of the assessment framework: pyrolysis, gasification, and electrolysis.

There are two major potential cost reduction components for pyrolysis. The first is the type of biomass used, due to the large impact of its unit cost. Optimising the type of biomass and how it is processed to meet the requirements of upgrading processes is the subject of ongoing research by market parties. The second major cost reduction component is the standardisation of plant design that leads to an optimised production process at suppliers of parts for the plants.

The main variable cost drivers for the gasification process are the availability and quality of the feedstock and the forecast revenues from its outputs. It is therefore important to invest in scaling different gasification technologies, as the efficiency and effectiveness of the process might differ between the combination of technology and feedstock used. Cost reduction is expected to take place mainly through the deployment of multiple scaled production facilities.

This allows for learning on the optimisation of processes, and test results of various types of feedstock and enhance the application of the main product output and side-outputs.

Cost reduction for Alkaline electrolysis can be achieved by making incremental efficiency improvements to the cells, while simultaneously scaling up the size of plants. In addition, literature as well as experts highlight the importance of supportive developments, such as the standardisation of the supply chain and greater knowledge sharing. PEM electrolysis seems to still be in an earlier phase of the cost reduction curve. Literature proposes cutting costs by changing fundamental facets of the PEM cell, such as the materials used for the bipolar plates and the catalysts.

In general, the most promising areas for cost reduction are the following:

a) The scaling and standardisation of underlying component manufacturing processes. As highlighted in the pyrolysis deep dive, producers face risks when scaling up manufacturing plants because it is uncertain whether a technology will scale up in the future or remain in the ‘valley of death’. In addition, no common standards exist for such plants. Effective policy can help alleviate both these risks.
b) The availability and transport of feedstock should be optimised for effective scaling. Regarding pyrolysis and gasification technologies, the availability of input feedstock is a key factor in determining the cost of the feedstock. Which is in turn a key factor in determining the business case and viability of the plants.
c) Sufficient renewable energy must be available for scaling-up. The price of electricity is dominant (especially for electrolysis) in determining the cost of the hydrogen output. Without a significant price reduction of renewable electricity, it is unlikely that electrolysis-based hydrogen can compete with fossil fuel based hydrogen, given current regulations.
d) Increasing the carbon price will improve the relative competitiveness of carbon-neutral technologies. This will make the technologies commercially viable sooner, resulting in market parties investing in their deployment. This will likely result in further cost reductions through standardisation and economies of scale.

1 Introduction

The coalition agreement of the Dutch government acknowledges that new technologies are needed to meet the 2050 climate targets. It proposes a new subsidy instrument to bridge the gap between support mechanisms for established technologies (especially the SDE++ support scheme) and support for (applied) research (e.g. DEI+, MOOI).

The new subsidy instrument is part of a package of policy instruments aimed at energy innovation and the targets for 2030 and later.[2] There are also other instruments aimed at the scale-up phase, such as the national growth fund (Nationaal Groeifonds) that focuses on specific projects, and the support for hydrogen production ('Opschalingsregeling waterstof'). Other support instruments such as InvestNL help scale-up technologies to obtain financing.

Our approach

The goal of this study is twofold: first to identify technologies used for the production of high-quality energy carriers and assess their potential for scaling using an assessment framework as developed by the Ministry of Economic Affairs and Climate Policy. Second, to review and evaluate the assessment framework.

Figure 1.1 presents a schematic overview of our overall approach. Our approach includes four key activities:

1. First, we performed an initial scoping exercise to identify innovative technologies that could contribute to reaching the climate objectives of the Dutch government using a set of criteria.
2. Second, we applied the assessment framework developed by the Ministry of Economic Affairs and Climate Policy to the technologies identified in Phase 1. During focus group sessions we involved experts from the IEA, TNO, TU Delft, Biomass Technology Group (BTG), and Fraunhofer IEE.
3. Third, the assessment framework was reviewed and checked for appropriateness.
4. Fourth, we performed an in-depth assessment of the technologies, including the identification of the cost-reduction potential of a selected list of technologies.

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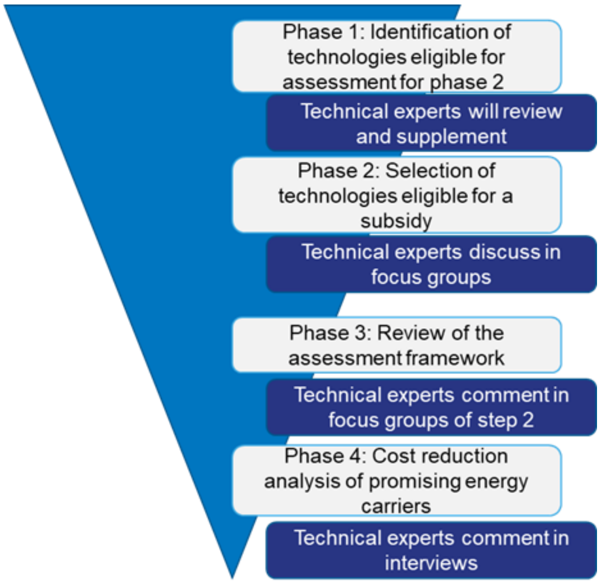
[2] Rijksoverheid (2022), 'Ontwerp Beleidsprogramma Klimaat'

Figure 1.1 Schematic overview of our approach



Structure of this report

Chapter 2 describes our approach to identifying innovative technologies for the production of high-quality energy carriers that have a high potential for scaling up. Chapter 3 elaborates on the application of the assessment framework and the resulting scope of technologies. Chapter 4 gives a review of the assessment framework itself. Finally, Chapter 5 provides further insight into the cost reduction potential of the most promising technologies.

2 Phase 1: Identification of technologies eligible for assessment for phase 2

To determine which technologies will be assessed using the assessment framework, a first identification and initial assessment is required. The aim is to cast a wide net of technologies that produce high-quality renewable energy carriers. These technologies are in an early phase of their commercial development and can contribute to the climate goals of the government. When identifying suitable technologies, a set of criteria are used to ensure the goals of the Coalition Agreement are met. Following discussions with the Ministry, we assessed the technologies on a standalone basis.

The Coalition Agreement defines the scope as 'technologies for the production of high-quality renewable energy carriers' that furthermore 'will only result in cost-effective CO_2 emission reduction when scaled up substantially.'

We define four characteristics that potential technologies need to have to fulfil the scope as outlined in the Coalition Agreement:

1. the technology must produce an energy carrier;
2. the energy carrier must be of high quality;
3. the energy carrier must be renewable;
4. the energy carrier must be able to result in cost-effective CO_2 emission reduction when scaled up substantially.

Below we present an overview of the definition of the criteria. Annex 2 includes more details on the methodology.

2.1 Criterion 1: The technology must produce an energy carrier

To define what constitutes an energy carrier, we use the definition provided by the Intergovernmental Panel of Climate Change (IPCC) of the United Nations:

[An energy carrier] occupies intermediate steps in the energy-supply chain between primary sources and end-use applications. An energy carrier is thus a transmitter of energy. […] Technology issues surrounding energy carriers involve the conversion of primary to secondary energy, transporting the secondary energy, in some cases storing it prior to use, and converting it to useful end-use applications.[3]

Primary sources of energy are generally considered to be natural resources without any interference or engineering from humans. For example, solar, wind, and tidal energy are

[3] IPCC (2007) Climate Change 2007: Working Group III: Mitigation of Climate Change

included; but also biomass, natural gas, oil, and even energy from waste are considered primary sources. Secondary sources contain energy from a converted primary source. Tertiary sources are not generally defined or used in literature, but they are commonly labelled as power-to-x technologies. It is however useful to introduce the term in this study. A tertiary energy source contains energy from a converted secondary source. For example, hydrogen produced from water using electrolysis is an energy carrier and a secondary source. When one uses this hydrogen to produce ammonia, the ammonia is considered an energy carrier of the third degree.[4,5]

Both secondary and tertiary energy carriers are included.[6] We excluded fossil fuels and technologies that dominantly rely on them as their contribution to a renewable energy system is difficult to justify.

Using this definition, electricity can be considered an energy carrier. We will, however, exclude technologies that produce electricity, since there are ample mature technologies to produce renewable electricity, so there is less need to scale them. Moreover, our understanding is that the scale-up instrument is primarily aimed at adding energy carriers (that are not widely used yet) to the energy mix.[7] Technologies that primarily produce heat are also excluded since heat is a type of energy, not an energy carrier. Technologies that integrate the capture of heat in another medium in the process are considered, insofar as they can be considered a single technology, and the resulting carrier meets the other criteria.

2.2 Criterion 2: The energy carrier must be of high quality

For an energy carrier to be of high quality, it should be able to play an efficient role in any integrated energy system. This means it should be able to provide (i) sufficient energy (i.e. it should be in the same order of magnitude as fossil based carriers) and should provide it (ii) whenever and (iii) wherever it is required to do so. In a fossil-fuel-based energy system, oil and gas fulfil this role perfectly. They are easy to transport and, more importantly, provide a lot of energy relative to their mass. The denser the energy in the carrier, the less you have to transport, making it a more efficient energy carrier in terms of transport and storage.

Technologies are included when the energy per kg (called specific energy) of the carrier it produces is in the same order of magnitude (or greater) as that of fossil-based carriers. Fossil fuels have a specific energy of around 40-60 MJ/kg. The threshold we use is that any energy carrier should have an energy density of at least 10% of the density of fossil fuels to be included. This translates to an energy density threshold of 4 MJ/kg.

The efficiency of the technology is not used as a criterion. However, especially for energy carriers that are a tertiary source, the efficiency of the process is important. In those instances,

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4 EC (2019), what kind of energy do we consume (link)

5 EIA (n.d.), Primary energy definition (link)

6 We did not include technologies to convert 'tertiary sources' in another carrier (e.g. ammonia cracking to produce hydrogen).

7 See a study that informed the coalition agreement (Studiegroep Invulling klimaatopgave Green Deal (2021), 'Bestemming Parijs'). 'Met het oog op 2050 is marktontwikkeling van hoogwaardige hernieuwbare energiedragers noodzakelijk. Dit gaat in ieder geval om technologie voor de productie van hoogwaardige hernieuwbare energiedragers, waaronder waterstof, biogas en bio-olie. In nagenoeg alle sectoren is een mix van CO2-vrije brandstof onmisbaar in de transitie naar 2050. Voor opschaling en commercialisering van de noodzakelijke technologieën zijn substantiële en risicovolle investeringen nodig.'

you have several conversion processes following each other, each using some energy. The production of secondary energy carriers has one conversion step less than tertiary energy carriers. This generally makes the production of secondary energy carriers more energy efficient.

2.3 Criterion 3: The energy carrier must be renewable

We operate under the assumption that any energy required to operate the process itself, originates from renewable sources. The renewability of a carrier is thus largely determined by the input and the output of the process. Both cannot increase the emission of CO_2 and the input must be readily available to prevent any strain on the environment.

First, the feedstocks used are mainly primary energy sources from non-fossil origins, so no strain is put on the environment. The technology also cannot increase CO_2 emissions, which cannot be offset within a limited timeframe. Second, only technologies that operate either without CO_2 emissions or in the short carbon cycle are included. Biomass is thus included as feedstock since possible CO_2 emissions are captured by trees and plants that make up the next generation of feedstock in a maximum of a few decades. Fossil fuels are excluded because it takes millennia before the emitted CO_2 is converted to a fossil fuel again.

2.4 Criterion 4: The energy carrier must be able to result in cost-effective CO_2 emission reduction when scaled up substantially

The ministry is interested in technologies that result in cost-effective CO_2 emission reduction when scaled up substantially. This goal can be divided into two parts: (i) the technology must be ready for scale-up and (ii) have to be a cost-effective contributor to the climate goals when scaled up.

Whether technologies are ready for scale-up is determined by their TRL (technological readiness level). TRLs are widely used in literature to estimate the maturity of any technique or process. TRL is therefore an excellent indicator of the stage a technology is currently in and whether it is ready for scale-up. Included are levels in the demonstration and deployment phase (levels 7, 8, and 9).

We based the contribution of the technology to the climate goals on research by the IEA. The IEA created a dashboard (ETP Clean Energy Technology Guide) with indicators for many energy production and storage technologies. Included is an assessment of their impact on net-zero emissions, which corresponds with the climate goals of the Dutch government. We have not been able to determine precisely on which indicators the IEA based the impact, thus this criterion is not applied strictly. Included are technologies categorised as having a ‘moderate’, ‘high’, and ‘very high’ impact. Low-impact technologies are excluded.

Technologies eligible for assessment in phase 2

Ten technologies were found to be eligible for assessment in phase 2 and thus have high scaling potential for the production of high-quality renewable energy carriers. These technologies are mainly based on three key processes: electrolysis, thermochemical conversion, and a combined group of technologies to produce tertiary sources. Table 2.1 presents an overview of energy conversion technologies that meet the criteria.

Some technologies which were not found to be eligible include, for example, depolymerization because it is more of a catch-all term that covers several specific subprocesses, which have been included separately on the longlist. Chemical dissolution did not qualify due to the technology not being sufficiently developed for scale-up, indicated by a TRL of 5. On the other hand, anaerobic fermentation, anaerobic bacterial digestion, and transesterification were deemed sufficiently widespread, large-scale, and conventional to not require assistance in scaling up and have not been included on the shortlist for that reason. Annex 2 includes a table of all technologies considered including a reason why there were not deemed eligible for assessment in phase 2.

Table 2.1 Selected technologies for assessment in phase 2

Technology	Output	Specific Energy (MJ/kg)	Description	Order of energy carrier	(Indicative) TRL	Carbon cycle	IEA impact on net-zero emissions
Thermochemical conversion							
Gasification	Syngas	26	A feedstock is converted to syngas under a controlled steam and oxygen process. Widely used and scaled production technique. The feedstock is often biomass, but fossil fuels, waste, and plastics can also be used.	Second	9	Short cycle	Very High
Biomass pyrolysis	Bio-oil	42.2	A feedstock is heated in an anaerobic environment to create the desired bio-fuels. The temperature is lower than that of gasification. The feedstock is often vegetable oil or other biomass, but fossil fuels, waste, and plastics can also be used.	Second	7	Short cycle	Moderate
Methane pyrolysis	Ammonia	18.6	Through the pyrolysis of methane, hydrogen can be produced for other inputs. It is occasionally (theoretically) coupled with Haber-Bosch for the production of ammonia.	Tertiary	8	Short Cycle	High
Electrolysis							
Alkaline electrolysis	Hydrogen	130	Water-based electrical hydrogen production method. Alkaline electrolysis is the most widely used electrolysis method. Production requires a high amount of electricity and is often envisioned nearby renewable energy sources, either onshore or offshore.	Second	9	No carbon present	Very High
Proton exchange membrane electrolysis (PEM)	Hydrogen	130	Water-based electrical hydrogen production method. PEM electrolysis is the second most widely used electrolysis method. Production requires a high amount of electricity and is often envisioned nearby renewable energy sources, either onshore or offshore.	Second	9	No carbon present	Very High

Technology	Output	Specific Energy (MJ/kg)	Description	Order of energy carrier	(Indicative) TRL	Carbon cycle	IEA impact on net-zero emissions
Tertiary energy sources							
Hydrogenation-based chemical methanation	Methane	55.6	Carbon monoxide (from syngas) and carbon dioxide are converted into methane using hydrogenation with a chemical (nickel) catalyst (Sabatier reaction).	Tertiary	7	Short Cycle	Moderate
Hydrogenation-based biological methanation	Methane	55.6	Carbon monoxide (from syngas) and carbon dioxide are converted into methane using hydrogenation with a biological catalyst (Sabatier reaction). This process is more robust to impurities in feedstock than its chemical equivalent.	Tertiary	7	Short cycle	Moderate
Mobil Process (Methanol-to-X)	Methanol	30	In a series of chemical reactions (Steam reforming, Water shift reaction, and Synthesis) methane (from syngas or natural gas) is converted to methanol.	Tertiary	9	Short cycle	High
Hydrocarbon production based on the Fischer-Tropsch process	Liquid hydrocarbons	42.2	The Fischer-Tropsch process is used to convert syngas (CO1 and H2) into liquid hydrocarbons, such as methanol. CO2 is used to generate CO1 using water-gas-shift reactions.	Tertiary	7	Short Cycle	Very High
Electrolytic Haber-Bosch ammonia production	Ammonia	18.6	Using hydrogen generated from electrolysis, the Haber-Bosch process is applied to generate ammonia from H2 (from electrolysis) and N2 (from air).	Tertiary	8	No carbon present	Very high

Thermochemical conversion technologies and electrolysis technologies are grouped based on the high degree of similarity between the processes. Additionally, these are all secondary energy sources, which have an advantage over tertiary sources in terms of production efficiency. The technologies that produce energy carriers of the third degree are also grouped based on that same rationale.

3 Phase 2: Selection of technologies eligible for a subsidy

3.1 Approach

Next, the selected technologies are assessed based on the framework provided by the Ministry of Economic Affairs and Climate Policy. The assessment framework is further described in Section 3.2.

We prepared the assessment for each technology through a combination of desk research and in-depth expert input. We first drafted the assessment based on desk research. The draft assessment was shared with technical experts in several focus groups and interviews. In the focus groups and interviews, the experts validated the assessment and provided us with their feedback on the necessity of the technology in a climate-neutral society, their readiness for scale-up, possible governmental intervention, and the impact of that intervention. Following the discussion in the focus groups, we adjusted the draft assessments and asked experts for another review.

The experts that were involved are listed in Table 3.1. The Ecorys study team (and not the experts) take full responsibility for the application of the assessment framework and the assessment of technologies. The full assessments are included as attachments to this report. Section 3.2 describes the assessment framework, followed by a summary per technology in section 3.3.

Table 3.1 Technical experts involved in phase two

Technology	Expert	Organisation
Alkaline and PEM Electrolysis	Dipl.-Phys. Jochen Bard	Fraunhofer IEE
	Lennart van der Burg	TNO
	Dr -Ing. Ramona Schröer	Fraunhofer IEE
Biomass Pyrolysis and Methane Pyrolysis	Dr Bert van de Beld	BTG
	Luc Pelkmans	IEA
	Berend Vreugdenhil	TNO
Gasification	Dr Bert van de Beld	BTG
	Luc Pelkmans	IEA
	Berend Vreugdenhil	TNO
Chemical (catalytic) and Biological hydrogenation-based Methanation	Dr -Ing. Ramona Schröer	Fraunhofer IEE
	Dipl. -Ing. Frank Schünemeyer	Fraunhofer IEE
Mobil Process (Methanol-to-X)	Prof. Dr André Faaij	TNO
	Prof. Dr Fokko Mulder	TU Delft
Hydrocarbon production based on Fischer-Tropsch process	Prof. Dr André Faaij	TNO
	Prof. Dr Fokko Mulder	TU Delft
Electrolytic Haber-Bosch ammonia production	Prof. Dr André Faaij	TNO
	Prof. Dr Fokko Mulder	TU Delft

3.2 Assessment framework

The assessment framework was developed by the Ministry of Economic Affairs and Climate Policy. It includes four main criteria: (1) the technology is necessary for a climate-neutral society, (2) the technology is ready for scale-up but needs government help to do so, (3) government intervention at this stage of the technology's development is effective, and (4) government intervention will have deep and broad impact.

For each criterion, one or more indicators are included to operationalise the assessment. The table below provides an overview of the criteria and corresponding indicators. The next section then provides a summary of the assessment. The full assessment per technology is included in Annex 3.

Table 3.2 Overview of the assessment framework

Criterion	Indicator	Guidance questions
1. The technology is necessary for a climate-neutral society *- Also aiding emission reduction in the period 2040-2050*	i. Bandwidth of market share in climate neutral society	Is the technology a no-regret option? What is the expected market share of the technology in a climate-neutral society? What other technologies is it competing with?
2. The technology is ready for scale-up but needs government help to do so *- Import is not a feasible alternative*	ii. Technology is sufficiently developed and tested in the pilot phase (y/n) iii. Current government support schemes for demonstration projects are insufficient (y/n) iv. Market introduction is not commercially viable, even including existing government support schemes (y/n)	Are there examples of successful pilot projects for the technology? Are there examples of successful demonstration projects for the technology? Why not? What are the (financial) barriers to a market introduction?
3. Government intervention at this stage is effective - cost reduction is sufficient for enabling commercial introduction	v. Cost reduction that can be achieved by scaling up, per cost category	What is the expected unit cost of the technology output in 2040? And in 2050? Will the cost reduction follow a linear/ exponential/ another curve?
4. Government intervention will have a deep and broad impact - Enabling scale-up and replicability in the Netherlands - Applicable in all climate agreement sectors: Electricity, Industry, Mobility, Built environment, Agriculture	vi. Bandwidth of market size for the technology after scale up vii. Bandwidth of market size for the technology output after scale up viii. Applicability in several end-user sectors after scale up	What could be the total technology output in PJ/year after scale-up? What could be the total technology output in terms of CO_2 reduction/year after scale-up? Which sectors could benefit from the application of the technology and its output?

3.3 Assessment of technologies

In this section, we present a summary of the assessment for each technology. In Table 3.3 we present an overview of the assessment for all technologies and below we provide a summary per technology. The green shaded box indicates that the criteria is met, the yellow shaded box indicates that the criteria could be met under special circumstances, and red shaded box indicates that the criteria is not met.

The assessment is done for each technology group. Several technologies can be subdivided into sub-technologies. These sub-technologies may have different characteristics in terms of product quality, flexibility, market readiness, viability in a system, etc. An assessment for sub-technologies may differ (slightly) from the technology group in general. The assessment per technology group in Annex 3 contains more detail but does also not cover all sub-technologies.

Table 3.3 Assessment of energy conversion technologies

Criterion	Indicators	Alkaline and PEM Electrolysis	Biomass gasification	Biomass pyrolysis	Methane pyrolysis	Hydrogenation-based Chemical and Biological methanation	Mobil process (methanol-to-x)	Hydrocarbon production based on the Fischer-Tropsch process	Electrolytic Haber-Bosch ammonia production
The technology is necessary for a climate-neutral society	The bandwidth of market share in climate neutral society	Yes, widespread adoption in multiple sectors.	Yes, gasification is one of two key technologies that are capable of processing biomass, the other one being pyrolysis.	Yes, pyrolysis is one of two key technologies that are capable of processing biomass, the other one being gasification.	No, fossil fuels are required	Limited use in the Netherlands.	Limited, it is likely that in a climate-neutral society, some form of high energy-density fuels remains.	Limited, it is likely that in a climate-neutral society, some form of high energy-density fuels remains.	Yes, it is one of the most efficient chemical storage vessel for hydrogen, allowing easy and long term energy storage.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, alkaline and PEM electrolysis are sufficiently developed.	Yes. Fluidised bed gasification is most mature and successfully demonstrated.	Yes, several plants in the Netherlands are in use.	Yes, large scale demonstration in the USA has been developed and active.	Catalytic methanation - Yes, fixed-bed reactors sufficiently developed. Biological methanation – yes, stir-tanks and packed columns are sufficiently developed.	Yes, fixed bed reactors are sufficiently developed.	Yes, Fischer-Tropsch is a mature technology.	Yes, Haber Bosch is a mature technology.

Criterion	Indicators	Alkaline and PEM Electrolysis	Biomass gasification	Biomass pyrolysis	Methane pyrolysis	Hydrogenation-based Chemical and Biological methanation	Mobil process (methanol-to-x)	Hydrocarbon production based on the Fischer-Tropsch process	Electrolytic Haber-Bosch ammonia production
	Current government support schemes (e.g., funds available for demonstration projects) are insufficient for scale-up (y/n)	Yes; SDE++, GroeifondsNL, GSUHPE[8], EU IPCEI hydrogen are sufficient for demonstration and limited scale up. Scale up to national scale requires more support.	Yes. Current support schemes do not sufficiently cover last steps in innovation process for full market implementation	Yes, governmental support is too limited in scope and amount.	Yes, methane pyrolysis is not covered.	Yes, methanation is not covered.	Yes, no governmental support is present for MTX, only for methanol production.	Yes, Horizon 2020 supports European demonstration facilities, intermittent processes might be demonstrated. It is not sufficient for large scale implementation.	Yes, support for Haber Bosch is limited. Support for scaling up electrolysis and intermittent operation of Haber Bosch is needed.
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes	Yes. There are some commercial plants being developed in the USA and Canada, but support in NL seems required.	Yes, due to high capex and high energy use.	Yes, not viable. No government support covers methane pyrolysis and no projects outside of lab scale exist in Europe.	No, large scale operations are planned	Yes, for MTX in a renewable route including biomass. No for the route based on fossil fuels.	Yes, mostly dependent on feedstock used, CO2 capture, and maturity of 'chain' processes such as gasification.	Yes, the price of green hydrogen is too high.
Government intervention at	Cost reduction that can be	Yes	Cost reduction is expected,	Yes, due to economy of	Unknown, but it is likely that	Significant cost reduction can	Unknown, too few studies	Cost reduction is expected for	Significant cost reductions are

8 Grant Scheme for Upscaling Hydrogen Production through Electrolysis

Criterion	Indicators	Alkaline and PEM Electrolysis	Biomass gasification	Biomass pyrolysis	Methane pyrolysis	Hydrogenation-based Chemical and Biological methanation	Mobil process (methanol-to-x)	Hydrocarbon production based on the Fischer-Tropsch process	Electrolytic Haber-Bosch ammonia production
this stage of the technology's development is effective	achieved by scaling up, per cost category		though currently fossil-fuel based processes are still favourable.	scale advantages in plant construction and process efficiencies.	some reductions can be achieved in scaling up, as with most technological advances in general.	be achieved due to (i) technological development of the process and (ii) economies of scale.	have been found.	the entire production of a carrier, though it will likely not take place in FT (rather gasification).	possible in the hydrogen component of ammonia production.
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Larger market share of Alkaline relative to PEM on the short term, with the difference reducing on the long term.	First focus on using waste, later various biomass streams can be used as input.	Significant market share of the available biomass.	Limited use, potential market share as bridging technology on the medium term.	As part of P2G chain and as transition technology, methanation has a sizable use. As an individual technology, its bandwidth is limited.	Limited size, the bandwidth of base processes upstream (such as pyrolysis, gasification and fermentation) should have a significant market share before scaling up MTX.	Multiple inputs possible, could contribute to energy diversification. Highly dependent on availability of biomass feedstock as carbon input, which is likely to be limited.	Widespread adoption in the shipping industry and hydrogen storage.
	Bandwidth of market size for the technology output after scale up	Widespread adoption	Syngas and methanol have a broad application.	The bandwidth can be significant when including bio-oil as carbon source for	Widespread adoption of hydrogen.	Use cases for methane are not sufficiently impactful to warrant major government	As transition fuel, hydrocarbons from MTX could accelerate the transition away	FT outputs have a broad application. In a climate-neutral society, its	25% market share of shipping fuels by 2050, large bandwidth for hydrogen

Criterion	Indicators	Alkaline and PEM Electrolysis	Biomass gasification	Biomass pyrolysis	Methane pyrolysis	Hydrogenation-based Chemical and Biological methanation	Mobil process (methanol-to-x)	Hydrocarbon production based on the Fischer-Tropsch process	Electrolytic Haber-Bosch ammonia production
				chemical processes. Limited for bio-oil as energy carrier, due to its dependencies on the use of fossil fuel.		intervention. Most of its use is for industrial, heating and fuel for mobility uses. As energy carrier, hydrogen fulfils much the same role and is cheaper to produce.	from fossil fuels. In a climate-neutral society, its market share will be limited.	market share will be limited.	storage and other uses.
	Applicability in number of end-user sectors after scale up	Industry, chemical industry, freight transportation, energy (grid balancing) Industry, chemical industry, freight transportation, energy (grid balancing)	Applicability (after upgrading) for transport, refinery sector, chemical sector and heating.	Transport, chemical industry, energy sector	Industry, freight transportation, energy	Other technologies serve end-user sectors better, except for specific industrial uses.	Three major sectors: Oil/Energy industry, chemical industry and mobility.	Applicability for transport, refinery sector, chemical sector (most likely).	Shipping, energy import and -export, energy storage and fertilizer industry.

3.3.1 Alkaline and PEM electrolysis

Description and role in climate-neutral society

Water electrolysis is the process of using electricity to decompose water into oxygen and hydrogen. Hydrogen has an important role in all climate-neutral scenarios and electrolysis is expected to be the main process to produce it. Although there are other technologies such as Solid-Oxide Electrolyser Cells (SOEC), alkaline electrolysis and proton exchange membrane (PEM) electrolysis are the most developed and mature technologies. Overall, alkaline and PEM electrolysers do not differ much in practice. Once installed, both technologies function the same. Alkaline electrolysers are cheaper to manufacture but have a lower average yield and lifetime. The higher costs of PEM electrolysis are partly due to the rare raw materials that PEM requires, iridium in particular.

Scale-up potential and need for support

Both alkaline and PEM electrolysis are well-understood. Compared to alkaline, PEM electrolysis has been less applied in practice. There are new projects for alkaline and PEM electrolysis under development in and outside the Netherlands. In addition, infrastructure to transport hydrogen is also under development.

The costs of alkaline and PEM electrolysis are expected to fall substantially. The key drivers behind this cost reductions are stated to be technological innovation, scaling up manufacturing processes, standardisation and economies of scale. The price of green electricity is the main driver behind the unviability of large scale rollout at this time. While green electricity prices in the Netherlands are expected to come down, projections do not trend down early enough to meet the Dutch governments' ambitious capacity targets for 2025 and 2030.

Another barrier for scale-up is the still developing supply chain of electrolyser components. This poses both a risk and an opportunity for hydrogen production in the Netherlands. Experts point to the potential for the Netherlands to develop itself into a key manufacturer of electrolyser components.

Several funds exist for the purpose of supporting the research, development, deployment and scaling of hydrogen projects. Electrolysis project can also apply for SDE++ subsidy but in practice the technology is still too expensive to qualify for it. Based on this we conclude that there exists ample funding to support an increase in the number of demonstration projects but that existing funding is still insufficient for a scale-up phase.

3.3.2 Gasification

Description and role in climate-neutral society

Gasification is a process that converts biomass and other materials that include carbon into gases. The largest shares involve nitrogen, carbon monoxide, hydrogen and carbon dioxide. The process involves reacting the biomass at high temperatures (usually over 500 °C), while controlling the amount of oxygen and steam. The output of the process is known as syngas (synthetic gas) and can directly be used as a fuel. After upgrading, it could also be used in the production of methanol and hydrogen, or converted to synthetic fuels using for example the Fischer-Tropsch process. The resulting hydrocarbons remain important in a climate-neutral society as feedstock for the (chemical) industry. Additionally, carbon-based fuels could remain useful in situations where an energy dense fuel is required, for example aviation fuel. Gasification has been sufficiently developed, but requires (government) support to scale up.

Scale-up potential and need for support

There are several sub-techniques used to apply gasification, some more mature than others. These include: fixed bed gasification, fluidised bed gasification, entrained flow gasification and supercritical water gasification. For some techniques pilot and demonstration plants have been realised in Europe, including the Netherlands. For example, one demonstration facility for supercritical water gasification is currently being constructed by Gasunie and SCW Systems in Alkmaar. Internationally, there are large-scale plants, but these have not yet operated continuously over several thousand hours.

One barrier for scale-up is the availability and cost of biomass as input to the process, with costs of current facilities being approximately three times higher than natural gas. Based on current demonstration facilities it can be concluded that large-scale application does result in cost reduction. These plants often have been operating only for a limited number of hours though.

Thus, further development is needed and current government support measures are insufficient to successfully realise scale up. Cost reduction for gasification technologies can be expected through economies of scale in the size of plants and learning through more continuous operation, though future cost of biomass and carbon (retrieval) will become (more) important cost drivers in the future.

Gasification and syngas are easily applied in the chemical and refinery sectors in the Netherlands and are promising in greening these competitive industries.

3.3.3 Biomass Pyrolysis

Description and role in climate-neutral society

Pyrolysis is one of two main technologies available for processing biomass, which in turn is one of the few viable renewable sources for carbon. Additionally, it can process plastics to the same result. Pyrolysis works by heating the input in an oxygen starved environment, usually between 100 – 500 degrees. The temperature breaks the molecular bonds of the input matter, while the lack of oxygen prevents combustion. The output consists of three elements: (i) gasses, (ii) bio-oil and (iii) solids called char. The bio-oil is feedstock for many carbon-based upgrading processes. The resulting hydrocarbons remain important in a climate-neutral society as feedstock for the (chemical) industry. Additionally, carbon-based fuels could remain useful in situations where an energy dense fuel is required, for example aviation fuel. Pyrolysis has similarities to gasification, but is expected to be the junior of the two. This does not mean however that it is not an important processing technology of biomass.

Scale-up potential and need for support

Several pilot and demonstration plants have been realised in the Netherlands, for example the Empyro plant in Hengelo. Current government support for pyrolysis is insufficient to realise scale up. For example, the SDE++ scheme limits biomass for pyrolysis plants to only lignocellulosic biomass. Cost reduction for pyrolysis is expected in both economies of scale and economies of numbers advantages. Scaling is set to reduce cost in the construction of pyrolysis plants. Economies of numbers can increase efficiency by basing the installed pyrolysis capacity per region more specifically on the local biomass availability. Further reductions are expected in the upgrading processes that follow the pyrolysis process itself.

Pyrolysis and bio-oil could relatively easily connect to the well-developed oil and gas industry in the Netherlands and make use of its infrastructure and knowledge.

3.3.4 Methane pyrolysis

Description and role in climate-neutral society

Methane pyrolysis is a specific application of pyrolysis, where methane (natural gas) is heated in an anaerobic environment. The temperature breaks the molecular bonds of the methane, releasing hydrogen and solid carbon matter. Methane pyrolysis could theoretically play a role in a climate-neutral society, since it could act as a carbon sink. The solid carbon residue is easily extracted from the process and can be used in other industries after purification. Additionally, it is another source of hydrogen next to electrolysis. However, experts indicate that energetically the technology is not interesting. Especially when compared to electrolysis, which is cheaper and more efficient to produce. Additionally, methane is likely to be too valuable to break down to hydrogen and carbon products. Therefore, the practical application of methane pyrolysis is deemed to be severely limited.

Scale-up potential and need for support

Methane pyrolysis is demonstrated in practice in the USA, where a full scale plant is operational. No such projects have been found in Europe and no subsidies for methane pyrolysis have been discovered. It is unlikely to be commercially viable in the foreseeable future and does not seem practically ready for scale up in the Netherlands.

3.3.5 Hydrogenation-based Chemical (catalytic) and Biological methanation

Description and role in climate-neutral society

Methanation is the process where CO_x is converted to methane, using hydrogenation. This means that the CO_x is fed into a reactor, where it reacts to hydrogen using a catalyst. This catalyst can either be chemical (usually nickel or ruthenium) or biological (micro-organisms). The role of both methanation types in a climate-neutral society is based on the use cases of methane. Methane can play an important role in a climate-neutral society and has two use cases, methane as fuel and methane as feedstock. The role of methane as fuel is likely limited, when it is produced using methanation. It is expensive and energy inefficient to convert hydrogen to methane, especially when hydrogen is a capable gaseous fuel by itself. Methane from biogas plants using fermentation is more likely to be used as fuel by feeding it into the gas network, reducing the use of natural gas. Methanation has more economic value as an upgrading process in the production chain from biomass to complex hydrocarbons, where methane is used as feedstock for many chemical and production industries.

Scale-up potential and need for support

Chemical and biological methanation are not always commercially viable, the cost of feedstock determines the operating cost for a large part. The feedstock consists of hydrogen and carbon. The price of hydrogen is expected to drop when production increases. The availability of carbon might become a bottleneck since there are few viable renewable carbon sources. The only energy-viable option at the moment is biomass, which require gasification or pyrolysis plants to process the biomass. Next to hydrogen availability, cost reduction is expected for both types by increasing efficiency of the processes.

Chemical methanation knows four main reactor designs based on nickel or ruthenium catalysts: (i) Fixed-bed reactor, (ii) Fluidized-bed reactors, (iii) three-phase fluidized-bed reactor and (iv) a Honeycomb reactor. The Fixed-bed reactor is the most developed design and is a fully mature technology. Worldwide several hundred plants are operational. Seven are located in the Netherlands with over 15 MW capacity in 2024, these are projects like Eemsgas and Ambigo. No subsidies support methanation as technology by itself, but as part of the full power-to-gas chain the DEI+ and SDE++ schemes support methanation (indirectly).

There are three types of biological methanation: (i) the stir tank, (ii) the packed column (iii) or in-situ in fermentation plants. They require less heat than catalytic reactors. The stir tank and packed column are both often employed, the in-situ method is significantly less efficient. Where catalytic methanation is more suitable to a centralised approach, biological methanation is more suited to decentralised implementation. This is because biological methanation is more resilient to impurities in feedstock and operates at a lower temperature than catalytic methanation.

3.3.6 Mobil Process (methanol-to-x)

Description and role in climate-neutral society

The Mobil process converts methanol to gasoline. Based on this technology several other processes were developed to produce complex hydrocarbons from methanol, combined named methanol-to-x (MTX). MTX are fully matured advanced upgrading technologies. In a climate-neutral society the role of their output could be two-fold:

- First, the hydrocarbons could be used as fuel. However, using MTX to produce fuels is energetically inefficient and relatively expensive as several conversion steps are required in the chain from biomass-to-fuel. Fuel via MTX will only be interesting for parties that are willing to pay for energy dense fuels.
- Second, hydrocarbons could be used as feedstock for other industrial processes. The selectivity of outputs of MTX is an advantage, as the output can be tailored towards the next step in the production chain. As with the other tertiary processes based on carbon, they are limited by the first link in the chain (i.e. the amount of biomass that can be converted to usable feedstock).

Therefore, the role of MTX is limited, but not insignificant. It is likely that in a climate-neutral society some form of high energy density fuels remain.

Scale-up potential and need for support

Several large MTX plants are operating globally, with five notable large fixed-bed plants operating commercially in China. The fluidised-bed reactor has not been commercially implemented yet. No subsidies have been found for MTX processes in the Netherlands, but the preceding step of producing methanol is covered under RDM, SDE++, Horizon 2020 and EU innovation Fund. While carbon from fossil fuel is abundant, it is unlikely that MTX can be competitive in a climate-neutral society because the stacked inefficiencies of several conversion and upgrading processes makes it an expensive technology.

3.3.7 Hydrocarbon production based on Fischer-Tropsch process

Description and role in climate-neutral society

Fischer-Tropsch is a process that involves the production of liquid hydrocarbons using a mixture of carbon monoxide and hydrogen. For the reactions, catalysts are used, typically at relatively mid to high temperatures (100 to 300 °C). Fischer-Tropsch processes are known in two distinct process options using very different reactor types (fixed bed and bubbling bed) and catalysts (iron and cobalt based). Fischer-Tropsch can play a similar role to MTX in a climate-neutral society. While Fischer-Tropsch requires fewer upgrading steps from biomass, its output is less selective than MTX. Thus requiring cleaning and separation processes. It could play an important role in the carbon-based process biomass-to-x. Although the resulting hydrocarbons are likely to have limited use as a fuel, they could be important for the chemical sector. Therefore, the role of Fischer-Tropsch is limited, but not insignificant.

Scale-up potential and need for support

There are a number of commercially run facilities using Fischer-Tropsch to produce biofuels, notably Sustainable Air Fuels (SAF). In the Netherlands Shell and Enerkem are planning on transforming one of Shell's refineries in such a plant (with government support). Furthermore, Horizon2020 successfully supports demonstration facilities throughout Europe. It is likely that especially integrated processes including for example both Fischer-Tropsch and gasification will need government support.

One barrier for scale-up involves the availability and cost of feedstock as input to the process. There is a limited amount of biomass (as feedstock) available, putting a limit to scaling up Fischer-Tropsch processes. Moreover, it can be argued that carbon-based feedstock will be of more value as embedded carbons in materials, such as plastics, rather than in combustion processes.

A potential issue that needs to be solved it that plants likely will have problems operating intermittently, thus requiring constant inputs. Intermittent operation has not been demonstrated.

3.3.8 Electrolytic Haber-Bosch (EHB) ammonia production

Description and role in climate-neutral society

The production of ammonia with the Haber-Bosch process is by no means a new technology. Haber Bosch is a mature technology that is employed widely that converts nitrogen to ammonia by a reaction with hydrogen. Traditionally the emission-intensive Steam-Methane Reforming (SMR) is used to create the necessary hydrogen. SMR is not a necessary process in the Haber-Bosch reaction and it can be replaced by electrolysis.

Electrolytic Haber-Bosch ammonia production attracts attention for a climate-neutral society due to ammonia's capability of carrying energy and being relatively easy to handle. Not only does ammonia function as feedstock (for fertilizer), but is has the capability of being a renewable fuel for the shipping industry for example. A third use of ammonia is to use it as long term hydrogen storage. Experts deem ammonia to be a viable alternative to storing hydrogen in salt caverns.

Scale-up potential and need for support

In the Netherlands alone two SMR facilities produce over 3.000 kton ammonia each year with, all for the fertilizer industry. This does indicate that Haber Bosch is sufficiently developed to be commercially viable. One area of interest is how well Haber Bosch reacts to an intermittent feedstock supply, which comes from intermittent power supply to the preceding electrolysis. Expert judgement is that Haber Bosch is sufficiently resilient. This means the barriers for replacing SMR with electrolysis are mainly economic, not technical.

Haber Bosch is not included in any subsidy scheme and has outgrown the scale up phase a while ago. Hydrogen production through electrolysis is not commercially viable on scale compared to SMR, even with the current subsidy schemes. A necessary condition for EHB green ammonia to scale up is that electrolysis-based hydrogen comes down in price.

A hard limitation of EHB is the process efficiency. Being a tertiary fuel, EHB ammonia will by definition require an extra conversion step on top of hydrogen electrolysis. The process efficiency of EHB ammonia production will therefore always be lower than electrolysis by itself.

3.3.9 Conclusion

Out of the ten technologies, four meet the requirements of the assessment framework, six do not. A detailed assessment of each technology can be found in Annex 3. The four that meet all requirements are:

- Electrolysis (alkaline)
- Electrolysis (PEM)
- Gasification
- Biomass pyrolysis

The technology groups that do not meet the requirements are:

- Methane pyrolysis
- Hydrogenation-based chemical methanation
- Hydrogenation-based biological methanation
- Mobil Process (Methanol-to-X)
- Fischer-Tropsch synthetic hydrocarbon fuel production
- Electrolytic Haber-Bosch ammonia production

The technology groups that meet all requirements are likely to play a major role in a climate-neutral society and are ready to be scaled up. They are technologically sufficiently developed, but require support to do so. Electrolysis technologies are covered by several subsidy schemes, but these prove insufficient to scale up electrolysis. Subsidies for gasification and pyrolysis are limited and aimed at the development of the pilot- and demonstration phase, not the scale-up phase. Notable about these technologies is that they are all processes that are the starting point of a chain of upgrading processes. The resulting hydrogen, syngas, and bio-oil are feedstock for other technologies. This makes them a foundation for other processes and possibly a bottleneck in the energy system if yields are insufficient.

There is a need for hydrogen and carbon atoms in a climate-neutral society, either as separate matter or to create complex molecules. For hydrogen, the technologies that are viable and ready for scale-up are alkaline and PEM electrolysis. There are few renewable sources for carbon, generally they are considered to be biomass, plastics and air capture. Of these three, techniques to process biomass are most advanced and ready for implementation. Additionally, the energy requirement of plastics and air processing is significantly higher, leaving biomass as the logical source.

For processing biomass, two technologies are viable and ready for scale-up: gasification and pyrolysis. Together with electrolysis, they can become the foundation for other technologies to build on. These technologies provide renewable hydrogen and carbon, which can subsequently be used in tertiary (Power-to-X) technologies. If hydrogen and carbon are scarce, this forms a bottleneck for all other technologies that are needed in a climate-neutral society

The impact of scaling up these four technologies is significantly higher than scaling up the tertiary (Power-to-X) technologies. Scaling up tertiary technologies before there is sufficient supply of feedstock to operate those technologies leads to inefficiencies and scarcities.

Note that in our analysis and following the assessment framework, we did not specify the magnitude of support needed per technology. Nor does it include detailed guidance on the phasing of support or the form that the support should take.

There are several similarities between the technologies that did not meet the requirements of the assessment framework. Hydrogenation-based chemical methanation and hydrogenation-based biological methanation (hereafter: methanation), the Mobil process (hereafter the more general methanol-to-x or MTX), Fischer Tropsch and Haber Bosch ammonia production are all advanced upgrading processes. They were developed with fossil fuels as feedstock and are mature technologies. They are employed globally on a large scale and are generally commercially viable in current fossil-based production methods. Thus these processes do not need to be scaled up. Methane pyrolysis is the only technology on this list that is (relatively) new. Nonetheless, it does not meet the criteria, as it is not sufficiently developed and its role in a climate-neutral society is likely to be limited. The methane it consumes is expected to be considered too valuable to convert to hydrogen in the future.

However, that does not mean that these technologies could not be important in a climate-neutral society. As tertiary technologies they are further down the production chain and therefore less energy efficient, but they have added value in specific use cases. For instance, methanation, MTX, and Fischer-Tropsch are used to produce a wide range of carbon-based materials, that are required by many industries. In a fossil-free society, these processes are valuable for creating high-quality hydrocarbons. Haber Bosch is an attractive method of storing hydrogen in ammonia both long- and short-term if the practical implications of storing ammonia are addressed. Technologies for transporting and storing ammonia are essential in all scenarios. The tertiary processes are logical next steps to take. They should be further developed and supported to iron out technicalities that hinder their application in a green energy system. Mostly they are developed with fossil-fuels as feedstock. Feedstocks for these processes are often not directly interchangeable. Adjustments to the plants, their settings, etc. need to be researched and made.

4 Phase 3: Review of the assessment framework

In this chapter we present a review of the assessment framework of the ministry and provide recommendations for improving the framework. The aim is to understand whether the framework can be executed in a manner that leads to consistent, objective and distinctive assessments.

During our research in phases one and two, we encountered aspects of technologies that are currently not reflected in the assessment framework. These considerations were put forward to the technological experts during the workshops of phase two. Additionally, we asked the experts in the workshops directly for feedback on the framework. We organised, grouped and detailed their feedback on the assessment framework in the next section.

Overall, the experts agreed with the application of the framework and consider it fit for assessing technologies for the production of high-quality energy carriers. Notable points of encouragement were:

- the ranking of the criteria offers a clear narrative;
- the framework is complete and covers most, if not all, relevant items;
- the economic and scale-up questions are phrased correctly.

Nevertheless, the experts raised considerations and suggestions for improvement to consolidate technological learning experiences as well as the application of these technologies in the assessment framework. The chapter first provides a review on the framework design, followed by a review of the framework application, and finishes with recommendations on how to improve the assessment framework.

4.1 Review of framework design

Based on our review, with input from the experts, there are four ways to improve the assessment framework.

1. A production chain perspective is crucial in the assessment
2. The timespan under assessment is unclear
3. The scope of ‘a climate neutral society’ is very broad
4. A portfolio perspective is missing

The first two are considerations not addressed by the criteria of the framework. The latter two are improvements to the first and third criterion respectively.

4.1.1 A production chain perspective is crucial in the assessment

As described in the scoping of the assessment framework[9], the support scheme should focus on technology groups that have high-quality energy carriers as an output. Currently, the assessment framework evaluates technology groups and the scope defines them as standalone entities. However, the Dutch and European energy systems are a complex web of interdependencies that will become more diverse and complex as fossil fuels are phased out. In this complex web, each technology is only one link in a chain from feedstock to final output. Assessing technologies as standalone does not offer sufficient insight into their position in the chain and the effect it might have up- or down the production chain. The output for one process is the input for another, dependencies like these can only be considered with a system-wide approach. Therefore, when only specific technologies in such a 'chain' will be supported, it is likely that the full cost-reduction potential is not achieved. Learning benefits will also occur in the preparation of feedstock and upgrading of the output, where other technologies and processes are used.

Experts and literature therefore usually do not speak of a single technology. It is often phrased as 'technology to an output' ('technology-to-x'), highlighting their position as a link in a production chain towards an output at the end of the chain. The scope of the assessment framework should therefore broaden to include other technologies and processes that are required for the production of high-quality energy carriers. In doing so, we consider it essential to focus on the output or application of the integrated process, rather than the individual technology groups. For example, for the production of biomethane through gasification, the process from preparing the feedstock, gasification and upgrading the syngas for grid injection are all necessary steps in the use of the final output (biomethane). Similarly, if bio-oil is taken as the final product, one needs to invest in pyrolysis technologies to produce pyrolysis oil from biomass and e.g. Fischer-Tropsch processes for upgrading to bio-oils.

Focusing on individual technologies (e.g. gasification) might result in supporting the production of intermediate products (e.g. syngas), which need to be converted or upgraded further with different technologies downstream (e.g. Fischer-Tropsch to produce synthetic fuels). These integrated processes might require support even though specific elements of those processes have been commercially viable as standalone technologies for decades (e.g. Fischer-Tropsch processes). Taking such an approach has several benefits:

- If the output/application of the integrated process is taken as starting point, high-quality energy carriers that have a potentially wide use are supported. This way, it is likely the full cost-reduction potential is utilised as learning needs to take place not just in the processes of individual technologies (e.g. pyrolysis) but also in the integrated processes to produce high-quality energy carriers (e.g. pyrolysis plus Fischer-Tropsch for the production of synthetic fuels).
- The government can target its policies more clearly in line with the climate goals of the Paris agreement and Coalition agreement. This also supports setting and propagating a vision of what a climate-neutral society should look like. It allows the government to plan and control the required diversification of the energy system while remaining technology-neutral.

[9] Kader Klimaatfondsperceel Vroege Fase Opschaling

- Taking the integrated processes into account allows for better alignment of the use of various biomass streams. Through the framework, one can then assess the integrated processes based on the yield of the inputs or weigh the application of the output. This could be used to better optimise the use of limited feedstocks. For example, one could support the production of synthetic kerosine, because it would enable greening one hard-to-abate sector rather than the production of wider synthetic fuels, as more alternatives are available for this general category.

4.1.2 The timespan under assessment is unclear

In the assessment of the criteria, the timeline of government support is of great importance. The first criterion limits the scope to a climate-neutral society in 2040-2050. This scope does not put sufficient emphasis on the road toward reaching this goal. For example, one could argue that technologies that currently make use of fossil fuels (e.g. methanation, fossil-fuel based Fischer-Tropsch and methane pyrolysis) could be of importance in the transition towards a climate-neutral society, but have limited value once we are in a climate neutral society.

Similarly, for criterion three (The intervention is effective), the timeline matters for determining the commercial viability. Learning takes place through the deployment of multiple industrial-scale plants. Whether plants can operate commercially is determined for a large part by when it is deployed and how the learning process develops. Some technologies are expected to be commercially viable in the short term, while others likely require a longer time-span. Finally, some technologies are viable for scaling only in a few years as they are currently only in the pilot phase, and others might only become viable after our society becomes climate-neutral. These technologies are not considered by the criteria, since they are not currently ready for scale-up. It is however unclear during which timespan technologies should be ready for scaling and when scaling should be sufficiently advanced.

Some more details on a timeline or assessing the criteria for different timeframes could allow for an improved assessment.

4.1.3 The scope of ‘a climate neutral society’ is very broad

The definition of a climate-neutral society by the ministry is not made explicit in the framework, and can thus be interpreted in many different ways. This leaves room for uncertainty in the assessment of the technologies. Feedback from the experts included:

- Climate neutrality should not be the only consideration for an energy system, circularity (and limited availability) of resources should also be included in the consideration. By including circularity in the criteria, you will include the impact of the production of feedstock and the lifecycle of the production assets.
- The reduction of CO_2 emissions is part of the first criterion of the framework. However, the contribution of technologies to CO_2 emission reduction is of such importance that is should either be (i) included more explicitly in the definition of a climate-neutral society, or (ii) a criterion by itself.

- A climate-neutral society could be composed of different types of technologies, depending on the chosen government policies. The criterion suggests that the composition of a climate-neutral society is exogenous to policy, whereas, in reality, it is endogenous. This should be reflected in the formulation of the criterion.

4.1.4 A portfolio perspective is missing

The technologies under assessment have distinct needs. Some technologies may be relatively close to commercial viability, whereas others may require more supportand face more uncertainty. The current assessment framework ranks the technology with the best perspective highest. This creates a risk of only subsidising those technologies which are already certain ‘winners’. While scale up of those technologies will be successful, other technologies for which there is a clear and urgent need in society may be overlooked because they seem less attractive. Furthermore, some technologies fit together better than others. For example, technologies may use the same feedstocks or produce the same end product. To prevent this, the assessment could be complemented with a portfolio perspective, where the group of technologies as a whole is assessed to check whether they cover different types of demand from society and match with available feedstocks. As a result technologies with a lower individual score on the criteria may be selected instead of (or in addition to) technologies with higher scores, because they form good complements

4.2 Review of framework application

Applying the framework and taking into account the considerations gives sufficient ground for assessing technologies that are ready for scaling.

Next to assessing each technology based on the individual indicators, one could rank the indicators differently. Ranking indicators can support assessing the maturity of specific technologies within a technology group. Consider for example giving indicator 2.iii (Current government support schemes for demonstration projects are insufficient) a higher weight than indicator 2.ii (Technology is sufficiently developed and tested in pilot-phase). One could argue that putting more emphasis on indicator 2.iii benefits technologies that are (close to) running a demonstration facility and struggle with scaling rather than those that successfully run a pilot facility. Demonstration of technologies often goes hand in hand with increased (financial) risks. Government support could reduce this (financial) risk for both the project developer as well as the financer. This allows the project developer to continue focusing on scaling the technology. In other words, reducing the innovation risk by creating financial certainty gives room for the technology to continue learning. We elaborate on the learning paths in the following chapter.

On the other hand, ranking indicators is less appropriate for comparing different technology groups. Consider for example technology A which has a high overall score, but fails on one criterium. One could argue this technology would be ranked lower than technology B which has a slightly lower overall score but is relevant for more sectors. However, say technology A is crucial for a hard-to-abate sector such as aviation. When it is decided to focus on technology B instead, it might harm the objective of reaching a climate-neutral society as the options for hard-to-abate sectors are reduced. The indicators are thus interlinked.

4.3 Recommendations on the assessment framework

In conclusion, based on the considerations presented above, we recommend the following to further improve the assessment framework:

- Broaden the scope of the assessment framework to include other technologies and processes that are required for the integrated production of high-quality energy carriers. Focusing on individual technology groups might result in the scale-up of intermediate products only.
- Define the timeline of the scale-up and, more notably, clarify the approach towards transitional technologies.
- Elaborate on the definition of a climate-neutral society and where relevant, include relevant indicators in the assessment framework (such as energy intensity of the production process and the estimated reduction in GHG emissions)
- Add a portfolio perspective to the assessment framework, by assessing the mix of technologies in scope. As a result, technologies with lower individual scores may be selected for subsidy on the grounds of their complementarity with other technologies.

5 Phase 4: Cost reduction analysis of promising energy carriers

This chapter presents a deep dive into the cost-reduction potential of the technologies identified as most promising in previous chapters. These technologies are pyrolysis, gasification and (water) electrolysis. In consultation with the Ministry, the analysis on pyrolysis technologies received the most depth. The research included extensive desk research and interviews with experts, project developers and equipment manufactures. The analysis on gasification and electrolysis technologies focuses more on overarching trends and was supported by desk research and review by experts.

The goal of the chapter is to identify the main cost drivers of each technology and to examine where these costs can potentially be reduced. Production costs can be reduced in several ways, notably for innovative technologies that are still under development. Before delving into each technology, we identify a framework to analyse the cost production potential of innovative technologies. This framework identifies generic categories of potential cost-reduction drivers that apply to all technologies and enables a clear comparison of cost reduction potential between the technologies. This framework is applied to the technologies in the following sections.

Next, we applied the framework to each of the three technologies separately. As a result, Sections 5.2, 5.3 and 5.4 describe the main cost drivers and potential reduction opportunities per technology along the lines of the framework. Each section concludes with the key findings on cost reduction of the technology in question.

Section 5.5 concludes with trends from the individual conclusions. In addition, the conclusion provides suggestions potential cost reductions can be realised.

5.1 Cost reduction analysis framework

Technologies aimed at providing clean energy carriers are relatively new, compared to fossil-based alternatives. Economic competitiveness is an essential requirement[10] for the widespread adoption of clean energy carriers. Cost reduction is therefore a key factor in making clean energy technology competitive. These reductions are usually realised during the early stages of a technology's development. Given that clean technologies are still in this early stage, a relatively larger reduction in cost can be expected compared to more mature fossil technologies.

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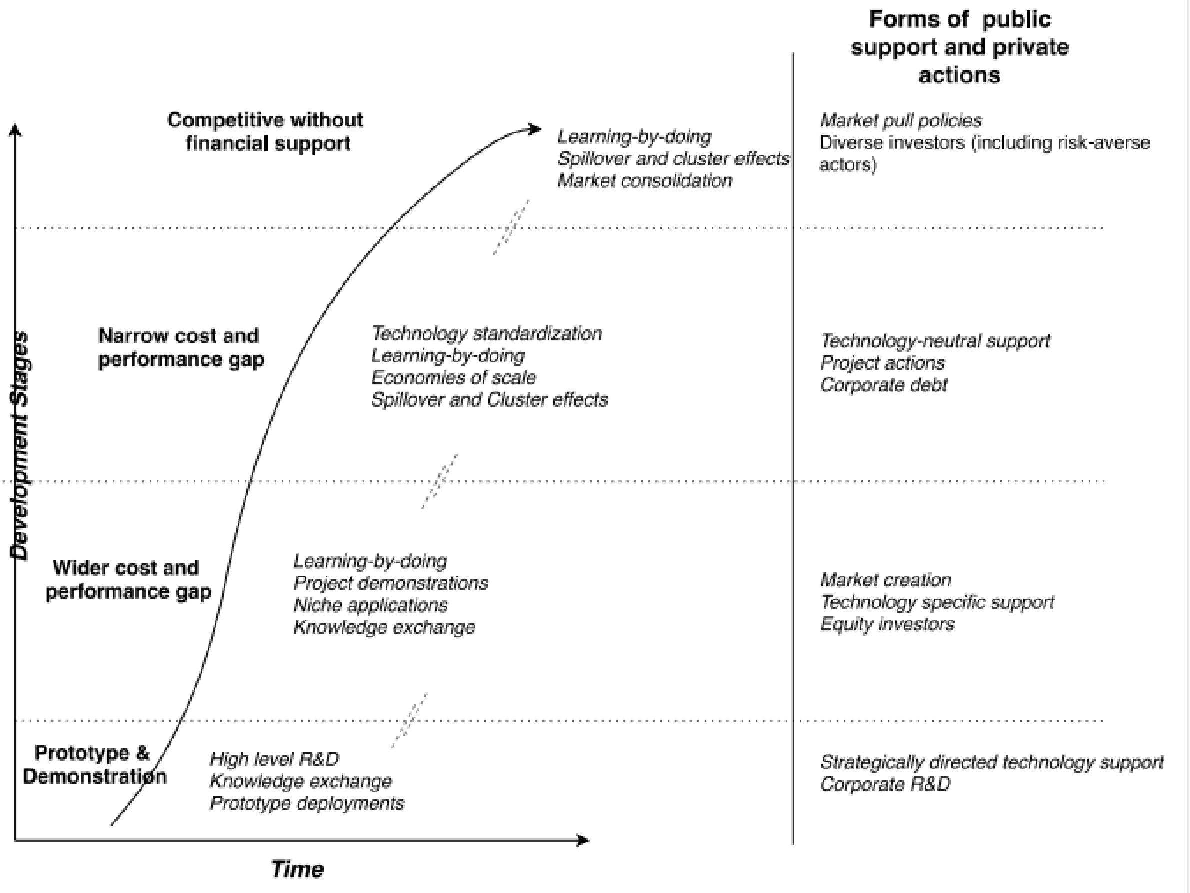
10 Sagar & Van der Zwaan (2006), Technological innovation in the energy sector: R&D, deployment, and learning-by-doing, link

As technologies mature, different options for cost reduction become available. Figure 5.1 shows a model of the energy technology development progress. As seen in the figure, different stages feature different cost-reduction drivers and require different types of support to progress. The final stage of the energy technology development process involves progress towards competitiveness without financial support. To truly reflect the societal costs, external costs should also be internalised, which puts the technology on the same level playing field as conventional technologies. Otherwise, the external costs of more polluting technologies are covered by society, giving them an unfair competitive advantage compared to cleaner technologies. This could for example be realised by instating a CO_2 price on all technologies.

Figure 5.1 Energy technology development process model[11]



5.1.1 Cost reduction categories

The cost reduction factors in Figure 5.1 are further generalized in literature[12] into the four categories of cost reduction drivers: learning by researching, learning by development, economies of scale, and market influence. These four categories will be used when analysing the cost reduction opportunities in various energy technologies.

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11 Santhakumar, Meerman & Faaij (2021), Improving the analytical framework for quantifying technological progress in energy technologies, link

12 Elia et al. (2021), Impacts of innovation on renewable energy technology cost reductions, link

Learning by researching

This category refers to cost reductions created by technological innovations. For example, this type of innovation includes efficiency improvements, material use improvements, and throughput speed increases.

Referenced actions from Figure 5.1: High-level R&D, prototype deployments, niche applications

Learning by deployment

This category refers to the range of improvements that can be achieved during the deployment of projects. Cost reductions through learning by deployment are especially prevalent in stages where the large-scale deployment of a technology is still relatively novel. This category also encompasses learnings gained by the exchange of information between similar projects. The interaction between learning by deployment with learning by researching creates synergies that guide both processes and create feedback loops that enhance cost reductions.

Referenced actions from Figure 5.1: Learning by doing, project demonstrations, knowledge exchange

Economies of scale

This category refers to cost reductions that can be attained by increasing the size of individual projects. Economies of scale have driven cost reductions in a wide variety of sectors. For example, cost reductions due to economies of scale can occur due to decreasing marginal costs, or the presence of fixed costs which reduce relative to total costs as plants increase in size[13]. Economies of scale furthermore reduce costs through supplying increasing flows of feedstock such as biomass and reduce risk premiums associated with these inputs.

Referenced actions from Figure 5.1: Economies of scale, spillover, and cluster effects

Market influence

This category drives cost reduction through the standardisation, optimisation, and scaling of the supply chain supporting a given energy technology. Policy changes that impact energy regulation (and therefore energy markets) also fall under the umbrella of market influence as well as cost reduction relative to a (fossil-based) competitor (e.g. because of environmental taxes).

Referenced actions from Figure 5.1: technology standardisation, market consolidation

These four categories identify the main drivers for the reduction of costs. In the next sections, the main cost drivers are identified and the framework is applied to each technology.

[13] Junius (1997), Economies of scale: A survey of the empirical literature, link

5.2 Deep dive 1: pyrolysis cost reduction

Pyrolysis involves heating solid biomass, waste, coal, or petroleum in an anaerobic environment to prevent the combustion of the input matter. The high temperature, usually between 400-600°C, breaks the chemical bonds of the matter, breaking it down into smaller molecules. The output of the pyrolysis process is a mix of gases (gas), pyrolysis oil (liquid) and char (solid). The ratio between the gas/liquid/solid outcomes is determined, among other factors, by the specific input feedstock, the operating temperature and the residence time. The bio-oil is the main output of interest for pyrolysis.

We only analyse the pyrolysis process using biomass. Three types of pyrolysis processes are generally distinguished: slow, fast and flash pyrolysis. These three types differ in the heating rate of the biomass, where in flash pyrolysis the biomass is heated very quickly for a short amount of time (up to half a second). Fast and/or flash pyrolysis is generally preferred due to its fast reaction rate and higher yield of bio-oil.[14]

Pyrolysis oil can be used directly as fuel for heating and power. For alternate uses, such as transportation fuel, the resulting bio-oil needs to be upgraded and refined to make it less corrosive, more stable and increase its heating value. One upgrading method employed is the introduction of a catalyst in the pyrolysis reactor, to remove oxygen and convert heavy molecules to lighter ones. However, the upgrading could also take place off-site. This method is generally preferred since in-situ upgrading is still under development.

5.2.1 Identification of key cost components

The CAPEX and OPEX of pyrolysis plants are both significant and are for a large part subject to the market. However, cost reductions for several components of the pyrolysis process are possible. Either by reducing investment and operating costs, increasing the yield of a plant or increasing the quality of the bio-oil.

The CAPEX consist mostly of the investment costs for the pyrolysis plants. Here, costs can be reduced by lowering the costs of constructing plants. A significant cost reduction can be achieved in the price of parts for the plants, by increasing the availability of parts on the market (see section 5.2.5)

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For the OPEX, several major cost components of the pyrolysis process can be distinguished:

- Feedstock
- Transport of feedstock
- Energy
- Plant overhead, maintenance and labour

[14] Hu and Gholizadeh (2019), Biomass pyrolysis: A review of the process development and challenges from initial researches up to the commercialisation stage.

The contribution of each component to the total yearly operating cost ranges between sources, due to variations in economic assumptions, reactor model and type of biomass.[15,16,17,18] Overarching can be concluded that the cost of biomass and energy are the main contributors to the costs of the pyrolysis-, upgrading- and refining processes. Between the two, the cost of biomass is the larger component. Estimations of the cost of biomass range between 40-70% of total yearly operating cost.[19],[20] The cost of biomass cannot be influenced by plant operators however, while reducing energy usage can. Reducing the amount of energy required for pyrolysis however is an ongoing field of attention, but it is unknown how much improvements can still be made. More cost reductions are possible by increasing the yield and quality of the bio-oil, reducing the OPEX per unit of output.

When mapped on the framework of Santhakumar, Meerman & Faaij[21], the following cost reduction factors can be distinguished. In the next section, these factors are discussed.

1. **Learning by researching**
   Matching type of biomass to the subsequent use-case, catalyst stability

2. **Learning by deployment**
   Optimisation of plant settings

3. **Economies of scale**
   Increased plant capacity

4. **Market influence**
   Biomass transportation and storage, plant design, CAPEX,

5.2.2 Learning through research

The single largest cost driver of pyrolysis is the price of biomass. Here cost reductions can be achieved by better matching the type of biomass to the use-case of the resulting bio-oil. Cheaper biomass usually has higher ash levels, negatively impacting the yield and quality of the bio-oil. This bio-oil can be directly used as fuel for combustion, for example for heating purposes. However, if the bio-oil is used for more advanced purposes, such as for marine- or air transport or as feedstock for the chemical industry, the quality needs to be significantly higher. For these purposes, the bio-oil needs to be upgraded and refined. Current research of a developer of pyrolysis plants is focused on the conversion of different types of biomass and the consequent upgrading of the bio-oil to transportation fuel. Research goals on one hand are to achieve high-quality bio-oil from lower-quality biomass, and on the other how to upgrade

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15 Fivga and Dimitriou (2020), Pyrolysis of plastic waste for production of heavy fuel substitute: a techno-economic assessment.

16 Arbogast, Bellman, Paynter and Wykowski (2012), Advanced biofuels from pyrolysis oil… Opportunities for cost reduction.

17 Shabbaz et al. (2022), Investigation of biomass components on the slow pyrolysis products yield using Aspen Plus for techno-economix analysis.

18 Makepa et al. (2023), A systematic review of the techno-economic assessment and biomass supply chain uncertainties of biofuels production fro fast pyrolysis of lignocellulosic biomass.

19 Shabbaz et al. (2022), Investigation of biomass components on the slow pyrolysis products yield using Aspen Plus for techno-economix analysis

20 Makepa et al. (2023), A systematic review of the techno-economic assessment and biomass supply chain uncertainties of biofuels production fro fast pyrolysis of lignocellulosic biomass.

21 Santhakumar, Meerman & Faaij (2021), Improving the analytical framework for quantifying technological progress in energy technologies, link

bio-oil in conjunction with existing (crude) oil upgrading processes such as cracking. Both are topics of ongoing research by not only plant developers, but also (crude) oil companies. Another cost component is the catalyst required to process the pyrolysis vapours that form during the pyrolysis process. In this subprocess, the vapours interact with a catalyst that reduces the amount of oxygen in the gas, which increases the quality of the pyrolysis oil. The catalyst becomes polluted and coke forms around it. This reduces the efficiency of the catalyst since it deactivates rapidly. Currently, acid-based catalysts are employed most often, such as zeolite, ZM-5, Y-zeolite and MCM-41. Main difference between them is the size of the pore structure of the catalyst, limiting the size of molecules that can enter and react with the catalyst.[22,23] More experimental catalysts are silica and biomass-derived activated carbon.[24]

Different, less tested or less efficient, reactor designs have to be used to slow the degradation of the catalyst. Current research into catalysts focusses on increasing their stability and lifespan on one side and lowering their production costs on the other.[25] A catalyst that can be used for a longer time means lower operating costs but also reduces downtime of the plant due to maintenance to, replacement of and regeneration of the catalyst.

5.2.3 Learning by deployment

Currently, the first pyrolysis plants are being developed commercially. The operators of the plant expect them to be commercially viable in the current market circumstances, the plants thus operate sufficiently efficiently. Further optimization of the pyrolysis process is expected due to continuing developing insight into the process. Pyrolysis remains a process with many variables of which the mutual interdependencies and effects are not always fully understood. As are the effects of the several subprocesses that occur during pyrolysis, such as dehydration, depolymerisation, isomerisation, aromatisation, decarboxylation and charring.[26] Applied research continues to look for an optimal yield of bio-oil as a function of the various variables and sub-processes.

One developer of pyrolysis plants is rolling out a pyrolysis plant with a 5-tonne per hour reactor. They estimate that, by optimising the design with practical insight obtained during operating, the plant could increase its throughput by 20-40% to 6-7 tonnes per hour without any loss of quality. Theoretically, this could happen within the next few years but no clear timeline for development has been set.

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22 Ratnasari et al. (2016), Catalytic pyrolysis of waste plastics using staged catalysis for production of gasoline range hydrocarbon oils.

23 Norouzi et al. (2021), What is the best catalyst for biomass pyrolysis?

24 idem

25 Griffin et al. (2018), Driving towards cost-competitive biofuels through catalytic fast pyrolysis by rethinking catalyst selection and reactor configuration.

26 Hu and Gholizadeh (2019), Biomass pyrolysis: A review of the process development and challenges from initial researches up to the commercialisation stage.

5.2.4 Economies of scale

Considerable cost reductions are likely possible due to economies of scale.[27] A larger plant operates more efficiently than smaller plants. Rogers and Brammer (2011) indicate that the largest cost potential reduction due to economies of scale can be achieved due to reduced capital costs and improved staff utilisation, as the costs are spread out over a higher yield. In their model, they encountered a turning point for plants with a capacity of 800 tonnes per day (of dried biomass). After this turning point, it is unlikely that significant cost reduction can be achieved. For plants this size, 75% of the operating costs would involve biomass and electricity, which are both within limited control of plant operators.

A developer of pyrolysis plants in the Netherlands echoes these potential cost reductions, but indicates that larger plants may not be practically viable. The limited (local) availability of biomass is a severe limiting factor. They are not developing larger plants since very few locations produce sufficient biomass to operate larger plants. Their current plant, capable of up to 5-tonne per hour, is large enough for the foreseeable future. Experts indicate that with limited local supply and the transportation of biomass to expensive, pyrolysis is best suited for decentralised wide-spread application as opposed to centralised.

5.2.5 Market influence

The main cost reduction due to market influence is the standardisation of the pyrolysis plant design. When standardising the design of the pyrolysis plants, the producers of parts for the plant can optimise their processes. A mature market where supply and demand dynamics are in play will drop the price of the parts. Companies will invest in their production lines for parts, making them more efficient. Equally, personnel construction of the plants will become more adept, reducing the time and effort required to build a plant. Currently, plant developers are conducting a study with their suppliers and partners what is required to scale up their plant production. Details regarding the cost reduction potential of specific components are unknown, other than that the reactor (heating the feedstock) and condenser (converting to oil/char/gas) are the most expensive components of a plant.

IEA bioenergy finds that a reduction of 10-20% in the total CAPEX and OPEX by standardising the design is achievable, when combined with reductions in investment- and staffing costs and efficiency improvements.[28] Experts attribute 90% of the total cost reduction potential of pyrolysis to this effect in combination with matching biomass (see 5.2.2). This makes a standardised design one of the largest possible cost reduction achievable for pyrolysis.

At this moment, plant developers and their suppliers (of parts) face a ‘valley of death’. Cost reductions are possible, but require investments from different parties in the supply chain. Each is hesitant to invest because of the risk of losing the investment when they cannot sell their product.

The government can help by providing insurance to market parties that pyrolysis is a technique that stays around for long enough to get a return on their investments.

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27 Rogers and Brammer (2011), Estimation of the production cost of fast pyrolysis bio-oil.

28 IEA Bioenergy, 2020, Advanced biofuels: potential for cost reduction.

A second possible cost reduction is a decrease in costs due to the technical efficiency of the reactor. The reactor design determines a large part of the yield of bio-oil, due to differences in (the amount of) heat transfer, the residence time of biomass particles, the residence time of bio-oil, gas and char after conversion, running temperature and feed-in capacity. It is largely unknown to what degree the yield can be increased with improved reactor designs.

A third important factor in pyrolysis cost reductions is the supply chain of biomass. Not only does the price of biomass determine the cost of pyrolysis for a large part, the type of biomass and when it is produced are of importance. Biomass with a lower alkali metal content (ash) is beneficial for bio-oil production. Biomass usually has a lower amount of alkali metals when the plants are harvested when they are dormant, for example in winter. However, since biomass is often a residual product, the availability is determined by other processes (such as optimal harvest time or forest management practises). This means that biomass has to be stored for up to almost a year. Long-term storage has to be constructed or rented, increasing the price. Additionally, some of the biomass is lost during storage, due to the continual drying of biomass during storage. These losses reduce the overall energy of the biomass, ranging from 0.3 – 4.2% each month, dependant on environmental factors such as microbial activity, available carbon, oxygen concentration, temperature and moisture level.[29] Optimised storage to ensure a year-round supply of high-quality biomass could be beneficial.

5.2.6 Conclusion

There are two major potential cost reduction components for pyrolysis. The first is the type of biomass used, due to the large impact of its unit cost. Optimising the type of biomass and how it is processed to meet the requirements of upgrading processes, is the subject of ongoing research by market parties. Their research focusses on two topics, namely how the highest quality bio-oil can be produced from different types of biomass and, secondly, how the bio-oil can best be upgraded using existing infrastructure.

The second major cost reduction component is the standardisation of plant design that leads to an optimised production process at suppliers of parts for the plants. Market parties indicate that their plant design is commercially viable and ready for widespread implementation. However, the construction of the plants is a novel process and faces a ‘valley of death’, where it is uncertain whether investments in optimised production of plant parts will pay off. The role of the government could be to support companies to overcome the valley and give assurances that their investment is worthwhile.

Further cost reductions are theoretically possible with technological optimisation and scale-up of single plants. However, the local availability of biomass quickly becomes an obstacle that prevents larger pyrolysis plants from operating commercially. This is mainly due to the inefficiency and costs associated with transporting biomass.

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[29] IEA Bioenergy (2019), Dry matter losses during biomass storage.

5.3 Deep dive 2: gasification cost reduction

The second analysis of the cost reduction potential of technologies used in the production of high-quality energy carriers is thermochemical gasification. Thermochemical gasification aims at converting biomass, waste and coal at elevated temperatures and reduced levels of oxygen or steam into syngas, and for some technologies biochar. Pilot and demonstration facilities have been applying various streams of biomass. Reactors ideally handle one specific type of input (e.g. wood chips, sewage sludge), to optimise its settings and environment. With limited biomass available and pyrolysis-driven processes also requiring biomass inputs scaling gasification-driven processes should take available biomass-streams into consideration. In our analysis, processes involving the input of coal are not considered, as they do not meet the assessment criteria.

The conversion process of thermochemical gasification consists of four steps resulting in the production of syngas: drying, cleaning, partial oxidation and finally reforming and/or gasification. Today, there are five main types of gasification reactors known:

- Fixed bed reactors
- Fluidised bed reactors
- Dual fluidised bed reactors
- Entrained flow reactors
- Plasma reactors

In the analysis, we do not make a distinction between the five types of reactors and the deep dive focuses on the cost reduction potential for thermochemical gasification as a technology. The five types of reactors are at different levels of development, but go through similar learning curves due to the nature of the technology used. The output of the gasification process, syngas, consists of a mixture of hydrogen, carbon monoxide, carbon dioxide and a few light hydrocarbons. The concentration of these elements can vary broadly, depending on e.g. the reactor and type of feedstock used.

5.3.1 Cost component analysis

So far gasification plants are mainly used to produce renewable heat and power (CHP), but recent developments focus on plants that aim to produce biomethane, hydrogen and biofuels. These plants produce products that have a higher energy-intensity than conventional waste-to-energy processes and are capable of converting a wide range of feedstock into a variety of outputs. These outputs can then be used for industrial processes that require fossil fuels. Gasification makes use of temperatures higher than 700°C, allowing the feedstock to be purified before transforming it into syngas, hydrogen or biofuels.

Currently, CHP plants using gasification are small plants. The main costs for these plants are capital costs and feedstock costs. Depending on its size, costs range from 21 to 44 €/MWh(th) and from 99 to 109 €/MWh.

For a viable business case of gasification plants, the main cost drivers include the availability and quality of the feedstock, production costs and the forecast revenues from its outputs. The European Biogas Association provides a summary of expected costs per application of the output of gasification plants.[30] They assumed these are cost ranges after scaling as not all sources specified this clearly. Although the year for which these costs apply is not always specified in the literature, they assumed these costs apply to 2030 and beyond (after successful development and scaling of plants). The production costs mainly depend on three cost components: feedstock costs (including gate fees), reactor size and costs (capex) and operating costs (opex). The cost ranges for various gasification products are presented in Table 5.1.

Table 5.1 Cost ranges of different products of thermochemical gasification

Product	Production costs
Electricity	99 – 109 €/MWh
Heat / Steam	21 – 44 €/MWh(th)
Synthetic Natural Gas (SNG)	37 – 90 €/MWh
Hydrogen	42 – 101 €/MWh (1.40 – 3.35 €/kg)
Ammonia	47 – 105 €/MWh (0.25 – 0.55 €/kg)
Fischer-Tropsch fuels	40 – 113 €/MWh (0.30 – 0.85 €/kg)
Methanol	37 – 90 €/MWh (0.21 – 0.50 €/kg)

5.3.1.1 Cost drivers for the production of SNG
To produce SNG, hydrogen and other biofuels, further syngas processing is required. It is expected that the projected costs per MWh to produce SNG vary between 37 and 90 €/MWh, based on a plant size of 20-40 MW (roughly 100-200 tonnes per day). These costs include feedstock costs, CAPEX and OPEX, and relate to the final output. Feedstock accounts for approximately 30% of total costs.

Waste-to-energy gasification is already economically viable in some European countries due to gate fee systems and energy prices. This means that gasification facilities receive a fee for the processing of waste. It is expected that the costs of gasification could be brought down by more than 30% because of technology development and scaling of plants. Furthermore, the costs of fossil fuels, for example through the costs of the EU ETS will play an important role in the uptake of SNG through gasification. At the lower end of the production costs range, SNG is already competitive with natural gas at an ETS price of 84 €/tCO2 and higher.[31]

It should be taken into account that additional costs apply to grid injection of SNG: biomethane must be brought up to the right quality for injection, compression costs might apply and grid connection costs might apply.

30 European Biogas Association, 2021, Gasification: a sustainable technology for circular economies. Scaling up to reach net-zero by 2050.

31 IEA Bioenergy: Task 33, 2018, Hydrogen from biomass gasification.

5.3.1.2 Cost drivers for the production of hydrogen and ammonia

The production costs for hydrogen via gasification are more or less similar to the production of SNG. IEA Bioenergy estimated in 2018 the future hydrogen costs at 2.70 €/kg, based on a dual fluidised bed gasification plant of 50 MW[32]. In line with the downward cost trend of the production of SNG, it is expected the cost ranges between 1.40 and 3.35 €/kg (42 – 101 €/MWh) depending on the size of the plant.

Ammonia produced from hydrogen via the Haber-Bosch principle will add an additional 10 – 15 €/MWh to the costs of hydrogen production through gasification, resulting in 47 – 105 €/MWh.

5.3.2 Learning through research

The first component that would allow costs to reduce in the future involves learning through research or continuous technological improvements. The GoBiGas plant converts woody biomass to biomethane as a first-of-its-kind industrial-scaled facility. Thus, lessons on the technological development of the technology can be drafted from this facility. Based on the deployed GoBiGas plant, Thunman et al. (2019)[33] argue that the investment cost related to the production equipment itself is unlikely to decrease dramatically. He argues that reactors used for gasification already contain components that are commercially available and used in many existing industrial processes. Thus, there is little potential in reducing costs through the equipment of reactors used. Instead, there is learning potential related to how the process is assembled and how one can plan and execute the project for constructing this type of plant. Furthermore, the experts mention there is further potential for cost reduction in applying AI and machine learning for predictive operations. This could result in further optimisation of reactor efficiency and transport of feedstock. This is not widely applied yet, but research attention can be directed to the topic to improve efficiencies.

Gasification reactors can diversify between various biomass-streams, but this affects other processing elements such as the purity of the product, efficiency of the reactor, amount of 'side-products', and the need for upgrading the product. In general, the purity of the feedstock directly influences the efficiency of the reactor, but learning could reduce the costs associated with e.g. cleaning the feedstock prior to the gasification process.

Additionally, studies find that producing biofuels or bio-methane from low cost waste-based fuels is significantly cheaper than from biomass feedstocks. The capital costs for plants using the two different feedstocks is not significantly different. Though the operating costs for waste-based plants are higher, these are offset by the lower feedstock costs.[34]

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32 IEA Bioenergy: Task 33, 2018, Hydrogen from biomass gasification.

33 Thunman, H. et al, 2019, Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant, Energy Science and Engineering.

34 IEA Bioenergy, 2020, Advanced biofuels: potential for cost reduction

5.3.3 Learning by deployment

Gasification plants have a relatively high capital intensity and high operating costs. Project developers indicated during one interview that there is a cost reduction potential on CAPEX investments through deployment. Learning experiences from optimal installation and continuous deployment of plants (maximisation of yields) can be used in the development of new plants, therefore reducing initial investment costs. Furthermore, the standardisation of plants and reactors will reduce CAPEX. This could furthermore be enhanced using AI and machine learning, improving the operational time of a plant. This should however be studied and applied further to determine the cost reduction potential.

Furthermore, technologies producing hydrocarbons generate tail gases that can be re-processed and reused or used to produce renewable electricity, thereby generating additional revenue.[35] Optimisation of production processes will still result in the production of 'side-products'. Even though these are not the main product, they could still be used as input for other processes or would have a societal benefit on their own (e.g. when harmful inputs are used in the process, the risk of contamination could be reduced).

5.3.4 Economies of scale

The potential for cost reductions through economies of scale is associated with improvements due to continuing project optimisation, improvement through on-going R&D and in some cases by moving to larger scale plants to further benefit from scaling factors. Similar to the case of pyrolysis processes, value chains for feedstock supply still need to be co-developed. Though, contrary to pyrolysis processes, experts indicate that highest cost reductions for gasification processes are achieved through centralised availability of feedstock. The cost-reduction potential thus increasing with importing large streams of biomass and process these in facilities close to the locations of entry. Therefore, successful economies of scale (beyond the 800 tonnes per day scale) will need specific requirements, such as a nearby port that enables sufficient feedstock supply.

There is also scope for cost improvement by improving the value obtained from by-products and improving integration with other processes. In addition, as the technologies become better established, the technical risks will be seen as less significant by project developers and financiers, and so capital for plants may become available on more favourable terms as confidence in the technologies grows. Reductions in capital and operating costs in the range of 10-20% are felt to be achievable, resulting from a combination of scale-up effects on investments, staffing costs as well as efficiency improvements affecting both CAPEX and OPEX.[36]

[35] IEA Bioenergy, 2020, Advanced biofuels: potential for cost reduction

[36] Idem

5.3.5 Market pull

The development of advanced processes and broader application of biomass gasification has been slowed down mainly by the competition from low-cost fossil fuels, combined with policy and investment uncertainty. Strengthening partnerships among developers, industry and other stakeholders in the value-chain thus further provide opportunities for cost-reductions.

Feedstock cost plays an important role in determining costs and access to low-cost feedstock will play an important role in future plant location. The theoretical availability and cost modelling indicate that large volumes of feedstock could be made available to users at costs around 20 EUR/MWh. Policy and investment uncertainty reduces an optimised production of feedstock, as for example outputs are classified as waste. This reduces the incentive to produce feedstock locally. Large-scale availability of low-cost feedstock is an important driver to reduce costs of gasification technologies. The costs of transporting the feedstocks and in some cases additional pre-processing will depend on local circumstances.[37] Moreover, it could be said that even if gasification technologies would be advanced enough to be employed now, the crucial fact for the market uptake is the price of fossil fuels and CO_2 price, which can be seen as a crucial benchmark for the economic feasibility of renewable-based technologies.[38]

5.3.6 Conclusion: gasification cost reduction

The main variable cost drivers for the gasification process are the availability and quality of the feedstock and the forecast revenues from its outputs. It is therefore important to invest in scaling different gasification technologies, as the efficiency and effectiveness of the process might differ between the combination of technology and feedstock used. Cost reduction is expected to take place mainly through the deployment of multiple scaled production facilities. This allows for learning on the optimisation of processes, and test results of various types of feedstock and enhance the application of the main product output and side-outputs.

In the various gasification applications, side products such as tail gases, biochar and CO_2 could further improve the business case of individual plants. However, the value of these side-products is unclear. It is expected that in the future, with power-to-X increasing in popularity, the need for clean and renewable carbon will also increase. Gasification-based processes will be one of the main suppliers of this renewable carbon, through carbon capture and storage (BECCS).

5.4 Deep dive 3: electrolysis cost reduction

Electrolysis involves using electricity to split water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2). The main advantage of electrolysis is its capability to create an energy carrier (hydrogen) directly from electricity, which could be supplied from renewable sources. Among the various methods of water electrolysis, Alkaline and Proton-exchange membrane (PEM) electrolysis were identified as the most promising methods for scale-up. As the underlying technology behind Alkaline and PEM electrolysis is well understood, it enables a detailed breakdown of cost reduction areas.

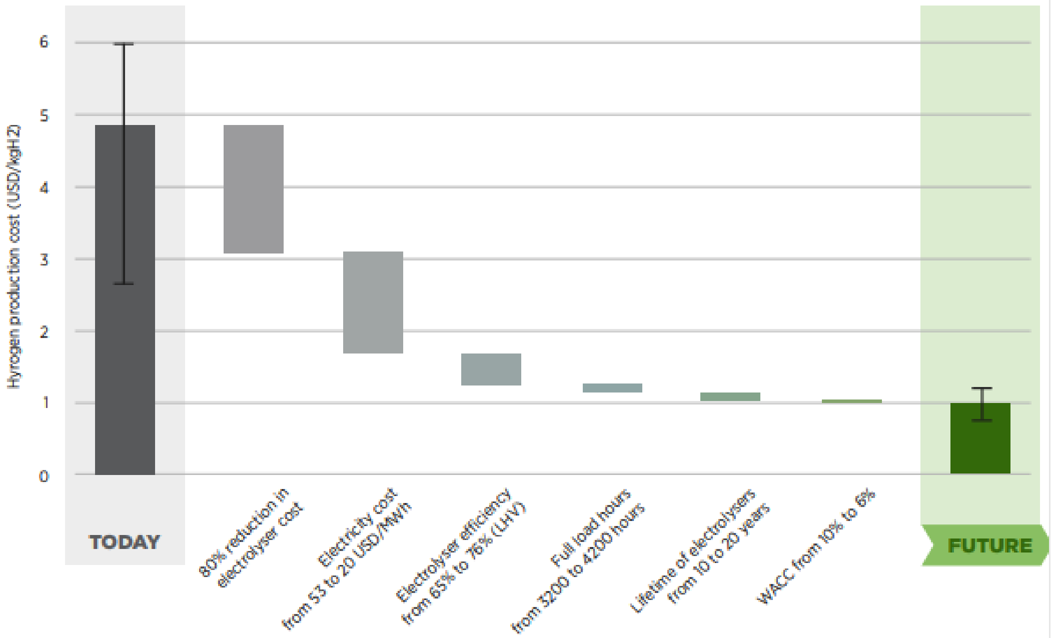
37 Idem

38 IEA Bioenergy, 2018, Thermal gasification based hybrid systems.

5.4.1 Cost component analysis

Electrolysis costs can be generally separated into CAPEX and OPEX. As it stands today OPEX, renewable electricity prices in particular, are dominant in determining the cost per kg of electrolysis-based hydrogen techniques. Electricity price reductions are vital to the point that significant price reductions to compete with fossil-based hydrogen cannot be achieved without them[39]. Figure 5.2 shows a general overview of the cost reduction path as estimated by IRENA. Electrolyser cost reduction (CAPEX) and electricity price (a large fraction of OPEX) account for about \$3.2/kgH_2 of cost reduction. In the scope of this analysis, electricity prices are considered an external development and will not be further investigated.

Figure 5.2 hydrogen cost reduction estimate, IRENA (2020)



5.4.1.1 Cost reduction areas for Alkaline and PEM electrolysis

While the previously referenced research by IRENA states that electricity price reduction has a vital impact on the price of hydrogen, the report and Figure 5.2 also clarify that this alone is not enough to make electrolysis-based hydrogen competitive with fossil alternatives. Innovations in CAPEX reduction are needed to provide additional cost reduction. Analyses by Badgett et al (2021)[40] and IRENA identify several areas where electrolyser investment costs can be reduced. Divided between the four categories of the framework, the options for cost reduction are as follows:

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[39] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

[40] Badgett et al. (2021), Methods identifying cost reduction potential for water electrolysis systems, link

Table 5.2 Cost reduction drivers of electrolysis

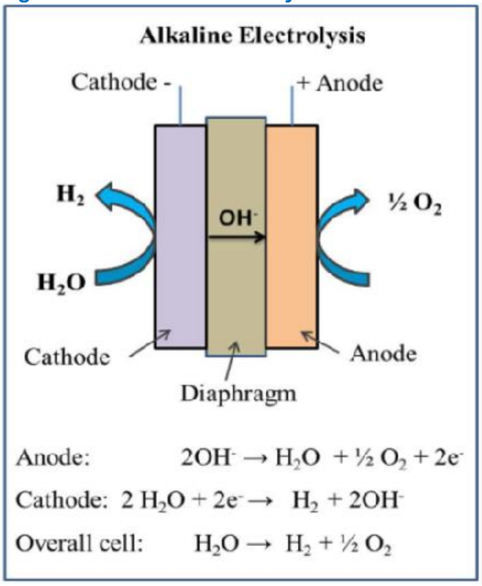
Framework category	Cost reduction driver
Learning by researching	Improving electrolyser stack design, reducing (rare) material use in electrolyser cells
Learning by deployment	Learning effects, exchanging information between projects
Economies of scale	Increase electrolysis plants from MW-scale to GW-scale
Market influence	Standardisation of stack balance components

5.4.2 Learning through research

5.4.2.1 Alkaline electrolysis overview

Figure 5.3 shows an overview of hydrogen generation in an Alkaline Electrolyser. Two electrodes, the anode and cathode, are suspended in a solution of (usually) potassium hydroxide (KOH). Water is split into hydroxide and hydrogen at the cathode. While hydrogen exits at the cathode, hydroxide passes through the diaphragm and reacts to oxygen and water at the anode.

Figure 5.3 Alkaline electrolysis reaction overview[41]



5.4.2.2 Technical cost components in alkaline electrolysers

The main components of an alkaline electrolyser are relatively cost-efficient. For example, the cathode and anode can be constructed from Nickel and stainless steel. Cost reductions at the stack design level can therefore best be focussed on making the design itself more energy efficient[42], as well as optimising the stack balance.

41 Kumar & Himabindu (2019), Hydrogen production by PEM water electrolysis – A review, link

42 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

Energy efficiency

Energy use can be decreased by reducing resistance at various points during the electrolysis reaction. For example, the thickness of the diaphragm can be reduced, which lessens the resistance placed on hydroxide passing through the diaphragm. Increasing the current density is also an option. Current density relates to the possible production volume over time. However, higher current densities raise the voltage, which reduces efficiency again. More research can be focussed on increasing the current density while mitigating the efficiency losses.

The exact cost reductions that these actions can attain heavily depend on the electricity price, as well as the balance between throughput and efficiency that is achieved.

Stack standardisation

A cell stack refers to the supportive structures that help the alkaline cell operate. The components needed for stack balancing (pumps, power, wiring etc.) are relatively generic components. Mass production and increasing the size of alkaline installations are expected to reduce the cost of balancing components quickly.[43]

Material use

As stated before, alkaline electrolysis components are already fairly cost efficient. Therefore changing the materials used will likely not be the premier method of reducing alkaline electrolyser cost. However an effort can still be made to make alkaline electrolyser stacks more recyclable. While not directly aimed at affecting cost, designing the cells to be recyclable from early on in the scale up can aid in other government directives such as circularity.

5.4.2.3 PEM electrolysis

Figure 5.4 shows an overview of hydrogen generation in a PEM-cell. PEM-electrolysis cell functions by inserting water into the cell, which flows through separator plates to reach the electrodes. At the anode, water is electrochemically split into oxygen, protons and electrons. A catalyst of iridium oxide is needed during this process. Subsequently the protons travel through the membrane, separating the hydrogen from oxygen.

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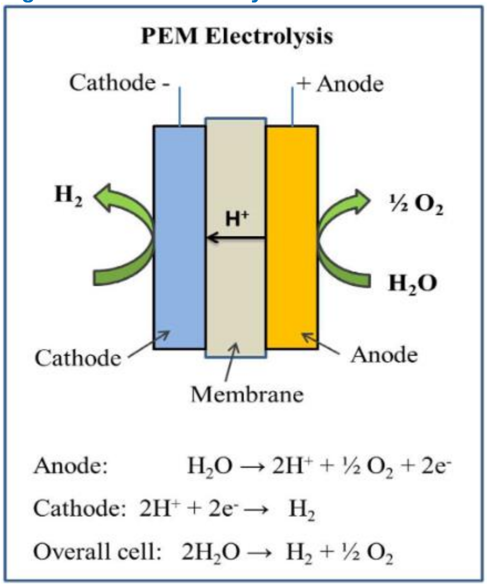
[43] IRENA (2020), Making the breakthrough: green hydrogen policies and technology costs, link.

Figure 5.4 PEM electrolysis reaction overview[44]



5.4.2.4 Technical cost components in PEM electrolysers

Within a PEM electrolysis plant, the cells comprise around 53% of the cost, with the remaining 47% being more generic components such as the power supply. The scope of this section focuses on the costs of the PEM cell in particular. These costs are largely concentrated into three areas[45]: the bipolar separator plates (48% of costs), the membrane assembly[46] (24%) and the cell/stack balance (28%). Cost reduction on the cell level can be made in each of these categories.

Bipolar separator plates (BSPs)

BSPs in PEM electrolysers are constructed mainly out of titanium, although stainless steel and graphite are also used. The main drawback of these materials is their high cost (especially titanium).

Any material used for BSPs has to ensure rigidity, thermal conductivity, and low permeability and resistance within the structure of the cell (Kumar & Himabindu, 2019). The material properties of titanium fit these criteria the best. However, even titanium requires expensive noble metal-based coatings to keep the plates from corroding over time.

Innovations that lead to either a titanium-free BSP or that remove the need for expensive noble metal coatings will significantly reduce BSP costs[47]. The resulting cost reduction is determined by the price delta between the current noble metals and the replacement components. However, finding a replacement for titanium is a difficult challenge. Improving upon the existing designs of the BSPs can already lead to a cost reduction in the shorter term. BSPs account for a large fraction of cell cost. Because of this, small cost reductions can already provide significant reductions for the entire cell.

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44 Kumar & Himabindu (2019), Hydrogen production by PEM water electrolysis – A review, link
45 Kumar & Himabindu (2019), Hydrogen production by PEM water electrolysis – A review, link
46 The membrane assembly includes the membrane itself and the adjacent porous transport layers
47 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

Membrane assembly

The most used membrane in PEM electrolysers consists of a sulfonated tetrafluoroethylene-based fluoropolymer-copolymer (TBFC), generally referred to by the widely used brand Nafion.[48] This material can provide the desired properties for a membrane such as high proton conductivity (by being thin), high current density and durability.

Cost reduction efforts regarding the membrane are not focussed on reducing the direct material cost. Instead, research is conducted into increasing the efficiency of various membrane types by reducing their thicknesses. A more efficient membrane leads to a reduction in electricity use for the entire cell, which indirectly reduces more costs than a cheaper membrane material could accomplish. The exact cost reduction will depend on the electricity price, as well as the attained efficiency increase. Aside from reducing the thickness of TBFC membranes, other membrane material types are also being investigated.[49] This research is also focussed on creating more efficient membranes in favour of reducing the material cost.

Stack balance

Stack balance refers to the supportive structures that help the PEM cell operate. The components needed for stack balancing (pumps, power, wiring etc.) are relatively generic. Mass production and increasing the size of PEM installations are expected to reduce the cost of balancing components quickly.[50]

Material use

PEM stands out from other electrolysis techniques for its relatively higher dependency on rare materials, especially Iridium.[51] Aside from Iridium being an expensive metal, global Iridium production is small and highly concentrated (e.g. 90+% of production is located in South-Africa).[52] Due to the limited availability of Iridium, PEM's dependency on it as a catalyst can be a bottleneck to the mass production of PEM facilities. Estimates on the maximum installation speed of PEM electrolysers based on Iridium supply range from 2GW/year[53] to 3-7.5GW/year[54] globally. This is orders of magnitude from the 100GW/year needed global expansion estimation by IRENA.

Innovations that reduce the dependency of PEM on Iridium can not only reduce costs, but also facilitate greater capacity installation speeds. Minke et al. (2021) add that an increased focus on end-of-life Iridium recycling can also help alleviate the bottleneck. Minke reports recycling rates for iridium around 20-30%, while similar materials can attain rates up to 90%.

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48 Nafion (N.D.), Meeting modern demands for water electrolysers, link

49 U.S. department of energy (2013), PEM electrolyser incorporating an advanced low-cost membrane, link

50 IRENA (2020), Making the breakthrough: green hydrogen policies and technology costs, link

51 Platinum dependency can also form issues, although not on the level of Iridium

52 Mindat (N.D.), Iridium overview, link

53 Minke et al. (2021), Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?, link

54 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

5.4.3 Learning by doing

Experts highlight the fact that for both electrolysis technologies to reduce project costs, there must be a greater emphasis on the sharing of learnings between demonstration projects. Increasing communication between various demonstration projects is one of the key drivers of technological advancement.[55] Projects such as EMP NL[56] encourage such knowledge sharing. However, current support schemes run the risk that the private endeavours that utilize these support schemes deliberately limit knowledge sharing, to gain a competitive advantage. Experts advise that providers of subsidies ensure that sharing of knowledge is possible for the recipients of the subsidies. Otherwise the benefits of 'learning by doing' may be suppressed.

5.4.4 Economies of scale

5.4.4.1 Alkaline electrolysis

A full design analysis of a 1 GW alkaline electrolysis plant in 2030 was performed by HIP (2022).[57] This analysis shows the potential for efficiency increase and cost decrease. The main result is an operating cost of € 730/KW, which depending on the price of electricity results in a hydrogen price of € 1.75-4/kgH_2.[58] Cost reductions were achieved by scaling up the plant balancing components, as well as assuming efficiency improvements in the alkaline cells. Balancing costs seem to benefit most from scaling up. Whereas balancing an entire plant (not only cell balancing) comprises around 55% of the cost on a 1MW alkaline electrolyser, this is reduced to 11% in the 1 GW plant designs. Overall HIP concludes that the Capex of the 1 GW alkaline installations will be 50% lower than the reference plant used.

5.4.4.2 PEM electrolysis

A full design analysis of a 1 GW PEM electrolysis plant in 2030 was also performed by HIP (2022)[59]. This analysis shows the potential for efficiency increase and cost decrease. The main result is an operating cost of € 830/KW, which depending on the price of electricity results in a hydrogen price of € 1.5-3.6/kgH_2.[60] Cost reductions were achieved by scaling up the plant balancing components, as well as assuming cost reductions in the PEM cells. Balancing costs seem to benefit most from scaling up. Whereas balancing an entire plant (not only cell balancing) comprises around 55% of the cost on a 1MW PEM electrolyser, this is reduced to only 5% in the 1 GW plant designs. Overall HIP concludes that the Capex of the 1 GW PEM installations will be 50% lower than the reference plant used. Do note that this model assumes that all materials, such as Iridium, are available for the construction of the plant.

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55 TNO (2020), European RTOs: accelerating development of electrolysis, link

56 EMP NL (n.d.), over ons, link

57 Hydrogen Innovation Program (HIP) (2022), A one-gigawatt green-hydrogen plant, link

58 Hydrogen costs per kilogram are not provided in the original HIP report. The results were obtained by interpolating the € /KW price on figure ES2 in IRENA (2020), which shows a correlation between € /KW and € /kgH_2 cost at various electricity price points.

59 Hydrogen Innovation Program (HIP) (2022), A one-gigawatt green-hydrogen plant, link

60 Hydrogen costs per kilogram are not provided in the original HIP report. The results were obtained by interpolating the € /KW price on figure ES2 in IRENA (2020), which shows a correlation between € /KW and € /kgH_2 cost at various electricity price points.

5.4.5 Market influence

Due to the relatively early phase of electrolyser scaling, established supply chains have yet to form. The U.S. department of energy has researched which steps the American government can undertake to help the supply chain develop. Their recommendations[61] can be seen as generally applicable for both PEM and Alkaline and largely overlap with recommendations done by IRENA. A list of key recommendations is provided below.

Develop necessary hydrogen infrastructure such as storage and pipelines
Pipeline infrastructure is a vital precondition to the formation of large-scale hydrogen-based activities in the Netherlands. Currently the formation of the ‘Dutch hydrogen backbone’ is already underway.[62] In this early stage of development, experts press the benefits for governments of taking a stronger guiding role in the spatial distribution of electrolysis capacity. This means not only laying out the transport infrastructure for hydrogen, but actively working with electrolysis stakeholders regarding where the production will be placed. By doing this, necessary transport infrastructure can be created or strengthened more efficiently. Hydrogen is ideally produced closely to where it is needed. If the spatial capacity distribution is left to the market, the Netherlands run the risk of congestion situations similar to the issues that affect solar capacity rollout.

Develop manufacturing codes and standards for key components in electrolyser installations
The government can play a role in reducing the CAPEX by stimulating Dutch electrolysis component manufacturers. Not only will this bring the cost down, but a Dutch supply chain enables the government to enact standards of quality and circularity that could influence the wider European (and worldwide) market.

Develop (ideally domestic) material supplies and recycling systems
Experts point to the potential for the Netherlands to be a large market player in the electrolyser materials supply chain. The European commission has previously expressed the strategic importance of developing a strong electrolysis supply chain in Europe.[63] Because the supply chain scaling is still in an early enough stage, the Netherlands can position itself as a key manufacturer of complex electrolysis components (‘The ASML of electrolysis’). Furthermore, this enables the Dutch industry to set standards for electrolysis that go beyond price, such as circularity and material use.

5.4.6 Conclusion: electrolysis cost reduction

Through studying the various categories of cost reduction for electrolysis, it can be concluded that all four categories show the potential to reduce costs for electrolysis. However, there are clear differences between Alkaline and PEM electrolysis that can be identified from the literature.

Alkaline electrolysis seems to be progressing well along the cost reduction curve of Figure 4.2. Literature primarily focusses on making incremental efficiency improvements to the cells, while

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61 U.S. department of energy (2022), Water electrolysers and fuel cells supply chain, link
62 Gasunie (2022) Development of the National hydrogen transport network of the Netherlands, link
63 Strategic Research and Innovation Agenda 2021-2027, link

simultaneously scaling up the size of plants. In addition, literature as well as experts highlight the importance of supportive developments, such as the standardisation of the supply chain and greater knowledge sharing.
PEM electrolysis seems to still be in an earlier phase of the cost reduction curve presented in Figure 4.2. Literature proposes cutting costs by changing fundamental facets of the PEM cell, such as the materials used for the bipolar plates and the catalysts. Until the use of rare materials such as iridium is handled more efficiently (or removed), research shows potential bottlenecks appearing in scaling up. The benefits that PEM can achieve through economies of scale are therefore more uncertain, as the fundamental technology still changes. The benefit is that, due to the high cost of components, there are more opportunities for cost reduction present in the 'Learning by researching' category than exist in Alkaline electrolysis. Finally (and similarly to alkaline), experts highlight the cost reduction potential of knowledge sharing and component standardisation.

IRENA expects the CAPEX of hydrogen electrolysers to come down from $650-1000/KW in 2020 to $130-307/KW in 2050. During the same period, the OPEX (notated in \$/kgH_2 in the IRENA report) comes down from \$2.2-5.2/kgH_2 to \$1.1-3.5/kgH_2, depending on the electricity price. While Alkaline and PEM electrolysers show differences in options for cost reduction, IRENA concludes that 'Gaps in cost and performance are expected to narrow over time as innovation and mass deployment of different electrolysis technologies drive convergence towards similar costs' (IRENA, 2020).[64]

5.5 Conclusions on cost reduction potential

This final section summarises the cost-reduction potential of pyrolysis, gasification and electrolysis technologies.

5.5.1 Cost reduction factors per technology

Pyrolysis cost reduction
There are two major potential cost reduction components for pyrolysis. The first is the type of biomass used, due to the large impact of its unit cost. Optimising the type of biomass and how it is processed to meet the requirements of upgrading processes is the subject of ongoing research by market parties. The second major cost reduction component is the standardisation of plant design that leads to an optimised production process at suppliers of parts for the plants.

However, the construction of the plants is a novel process and faces a 'valley of death', where it is uncertain whether investments in optimised production of plant parts will pay off. The role of the government could be to support companies to overcome this and give them assurances that their investment is worthwhile.

[64] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

Gasification cost reduction

The main variable cost drivers for the gasification process are the availability and quality of the feedstock and the forecast revenues from its outputs. It is therefore important to invest in scaling different gasification technologies, as the efficiency and effectiveness of the process might differ between the combination of technology and feedstock used. Cost reduction is expected to take place mainly through the deployment of multiple scaled production facilities. This allows for learning on the optimisation of processes, and test results of various types of feedstock and enhance the application of the main product output and side-outputs.
In the various gasification applications, side products such as tail gases, biochar and CO_2 could further improve the business case of individual plants. However, the value of these side-products is unclear. It is expected that in the future, with power-to-X increasing in popularity, the need for clean and renewable carbon will also increase. Gasification-based processes will be one of the main suppliers of this renewable carbon, through carbon capture and storage (BECCS).

Electrolysis cost reduction

Cost reduction for Alkaline electrolysis can be achieved by making incremental efficiency improvements to the cells, while simultaneously scaling up the size of plants. In addition, literature as well as experts highlight the importance of supportive developments, such as the standardisation of the supply chain and greater knowledge sharing.

PEM electrolysis seems to still be in an earlier phase of the cost reduction curve. Literature proposes cutting costs by changing fundamental facets of the PEM cell, such as the materials used for the bipolar plates and the catalysts.

5.5.2 Overarching cost reduction conclusions

Based on the analysis presented above, the following overarching factors influencing cost reduction are identified:

Support scaling and standardisation of manufacturing processes of key components

All three technologies share a similar benefit from the scaling and standardisation of the underlying component manufacturing processes. As highlighted in, for instance, the pyrolysis deep dive, producers face risks when scaling up manufacturing plants because it is uncertain whether a technology will become commercially viable in the future or remain in the ‘valley of death’. In addition, no common standards exist for such plants. Effective policy can help alleviate both these risks.

Availability and transport of feedstock should be optimised for effective scaling

Regarding pyrolysis and gasification technologies, the availability of input feedstock is a key factor in determining whether a scaled-up plant is viable. The availability of biomass feedstock is limited (in comparison with e.g. electricity and water for electrolysis) and decentralized. Unlimited scaling without considering the quantity and location of available feedstock could lead to logistical complications or an absolute shortage of input feedstock. These flaws can be reduced by differentiating between biomass streams and optimising import streams of biomass.

Sufficient renewable energy must be available for scaling the production of energy carriers

Regarding electrolysis technologies, the price of electricity is dominant in determining the cost of the hydrogen output. Energy prices affect pyrolysis and gasification as well, but not to the same degree as electrolysis. Without a significant price reduction of renewable electricity, it is unlikely that electrolysis-based hydrogen can compete with fossil fuel based hydrogen, given current regulations. Therefore, further expansion of green energy production is vital.

Increase the price for carbon emissions to improve the relative competitiveness of carbon-neutral technologies

While this is not a cost reduction in the strict sense, it is an important factor to keep in mind. In a competitive market, all three technologies offer alternatives to fossil-based counterparts. A major factor in determining their competitiveness is the price of carbon emissions. Should this price increase further in the future, all three technologies stand to gain a competitive advantage. This will make the technologies commercially viable sooner, which will lead to market parties investing in their deployment. This will likely result in further cost reductions through standardisation and economies of scale.

Annex 1: Sources phase 1

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Annex 2: Phase 1 methodology

The criteria described in chapter 2 was applied to the wide net of technologies through the use of indicators. In Table 0.1 we describe which indicators correspond with the selection criteria, and which indicators are included as background information.

Table 0.1 Correspondence of indicators to the selection criteria

		1. The technology must produce an energy carrier	2. The energy carrier must be of high quality	3. The energy carrier must be renewable	4. The energy carrier must be able to result in cost-effective CO2 emission reduction when scaled up substantially.	Additional background information
Indicators	Technology					x
	Output					x
	Specific Energy		x			
	Description					x
	Order of energy carrier					x
	High-quality renewable energy carrier	x				
	Technology Readiness Level (TRL)				x	
	Carbon Cycle			x		
	Minimum process efficiency					x
	Maximum process efficiency					x
	IEA impact on net zero emissions				x	
	Makes it to the shortlist					x

The first indicator identifies the technology used for the conversion process. The second indicator identifies the main output of the conversion process, other residuals are not reflected upon in this study. The third indicator describes the specific energy. The fourth is the conversion method used and the fifth is its energetical order. Next, the TRL is mentioned for each technology. Note that the TRL is an indicative value. Different sub-technologies may have different TRL scores. The TRL score is followed by the identification of the carbon cycle. This indicator indicates whether long-term carbon cycle elements (fossil fuels) are used as input to the process. The final indicator shows the expected impact of net-zero emissions. This assessment is based on the IEA's ETP Clean Energy Technology Guide[65].

The table below lists all the technologies that were analysed including a description and whether they were eligible for the analysis in phase 2.

65 IEA, ETP Clean Energy Technology Guide (link), accessed October 2022.

Table 0.2 Analysed energy conversion technologies

Technology	Description	Selected for assessment in phase 2
Alkaline electrolysis	Water-based electrical hydrogen production method. Alkaline electrolysis is the most widely used electrolysis method. Production requires high amount of electricity and is often envisioned nearby renewable energy source, either onshore and offshore.	Yes
Proton exchange membrane electrolysis (PEM)	Water-based electrical hydrogen production method. PEM electrolysis is the second most widely used electrolysis method. Production requires high amount of electricity and is often envisioned nearby renewable energy source, either onshore and offshore.	Yes
Gasification	A feedstock is converted to syngas under a controlled steam and oxygen process. Widely used and scaled production technique. Feedstock is often biomass, but fossil-fuels, waste and plastics can also be used.	Yes
Pyrolysis	A feedstock is heated in an anaerobic environment to create the desired bio-fuels. The temperature is lower than that of gasification. Feedstock is often vegetable oil or other biomass, but fossil-fuels, waste and plastics can also be used.	Yes
Electrolytic Haber-Bosch ammonia generation	Using hydrogen generated from electrolysis, the Haber-Bosch process is applied to generate ammonia from H2 (from electrolysis) and N2 (from air)	Yes
SMR Haber-Bosch ammonia generation	Using hydrogen generated from Steam Methane Reforming (SRM), the Haber-Bosch process is applied to generate ammonia from the generated H2 and N2 (from air)	Yes
Ammonia production using methane pyrolysis	Using hydrogen generated through methane pyrolysis, the Haber-Bosch process is applied to generate ammonia from the generated H2 and N2 (from air)	Yes
Hydrogenation-based chemical methanation	Carbon monoxide (from syngas) and carbon dioxide are converted into methane using hydrogenation with a chemical (nickel) catalyst (Sabatier reaction)	Yes
Hydrogenation-based biological methanation	Carbon monoxide (from syngas) and carbon dioxide are converted into methane using hydrogenation with a biological catalyst (Sabatier reaction). This process is more robust to impurities in feedstock than its chemical equivalent.	Yes
Hydrocarbon production based on Fischer-Tropsch process	The Fischer-Tropsch process is used to convert syngas (CO1 and H2) into liquid hydrocarbons, such as methanol. CO2 is used to generate CO1 using water-gas-shift reactions	Yes

Technology	Description	Selected for assessment in phase 2
Mobil Process	In a series of chemical reactions (Steam reforming, Water shift reaction and Synthesis) methane (from syngas or natural gas) is converted to methanol.	Yes
Anaerobic bacterial digestion	Biomass feedstock is broken down by bacteria in an anaerobic environment. Widely used methane production method, also called methanisation. Low lignocellulosic biomass if often used as input.	No, technology is already applied widely and is considered conventional.
Anaerobic fermentation	Bacteria or yeast convert a substrate of glucose into (m)ethanol. Low lignocellulosic biomass if often used as input.	No, technology is already applied widely and is considered conventional.
Food/vegetable oil transesterification	Biomass feedstock, in combination with ethanol and methanol is converted into methyl-esters (biodiesel)	No, technology is already applied widely and is considered conventional.
Lithium-sulphur battery	Rechargeable battery that consists of a lithium anode and a sulphur cathode submerged in an electrolyte. Electrons are not able to move through the electrolyte and provide the electric current. May replace lithium based batteries due to lower cost and higher energy density.	No, specific energy is too low to be considered a high quality renewable energy carrier. Technology is not developed sufficiently
Organic redox flow battery (organic RFB)	Rechargeable battery that converts chemical energy into electrical energy via reversible oxidation and reduction of organic working fluids, such as water.	No, specific energy is too low to be considered a high quality renewable energy carrier. Technology is not developed sufficiently
Solid-state-based battery	Rechargeable battery that uses an anode, cathode and a solid electrolyte, instead of a liquid electrolyte, and is used in combination with other batteries such as lithium-based batteries. Perceived to be safer in use than liquid electrolyte-based batteries.	No, specific energy is too low to be considered a high quality renewable energy carrier. Technology is not developed sufficiently
Salt water battery	Battery that consists of water storage tanks and membrane stacks. During charging, diluted salt water is separated into salt water and fresh water. By combining salt water and fresh water electrical energy is discharged and diluted salt water is produced.	No, specific energy is too low to be considered a high quality renewable energy carrier. Technology is not developed sufficiently
Lead-acid battery	Rechargeable battery that consists of an anode and cathode submerged in an electrolyte of sulfuric acid. Electrons are not able to move through the electrolyte and provide the electric current.	No, specific energy is too low to be considered a high quality renewable energy carrier

Technology	Description	Selected for assessment in phase 2
Sodium battery	Rechargeable battery that consists of an anode and cathode submerged in an electrolyte. Sodium-ions are used as charge carriers. Electrons are not able to move through the electrolyte and provide the electric current.	No, specific energy is too low to be considered a high quality renewable energy carrier
Nickel-based battery	Rechargeable battery that consists of a nickel anode and cathode submerged in an electrolyte. Electrons are not able to move through the electrolyte and provide the electric current.	No, specific energy is too low to be considered a high quality renewable energy carrier
Lithium-based battery	Rechargeable battery that consists of an anode and cathode submerged in an electrolyte. Lithium-ions are used as charge carriers. Electrons are not able to move through the electrolyte and provide the electric current.	No, specific energy is too low to be considered a high quality renewable energy carrier
Inorganic redox flow battery (inorganic RFB)	Rechargeable battery that converts chemical energy into electrical energy via reversible oxidation and reduction of inorganic working fluids, such as vanadium.	No, specific energy is too low to be considered a high quality renewable energy carrier
Electric double layer capacitor (EDLC)	The EDLC is a capacitor combined with an electrolyte, which provides a double layer. EDLCs usually use carbon electrodes and rely on an imbalance of electric charges within a material. EDLCs provide higher energy density compared with regular capacitors.	No, specific energy is too low to be considered a high quality renewable energy carrier
Pseudo capacitor	A capacitor combined with an electrolyte, which provides a double layer. Pseudo capacitors usually use conducting polymer electrodes and rely on chemical reactions to supply electric energy.	No, specific energy is too low to be considered a high quality renewable energy carrier
Hybrid capacitor	A capacitor which relies both on an imbalance of electric charges as well as chemical reactions to supply electrical energy.	No, specific energy is too low to be considered a high quality renewable energy carrier
Zinc-air battery	Mechanically rechargeable battery that consists of a zinc anode and carbon cathode submerged in an electrolyte. Electrons are not able to move through the electrolyte and provide the electric current.	No, specific energy is too low to be considered a high quality renewable energy carrier
Graphene enhanced Lithium-based battery	Lithium based batteries with components, such as electrodes, which are enhanced with graphene to enhance safety, power density and more properties of lithium based batteries.	No, specific energy is too low to be considered a high quality renewable energy carrier

Technology	Description	Selected for assessment in phase 2
Diabatic compressed air energy storage (CAES)	During periods of excess energy, air or another gas is compressed and stored under pressure. During periods of demand, the pressurized air is heated and expanded in a turbine driving a generator.	No, specific energy is too low to be considered a high quality renewable energy carrier
Adiabatic compressed air energy storage (A-CAES)	Same principle as CAES, however higher efficiencies are possible due to heat recovering during compression and reheating of the compressed air.	No, specific energy is too low to be considered a high quality renewable energy carrier
Geological compressed air energy storage	During periods of excess energy, air or another gas is compressed and stored in geologically subsurface under pressure. During periods of demand, the pressurized air is heated and expanded in a turbine driving a generator.	No, specific energy is too low to be considered a high quality renewable energy carrier
Industrial heat pumps	Heat pumps draw thermal energy from the environment to provide an efficient alternative to traditional heating methods	No, specific energy is too low to be considered a high quality renewable energy carrier
E-Boilers	E-boilers provide an electronic alternative to traditional gas-powered boilers. E-boilers are able to run on renewable electricity. If run on fossil energy, carbon emissions can exceed traditional gas boilers	No, specific energy is too low to be considered a high quality renewable energy carrier
Geothermal heat extraction	Naturally occurring hydrothermal sources are accessed through wells to generate a stable supply of heat. Availability of local geothermal sources necessary	No, specific energy is too low to be considered a high quality renewable energy carrier
Artificial reservoir heat storage	Artificial underground reservoirs of water are created and used to store energy in the form of heat	No, specific energy is too low to be considered a high quality renewable energy carrier
Fuel cells	A system that converts the chemical energy of a substance/fuel (such as hydrogen) in reaction with an oxidizer (such as air).	No, production of electricity is considered outside of scope
Rare earth mineral/circular design solar panel	Solar panels that are designed to use less (rare) earth minerals and can be reused in a circular fashion.	No, production of electricity is considered outside of scope

Technology	Description	Selected for assessment in phase 2
Hydrogen internal combustion	A type of engine comparable to traditional internal combustion engines, where hydrogen is burned instead of fossil fuels. It emits only water and oxygen.	No, product is not an energy carrier.
Electrified Oil cracking	Alternative to traditional oil cracking heating methods. Instead of gas furnaces, electric furnaces are used to heat up the hydrocarbons to be cracked	No, process is part of the long carbon cycle.
Direct Air capture of CO2	CCS: Removing carbon-dioxide from production processes before it enter the atmosphere and storing it. For example in geological formations.	No, output is not considered an energy carrier
Coal-assisted water electrolysis	Coal-catalysed electrical hydrogen production method. Coal is used to increase the resulting hydrogen production of the water electrolysis reaction.	No, not sufficiently developed technology. Process is part of the long carbon cycle.
Photo-electronical water splitting	Light-based hydrogen production method. Submerged photoelectrodes function as anode and cathode for water electrolysis. Potentially the cheapest method of hydrogen electrolysis due to the internal energy production from sunlight.	No, not sufficiently developed technology. No emission free process
Aqueous phase reforming	Biofuel-based hydrogen production method. Oxygenated feedstock materials are converted to hydrogen and CO2 in a low-temperature environment. Carbon monoxide levels in output are significantly lower than in traditional SR methods.	No, not sufficiently developed technology
Bio photolysis	Algae-based hydrogen production method. Algae convert water into hydrogen and oxygen gas in the presence of sunlight.	No, not sufficiently developed technology
Biomass fermentation	Bacteria-based hydrogen production method. Bacteria in the presence of light and acetic acid convert water into hydrogen and oxygen gas. Low lignocellulosic biomass if often used as input.	No, not sufficiently developed technology
Bio catalysed electrolysis/ Electrohydrogenesis	Bacteria-aided electrical hydrogen production method. Bacteria aid traditional hydrogen electrolysis by producing the protons and electrons needed for the reaction.	No, not sufficiently developed technology
Anion Exchange Membrane (AEM) water electrolysis	Water-based electrical hydrogen production method. AEM is still a developing technology.	No, not sufficiently developed technology
Solide oxide electrolysis (SoE)	Water-based electrical hydrogen production method. Higher electrical efficiency than Alkaline and PEM, but less well developed.	No, not sufficiently developed technology

Technology	Description	Selected for assessment in phase 2
Thermo-chemical water splitting	Thermal-based hydrogen production method. Heat is used to decompose water into hydrogen and oxygen gas.	No, not sufficiently developed technology
Ferrosilicon method	Chemical-based hydrogen production method. Hydrogen is generated through the reaction between ferrosilicon, sodium hydroxide and water. Popular is military used due to small generator size	No, not sufficiently developed technology
Micro-scale electrolyser	Water-based electrical hydrogen conversion method. A variety of small energy carriers, such as batteries, are used to create hydrogen form water.	No, not sufficiently developed technology
Enzymatic Hydrolysis	A process which enzymes facilitate the break-down of polysaccharides into monosaccharides. Input is lignocellulosic material from biomass sources. Low lignocellulosic biomass if often used as input.	No, not sufficiently developed technology
Microalgae bio-(m)ethanol	Modified cyanobacteria are used to directly produced ethanol from a biomass substrate, usually from low lignocellulosic biomass sources.	No, not sufficiently developed technology
Supercritical water gasification	Biomass feedstock is converted to hydrogen-rich syngas with the aid of supercritical water.	No, not sufficiently developed technology
Hydrolysis & fermentation	Hydrolysis is used to convert polysaccharides into free sugar molecules, such as glucose. Bacteria or yeast are used to convert free sugar molecules into (m)ethanol in an anaerobic fermentation process.	No, not sufficiently developed technology
Microalgae biodiesel production	Algae are used in a controlled environment of biomass substrate to create biofuel using light energy. Low lignocellulosic biomass if often used as input.	No, not sufficiently developed technology
Pumped Heat Electrical Storage	Surplus electricity is used to pump argon gas from a cold thermal storage to a hot thermal storage using a heat pump. When in demand of electricity, the flow is reversed and expansion of hot pressurized gas generates electricity.	No, not sufficiently developed technology
Hydrothermal Liquefaction (HTL)	HTL converts biomass into bio-crude oil in the presence of water/water-containing solvent and a catalyst.	No, not sufficiently developed technology
Aluminium redox system	To charge the redox system, electricity from renewable sources is used to transform/reduce aluminium (hydr)oxide to aluminium. During discharge, aluminium is oxidized releasing hydrogen, heat and aluminium (hydr)oxides to be charged again. Hydrogen could then be converted into electricity.	No, not sufficiently developed technology
Iron (powder) combustion system	Iron powder is combusted and releases thermal energy. This iron powder oxidizes into iron oxides (rust). This rust can be transformed to iron again by reacting with hydrogen.	No, not sufficiently developed technology

Technology	Description	Selected for assessment in phase 2
Magnesium energy cycle system	Magnesium generates hydrogen when it combusts in reaction with water and the magnesium transforms into magnesium oxide after combustion. With the aid of sunlight laser, the magnesium oxide transforms into magnesium again to be combusted again.	No, not sufficiently developed technology
Solid State Ammonia Catalysis (SSAS)	Water and the nitrogen from the air is, in a similar process to electrolysis, combined to form oxygen gas and ammonia. Process is more energy efficient then Haber-Bosch based methods, since no source of hydrogen is required.	No, not sufficiently developed technology
Concentrated Solar Synthesis	Syngas (CO and H2) is created in a reactor based on a CO2 photocatalytic conversion. The required high temperature is provided by solar energy, by concentrating sunlight on the reactor with reflectors.	No, not sufficiently developed technology
Direct CO2 to DME	Dimethyl ether has similar properties as LPG. DME can be produced directly in a reactor, by combining Syngas or CO2 and hydrogen.	No, not sufficiently developed technology
Methanol dehydration	Dimethyl ether has similar properties as LPG. DME can be produced indirectly by first producing methanol, which is subsequently dehydrated.	No, not sufficiently developed technology
Depolymerization/Solvolysis	The process where polymers, such as plastics, are reduced to smaller compounds. This process can be subdivided to other technologies in this longlist, such as pyrolysis and hydrolysis.	No, not sufficiently developed technology
Dissolution (Purification)	Polymers are slowly reduced to smaller compounds by submerging them in solvents, which can be filtered and purified after complete dissolution. The smaller compounds can be used in further processes.	No, not sufficiently developed technology
Steam reforming (SR)	Fossil fuel-based hydrogen production method. Currently the most widespread and cheapest technique. Feedstock usually comprised of natural gas	No, no emission free process without CCS
(Catalytic) partial oxidation (CPOX)	Fossil fuel-based hydrogen production method. Raw materials, often oil or (bio)gas is gasified near oxygen to create hydrogen and carbon monoxide gas.	No, no emission free process without CCS
Autothermal reforming (ATR)	Fossil fuel-based hydrogen production method. ATR combines SR and CPOX techniques whilst not requiring external heat input, therefore reducing cost	No, no emission free process without CCS
Water-gas shift POX (WGS)	Fossil-fuel based hydrogen production method. WGS uses SR techniques, but reduces carbon monoxide output and increases hydrogen concentration in output gas.	No, no emission free process without CCS

Technology	Description	Selected for assessment in phase 2
Biomass gasification	Biofuel-based hydrogen production method. Biomass such as animal/food waste, crops or plant products are converted to hydrogen and carbon monoxide gas (syngas). Hydrogen is extracted afterwards to create hydrogen gas.	No, low impact for net-zero emissions
Biomass pyrolysis	Biofuel-based hydrogen production method. Feedstock materials are gasified in an anaerobic environment, creating hydrogen gas and solid carbon as output. This process includes Torrefaction, which is a form of pyrolysis at lower temperatures	No, low impact for net-zero emissions

Annex 3: Assessment per technology (Phase 2)

This annex includes the full assessment for phase 2 for the following technologies:

- Alkaline and PEM electrolysis
- Gasification
- Biomass and methane pyrolysis
- Hydrogenation based and chemical and biological methanation
- Mobil process (methanol to X)
- Hydrocarbon production based on Fischer-Tropsch process
- Electrolytic Haber-Bosch ammonia production

Alkaline and PEM eletrolysis

Scope and introduction

1. Proton exchange membrane (PEM) electrolysis
2. Alkaline electrolysis

The experts that were consulted for this assessment highlighted the potential of a third electrolysis technology: Solide-Oxide Electrolyser Cells (SOEC). SOEC electrolyser technology shows promising results, among which are a higher efficiency than PEM and Alkaline, as well as its ability to use waste heat streams in its production process.

Rotterdam currently hosts the largest working SOEC demonstration plant (2.6 MW), under the project MultiplHy[66]. While larger SOEC installations up to 500MW are underway in other countries such as Denmark[67], SOEC is not currently at the phase of large gigawatt-scale utilisation in the Netherlands. Therefore, it is not further included in this assessment. Nevertheless, experts advise that SOEC not be discarded as a potential hydrogen production method once the technology matures further.

Defining differences between PEM and Alkaline electrolysis

The tables below give an overview of some key performance and cost estimates for PEM and Alkaline electrolysis. Data from these tables will also be referenced in other sections of the assessment.

The general difference between PEM and Alkaline is that currently Alkaline electrolysers are cheaper to manufacture, but with a lower average yield and lifetime. Alkaline electrolysers can be made predominantly using accessible materials such as nickel, although some rare raw materials are still needed. Additionally, Alkaline electrolysers are somewhat bulkier and are less well-suited to sudden large changes in operating rate.

PEM electrolysers on the other hand are currently more expensive to manufacture, but have a higher average yield compared to Alkaline. The increased cost are in part due to the rare raw materials that PEM requires, iridium in particular. Literature[68], as well as the consulted experts, states that solving PEM's dependency on iridium is key to its scale-up potential.

In practice, Alkaline and PEM electrolysers do not differ much. Once installed, both technologies function the same. Table 0.4 also shows that the differences in cost and efficiency are likely to reduce as well. What will be left to discern the technologies are technical differences such as the current density, specific volume and ramp speeds. However, experts note that these differences are only meaningful in a handful of possible use cases.

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66 MultiplHy (2020). Green hydrogen for renewable products refinery in Rotterdam, link

67 Renewables now (2022). Topsoe takes FID for 500 MW/year SOEC electrolyser plant in Denmark, link

68 Minke, C., Suermann, M., Bensmann, B., & Hanke-Rauschenbach, R. (2021). Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?, link

Table 0.3 Key characteristics, based on IRENA analysis[69]

	2020		2050	
	PEM	Alkaline	PEM	Alkaline
Cell pressure (bara)	<70	<30	>70	>70
Efficiency (kWh/kgH_2)	50-83	50-78	<45	<45
Lifetime (thousand hours)	50-80	60	100-120	100
Full installation capital costs (> 1 MW stacks) (USD/KW_{el})[70]	700-1400	500-1000	<200	<200

Table 0.4 additional characteristics of PEM and Alkaline electrolysis[71] [72]

	PEM	Alkaline
Current density (A/m^2)	10000-20000	2000-4000
Key materials for cell production	Iridium anode catalyst, platinum cathode catalyst Titanium anode, Carbon cathode,	Nickel anode & cathode, Zircon separator
Corrosion	Less corrosion than alkaline	Alkaline corrosion
Volume and weight	1/3 of alkaline electrolyser	Reference value
Ramp-up/down speed (% of full load/second)	10%[73]	0.13%-10%[74]

The technology is necessary in a climate neutral society

i. Bandwidth of market share in climate neutral society

Hydrogen's high energy density and lack of carbon emissions when burned make it one of the prime contenders for being the energy carrier of a climate neutral society. This potential is reflected in its use in several key scenario studies, such as by Berenschot & Kalavasta (2020)[75]. By 2050, some scenario's reach an installed peak electrolysis capacity in the Netherlands in the range of 45 GW. Primarily PEM electrolyse is cited as a technology to fill this capacity due to its potentially higher process efficiency, although the research does acknowledge that this is uncertain.

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69 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

70 Cost projections for 2050 as stated by IRENA are not conclusive in all literature. TNO expects a higher price and different reduction profile (link).

71 Guo, Y., Li, G., Zhou, J., & Liu, Y. (2019). Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis, link

72 Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis–A review, link

73 Cartner, N, O'Sullivan, T., Nolan, T. & Saba, E. (2020). Flexibility of Hydrogen Electrolysers – Opportunities in the Australian National Electricity Market, link

74 Basha Syed, M. (2021). Chapter 6 – Technologies for renewable hydrogen production in Bioenergy Resources and Technologies, link

75 Den Ouden, B., Kerkhoven, J., Warnaars, J., Terwel, R., Coenen, M., Verboon, T., Tiihonen, T. & Koot, A. (2020), Klimaatneutrale energiescenario's 2050, link

In anticipation to the rapid growth in hydrogen use, goals have been set in place in terms of generation capacity. The ambition is to have 500 MW of electrolysis-based hydrogen production in 2025, which increases to 3 to 4 GW in 2030[76]. Recently the cabinet has undertaken steps to increase this goal further to 6-8 GW in 2030[77]. In addition, construction has started on a national hydrogen transportation network[78]. Specific electrolysis technologies and their accompanying scale to use for the production of hydrogen have thus far not been specified.

The technology is ready for scale up, but needs government help to do so

i. Technology is sufficiently developed and tested in pilot-phase

Alkaline electrolysis is currently the cheapest and most used form of water electrolysis. The technology is well understood and has been used for many years.

PEM electrolysis is a well-understood, yet compared to alkaline less commercially applied electrolysis technique. Currently, PEM electrolysers make up 40% of the global hydrogen electrolysis capacity compared to 60% alkaline[79]. This difference is expected to equal out on the medium term
Given its potential for scalability and the absence of carbon in the production process, PEM electrolysis will be able to significantly contribute to the Dutch hydrogen production goals.

Multiple electrolysers have already been installed across the Netherlands and Europe. For example:

- A 10 MW PEM-installation by GreenH2UB in North-Brabant (not currently operational)[80];
- A 10 MW PEM-installation by Project Refhyne in the Rhineland in Germany;
- PEM electrolysis is also being considered as a production technology for the proposed 100 MW project H2ermes at Tata Steel, IJmuiden.

Alkaline electrolysis installations are also already being deployed, but on a larger scale. For example:

- A 1.4 MW Alkaline installation by Alliander in Oosterwolde[81]
- In Europe, the project $H_2$4All has presented plans to build a 100 MW Alkaline electrolysis plant[82];
- China is implementing several large scale Alkaline electrolysis plants, among which are Alkaline hydrogen plants up to a capacity of 300 MW[83];
- Alkaline electrolysis is also being considered as a production technology for the proposed 100 MW project H_2ermes at Tata Steel, IJmuiden[84].

76 Rijksoverheid, Overheid stimuleert de inzet van meer waterstof, link.
77 Nationaal Waterstof Programma (2022), Routekaart Waterstof, link
78 Nationaal Waterstof Programma (2022), Routekaart Waterstof, link
79 IEA (2022), Global Hydrogen Review, link
80 De Laat, P. (2022), Overview of Hydrogen Projects in the Netherlands, link
81 Alliander (2020). Deense elektrolyser maakt waterstof in Oosterwolde, link
82 H24All project seeks to build Europe's first 100MW alkaline electrolyser plant (2021), link
83 Farmer, M. (2021) Sinopec commits $470m to 300MW hydrogen electrolyser in China, link
84 Een groene economie binnen handbereik, link

ii. Current government support schemes for demonstration projects are insufficient

Several funds exist for the purpose of supporting the research, development, deployment and scaling of hydrogen projects. Examples include the 'Grant Scheme for Upscaling Hydrogen Production through Electrolysis'[85] (€250 million), GroeifondsNL[86] (€338 million) and the EU IPCEI hydrogen[87] (€783.5 million). The availability of funds coincides with a myriad of hydrogen electrolysis demonstrations in the Netherlands, of which 150+ have been listed by scale, category and process phase by Topsector Energie[88]. Based on this we conclude that there exists ample funding to support an increase in the number of demonstration projects.

Demonstrations of PEM and alkaline electrolysis almost completely concern onshore installations. Recent studies and developments are highlighting the potential of moving electrolysis production offshore. By directly converting electricity from offshore windfarms to hydrogen on site, the energy carrier to be transported back to the mainland would become a (more cheaply transportable[89]) gas instead of electricity.

When examining the potential for offshore electrolysis, experts describe two possible pathways for the technology. Firstly, the mimicking of onshore electrolysis, by placing large electrolysers on platforms, which can produce hydrogen directly from offshore wind energy. Pilots by H_2opZee[90] and PosHydon[91] fall into this category. Similar techniques to onshore electrolysis can be used in this case. Secondly, technology can be developed to fully integrate electrolysers into wind turbines. This would create offshore wind turbines that are fully optimised for hydrogen production and output no electricity. Pilots for demonstrating turbines with integrated electrolysers are currently being developed by Siemens[92]. While experts point out that this optimisation can bring efficiency benefits, this type of integrated electrolysis cannot be viewed as similar to onshore variants.

Experts highlight the fact that in order for electrolysis subsidies to increase their effectivity, There must be a greater emphasis on the sharing of learnings between the demonstration projects. Increasing communication between various demonstration projects is one of the key drivers of technological advancement[93]. Projects such as EMP NL[94] encourage such knowledge sharing. However, current support schemes run the risk that the private endeavours that utilize these support schemes deliberately limit knowledge sharing, in order to gain a competitive advantage.

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85 Rijksdienst voor ondernemend Nederland (2022), Consultatie en vragenuurtjes opschalingsregeling waterstof via elektrolyse, link

86 Q&A Groenvermogen NL, link

87 Rijksdienst voor ondernemend Nederland (2022), IPCEI Waterstof: Waterstofproductie door elektrolyse, link

88 De Laat, P. (2022), Overview of Hydrogen Projects in the Netherlands, link

89 Groenemans, H., Saur, G., Mittelsteadt, C., Lattimer, J., & Xu, H. (2022). Techno-economic analysis of offshore wind PEM water electrolysis for H2 production., link

90 RWE (2022), H2 op zee, link

91 PosHYdon, Over PosHYdon, link

92 Siemens Gamesa, Green hydrogen – fuel for the future, link

93 TNO (2020), European RTOs: accelerating development of electrolysis, link

94 EMP NL (n.d.), over ons, link

iii. Market introduction at large scale is not commercially viable

Cost estimations for large scale PEM and Alkaline electrolysers are given in table 1. The costs of these installations are an important factor in determining the resulting price of electrolyser-based hydrogen. Another important factor is the price of hydrogen. Irena[95] estimates that, if rapid scale-up is to take place, green hydrogen from PEM and Alkaline electrolysis will be able to compete with blue hydrogen by 2030. However, the main contributing factor to the competitiveness of electrolysis-based hydrogen was found to be the price of electricity ('cost reductions in electrolysers cannot compensate for high electricity prices' (Irena)).

In order to compensate for the unprofitable business case of scaling up hydrogen, the Dutch government provides additional subsidies through the SDE++ subsidy[96]. However, the instrument has proven to be too limiting for large electrolysis scale-ups, as none have formed as of yet following the release of the subsidy.

Regarding the market introduction of electrolysis at large scale, experts highlight the following facets that can affect this process:

- **The height of electrolysis OPEX is the primary limiter for market introduction on the short term, which shifts to CAPEX on the long term.** Currently the higher OPEX of electrolysis compared to fossil based hydrogen from Steam-methane reforming (SMR) limits the viability of business cases for large scale hydrogen electrolysis. The OPEX is dependent on the price of renewable electricity and is expected to come down. However, experts highlight that due to material shortages and the current energy crisis in the EU, previously made cost reduction targets for electrolysis in the short term are no longer realistic. This affects the capacity targets on the short term (2025). In the long run renewable electricity costs are expected to come down substantially. The business case viability then switches to depending on a favourable CAPEX. Availability of components, and per extension raw materials, are important external factors at this stage.

  For integrated offshore wind-to-hydrogen projects, the CAPEX and OPEX of the electrolysers can be included in the larger tender.

- **A limited production supply of electrolysis components can form a bottleneck when trying to scale up electrolysis plants**. In order for subsidy schemes to be more effective at reaching the goals for electrolysis capacity for 2025 and 2030, the development of the entire supply chain for electrolysis technology must be supported.
- **International differences in green energy availability may influence business case viability on the long term**. Electrolysis is ultimately a conversion method for renewably produced electricity. Geographical differences between countries result in some countries having a permanent comparative advantage in producing green electricity. Examples of this include the availability of large dams for hydropower, or latitude differences making solar panel yield higher near the equator. While electrolysis plants can be built on a large scale in the Netherlands if desired, some other countries will retain advantages in electricity production and price.

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95 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

96 Elzenga, H., Pisca, I. & Lensink, S. (2021), Conceptadvies SDE++ 2022 Waterstofproductie via elektrolyse, link

Government intervention at this stage of the technology's development is effective

i. Cost reduction that can be achieved by scaling up, per cost category

The costs of Alkaline and PEM electrolysis are expected to fall substantially, as shown in table 2. Irena estimates PEM and Alkaline electrolyser costs to come down around 40% in the short term and up to 80% in the long term[97]. The key drivers behind this cost reductions are stated to be technological innovation, scaling up manufacturing processes, standardisation and economies of scale. Any differences in cost between PEM and Alkaline are expected to reduce over time due to innovation and market functioning converging towards an optimum[98].

Many factors influence the price of hydrogen, including the scale of the production facilities and the demand for hydrogen. Given the ever-reducing cost of green electricity and the expected increase of demand, a market estimate by PWC expects the price of green hydrogen to fall by around 30%[99] in 2030 and 63%[100] in 2050 compared to current prices. An important factor to consider here is the comparison of green hydrogen prices, which currently hover around the €3-8 range, and fossil-based hydrogen prices, currently at around €2. Provided the proper measures are taken in cost reduction for green hydrogen as listed above, green hydrogen would be able to compete with fossil based hydrogen on price. If cheap renewable electricity becomes available on the short term, green hydrogen could come down to a competitive $1.5/kgH$_2$ by 2025[101]

When asked to reflect on cost reduction of electrolysis and the role that the Dutch government can play in this, experts highlight the following points.

- **CAPEX can be reduced by the standardisation and automatization of the supply chain, as well as further research in more efficient material use.** The government can play a role in reducing the CAPEX by stimulating Dutch electrolysis component manufacturers. Not only will this bring the cost down, but a Dutch supply chain enables the government to enact standards of quality and circularity that could influence the wider European (and worldwide) market.
- **OPEX can be reduced primarily by the gradual lowering of renewable energy prices, alongside enabling longer cell lifetime and a higher amount of full load hours per year.** The government has limited capacity in affecting the price of electricity aside from increasing wind and solar capacity. However, it is possible to adapt current subsidy schemes to allow a higher amount of full load hours.
- **The Netherlands has the potential to position itself as a key manufacturer of high quality electrolysers.** Experts point to the potential for the Netherlands to be a large market player in the supply chain. The European commission has previously expressed the strategic importance of developing a strong electrolysis supply chain in Europe[102]. Because the supply chain scaling is still in an early enough stage, the Netherlands is able to position itself as a key manufacturer of complex electrolysis components ('The ASML of

[97] IRENA (2021), Making the breakthrough: Green hydrogen policies and technology costs, link
[98] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link
[99] IEA (2019), The Future of Hydrogen, link
[100] PWC, The green hydrogen economy, link
[101] European Partnership for Hydrogen Technologies (2022). Strategic Research and Innovation Agenda 2021 – 2027, link
[102] Strategic Research and Innovation Agenda 2021-2027, link

electrolysis'). Furthermore, this enables the Dutch industry to set standards for electrolysis that go beyond price, such as circularity and material use.

Government intervention will have deep and broad impact

i. Bandwidth of market size for the technology after scale up

Given the higher capital cost of PEM electrolysis compared to Alkaline, a market without any intervention would be expected to further develop towards improving alkaline technologies. PEM electrolysis could only take up a smaller market share because of this reason. However, the assisted scale-up of PEM electrolysis could relieve the capital cost issues. Once operational, PEM's higher efficiency will enable the technology to be competitive with alkaline. Thus, a larger market share for Alkaline is expected in the short term, with the difference reducing in the long term. This coincides with the differences in cost between PEM and Alkaline reducing over time due to innovation and market functioning converging towards an optimum[103].

When discussing the market share that PEM and Alkaline may take relative to each other, experts note that a technology lock-in can occur nationally according to the road that is taken early on in the scale-up process. The costs of PEM and Alkaline are estimated to converge towards similar efficiency levels over time. However, the larger scaling up of one supply chain (e.g. PEM) over another can impact the market share greatly. Larger investments in one particular technology can give it a permanent advantage during later stages of scale-up.

ii. Bandwidth of market size for the technology output after scale up

Hydrogen is a high-density energy carrier that can be created using a widely available, carbon-free input: water. The EIA has identified hydrogen as a prime contender to be a promising energy carrier for a CO_2-neutral energy infrastructure[104]. In addition, large scale plans for hydrogen infrastructure are already being developed in the Netherlands[105]. Given its applicability in industry, transport and energy storage, the market size of hydrogen could reach scales similar to the current natural gas market.

The experts made the following remarks regarding the development of the market:

- **Clarity in spatial planning early in the scale-up phase can prevent inhibitory system bottlenecks.** Governing institutions and their subsidy schemes can take a stronger guiding role in the spatial distribution of electrolysis capacity. This means not only laying out the transport infrastructure for hydrogen, but actively working with electrolysis stakeholders regarding where the production will be placed. By doing this, necessary transport infrastructure can be created or strengthened in a more efficient manner. Hydrogen is ideally produced closely to where it is needed. If spatial capacity distribution is left to the market, the Netherlands run the risk of congestion situations similar to the issues that affect solar capacity rollout.

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103 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, link

104 IEA (2019), The Future of Hydrogen, link

105 Gasunie, Waterstofnetwerk in Nederland, link

iii. Applicability in number of end-user sectors after scale up

Hydrogen is applicable in a range of sectors. In industry, hydrogen-based heating installations are more easily able to replace current natural-gas based heating processes compared to electric solutions. In the transport sector, the high energy density of hydrogen compared to electrical battery storage gives hydrogen a distinct advantage for applications such as freight transport over roads and inland waterways. In the energy sector, hydrogen can be used as a large-scale buffer to balance supply and demand. As the Dutch electricity mix moves further away from fully flexible fossil-based production, this need for (hydrogen) balancing capacity will likely increase.

Assessment summary

Table 0.5 Assessment summary of electrolysis

Criterion	Indicators	Assessment
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	Yes, widespread adoption in multiple sectors.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, alkaline and PEM electrolysis are sufficiently developed.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes; SDE++, GroeifondsNL, GSUHPE106, EU IPCEI hydrogen are sufficient for demonstration and limited scale up. Scale up to national scale requires more support.
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes
Government intervention at this stage of the technology's development is effective	Cost reduction that can be achieved by scaling up, per cost category	Yes
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Larger market share of Alkaline relative to PEM on the short term, with the difference reducing on the long term.
	Bandwidth of market size for the technology output after scale up	Widespread adoption
	Applicability in number of end-user sectors after scale up	Industry, chemical industry, freight transportation, energy (grid balancing)

[106] *Grant Scheme for Upscaling Hydrogen Production through Electrolysis*

Criterion	Indicators	Assessment
		Industry, chemical industry, freight transportation, energy (grid balancing)

Gasification

Scope and introduction

Specific technologies

- Entrained flow gasification
- Supercritical water gasification
- Fluidised bed gasification
  - Indirect (dual fluidised bed) technology
  - Bubbling fluidised bed technology
  - Circulating fluidised bed technology

Literature suggests that fluidised bed gasification currently has the most potential for large-scale application. Other technologies, such as Entrained Flow gasification and supercritical water gasification[107] are considered too immature for scaling up production of energy carriers, but look promising in the longer term.[108] Biomass gasification techniques are especially relevant for the hard-to-abate sectors, such as aviation, shipping and as a replacement for natural gas, because of the carbon content of the biomass. Also, biomass gasification can be relevant for the production of hydrogen, because the gases produced by biomass gasification can be used as intermediates in high-efficiency power generation and in the synthesis of chemicals and fuels.[109,110]

Introduction

Gasification is a process that converts biomass and other materials that include carbon into gases. The largest shares involve nitrogen, carbon monoxide, hydrogen and carbon dioxide. The process involves reacting the biomass at high temperatures (usually over 500 °C), while controlling the amount of oxygen and steam. The output of the process is known as syngas (synthetic gas) and can directly be used as a fuel. After upgrading, it could also be used in the production of methanol and hydrogen, or converted to synthetic fuels using the Fischer-Tropsch process. The resulting hydrocarbons remain important in a climate-neutral society as feedstock for the (chemical) industry. Additionally, carbon-based fuels could remain useful in situations where an energy dense fuel is required, for

[107] Boukis & Stoll (2021). Gasification of biomass in supercritical water, challenges for the process design—lessons learned from the operation experience of the first dedicated pilot plant, link

[108] IEA Bioenergy (2020). Emerging Gasification Technologies for Waste and Biomass, link

[109] Al Nashrey, A. (2022). Comprehensive Overview of Hydrogen Production via Coal and Biomass Gasification Technologies, link

[110] El-Shafay, A. S., Hegazi, A. A., El-Emam, S. H., & Okasha, F. M. A Comprehensive Review of Biomass Gasification Process, link

example aviation fuel. Gasification has been sufficiently developed, but requires (government) support to scale up.

The technology is necessary in a climate neutral society

Bandwidth of market share in climate neutral society

Gasification has been identified by the Dutch government as one of the prime contenders for being a promising technology in a climate neutral society.[111] It unlocks the potential of transforming waste to produce high value gases (CH4, H2, NH3), fuels (MeOH, FT) and chemicals (MeOH, BTX). The technology is expected to contribute 'several Mtonnes' of CO_2-reduction in 2030.[112] Gasification is one of two key technologies that can process biomass, the other being pyrolysis. In a climate neutral society, where no carbon is emitted, carbon will become scarce. Technologies that process biomass can become an energy source of carbon, that we need for a wide variety of chemical processes. The other option is carbon from direct-air capture, but that is an energy intensive process.

In a quantitative study on a climate neutral energy system, Berenschot and Kalavasta assume that by 2050 50% of the conversion of biomass to green gas will be via supercritical water gasification and 50% via fermentation.. The allocation of biomass to biofuels ranges from 21 PJ to 174 PJ in 2050. However, simultaneously they indicate the share of supercritical water gasification as compared to other developing gasification technologies is based on very optimistic assumptions.[113]

The main feedstocks which are likely to have a significant impact on the transition to net zero will be biomass and residual MSW/C&I (municipal solid waste and commercial and industrial) waste. This is because both of these feedstocks are generated in significant quantities.[114] However not significant enough to replace all fossil fuel use. Import is therefore a topic which the Netherlands need to consider if our aim is to have a strong chemical sector here.

Gasification is likely to acquire a significant market share for its ability to produce syngas, an intermediate-good that is the basis for many upgrading processes. It is the first and crucial link in the chain from biomass to any carbon molecule used either as fuel or feedstock for other industries.

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111 Studiegroep Invulling klimaatopgave Green Deal (2021). Bestemming Parijs. Wegwijzer voor klimaatkeuzes 2030, 2050, link

112 Planbureau voor de Leefomgeving (2022). Klimaat- en Energieverkenning, link

113 Berenschot & Kalavasta (2020). Klimaatneutrale energiescenario's 2050 – scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, link

114 UK Government, Department for Business, Energy and Industrial Strategy (2021). Advanced Gasification Technologies - Review and Benchmarking, link

The technology is ready for scale up, but needs government help to do so

Technology is sufficiently developed and tested in pilot-phase (y/n)

Biomass gasification is demonstrated and is implementer commercially for direct production of electricity and heat through production of biogases.[115]

Dual fluidized bed gasifier (DFBG, also called fast internally CFB technology) is a technically proven technology that has already been implemented at demonstration scale and has been identified as a promising biomass gasification technology, especially for the production of high-quality syngas. Among the biomass gasification technologies, these gasifiers are the preferred type of reactors as these require small feedstock particle sizes which allow for rapid heat and mass transfer and good conversion of feedstock to syngas. Additionally, these gasifiers can also use larger particle sizes, creating a significant benefit to other gasifiers.[116]

Gasification under the conditions of **supercritical water** is a promising process for the conversion of wet waste biomass and wastes. It is suitable for decentralized (medium size) applications but has yet to be demonstrated with various feed materials. Several technical issues still have to be overcome.[117] Even though progress has been made in supercritical water gasification of biomass in recent years and this technology seems to be very interesting especially for wet biomass, technical solutions for large-scale commercial installations still **need to be developed**.[118] SCWG of biomass has been now investigated for decades and represents not a new technology**, however industrial scale SCWG of biomass is not existent and pilot plants encounter several problems due to the biomass pumpability and the high-pressure conditions**.[119]

Current government support schemes for demonstration projects are insufficient (y/n)

In the Netherlands two programmes under TKI New gases (*TKI Nieuw Gas*) aim to install two demonstration facilities for thermochemical gasification and supercritical water gasification.[120] The DEI+-scheme for 'hydrogen and green chemicals' is fully utilised for 2022.[121] The full utilisation of the scheme suggests there is interest in developing these technologies further, but likely is insufficient for scaling up.

The production of syngas via thermal gasification of biomass has not yet been demonstrated on an industrial scale in the Netherlands. However, extensive experience has been gained in several pilot plants, such as within the Ambigo project and the Torrgas project. This puts the

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115 Calì Deiana,Bassano, Meloni, Maggio, Mascia, & Pettinau (2020). Syngas production, clean-up and wastewater management in a demo-scale fixed-bed updraft biomass gasification unit, link

116 Richardson, Y., Drobek, M., Julbe, A., Blin, J., & Pinta, F. (2015). Biomass gasification to produce syngas, link

117 Boukis & Stoll (2021). Gasification of biomass in supercritical water, challenges for the process design—lessons learned from the operation experience of the first dedicated pilot plant, link

118 Heidenreich, S., Müller, M., & Foscolo, P. U. (2016). *Advanced biomass gasification: New concepts for efficiency increase and product flexibility*. Academic Press, link

119 De Blasio, C., & Järvinen, M. (2017). Supercritical water gasification of biomass, link

120 TKI Nieuw Gas (n.d.). Vergassing, link

121 Rijksdienst voor Ondernemen (2022). DEI+: waterstof en groene chemie link

current TRL at 6 - 7 in the Netherlands.[122] Gasification of coal and MSC/C&I are mature technologies that are commercially viable.

The main issue with demonstration facilities (in the Netherlands) is that these have high capital expenditures (CAPEX) and cannot run economically viable at first. Current subsidy schemed in the Netherlands, such as the SDE++, insufficiently support the necessary push and scale-up for gasification technologies. According to the experts, it would be more beneficial to reduce the risk of operating such a plant. Arguably, for scaling up the technology it would be more beneficial the facility would not run with a closed business case, but would reduce the risk and de-bottleneck future facilities.

Internationally, production of syngas **has been demonstrated using bubbling fluidised bed (BFB)** gasifiers at plant capacities up to 100,000 tpa.[123] Other known international projects of fluidised bed gasification can be found in the table below.

Table 0.6 Known demonstration projects of fluidised bed gasification technologies:[124]

Technology supplier	Feedstock	Product	TRL
Advanced Biofuel Solutions Limited	refuse derived fuel (RDF)	Methane	6
Enerkem	RDF	Methanol and ethanol	8
GoBiGas	Biomass	Methane	8
Kew Technology	Densified RDF	Electricity, H2 and fuel	6
Sumitomo Foster Wheeler	Biomass	Renewable diesel	7
Enerkem Alberta Biofuels LP[125]	Biomass	chemical-grade syngas, methanol, ethanol, and other chemicals	8

Market introduction at large scale is not commercially viable, even including existing government support schemes (y/n)

The Subsidy Scheme Sustainable Energy Production and Climate Transition (SDE++) includes an option for gasification of biomass for the production of syngas and biomethanol.[126] Though EUR 2.8 mln has been spent on the stimulation of low-CO_2 technologies in 2021 and 2022, in practice the technologies cannot compete with conventional technologies using fossil fuels, thus preventing successful commercial use.

Globally, the production of syngas via thermal gasification of biomass on an industrial scale demonstrated at GoBiGas' 20 MWSNG plant in Sweden. This makes the estimated TRL 8. In addition to the GoBiGas project, there are (or were) a number of initiatives for larger plants of 100 - 200 MWSNG, for which thorough engineering studies have been conducted. Examples include E.ON's Bio2G project in Sweden and the initiative of SunGas Renewables in California (US).

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122 BTG (2021). Technische status en perspectief van biomassavergassing in Nederland, link
123 Vargas-Salgado, Montuori, & Alcázar-Ortega (2021). Experimental analysis of a bubbling fluidized bed gasification plant fed by biomass: Design, implementation and validation of the control system, link
124 UK Government, Department for Business, Energy and Industrial Strategy (2021). Advanced Gasification Technologies - Review and Benchmarking, link
125 Alptekin, F. M., & Celiktas, M. S. (2022). Review on Catalytic Biomass Gasification for Hydrogen Production as a Sustainable Energy Form and Social, Technological, Economic, Environmental, and Political Analysis of Catalysts, link
126 Planbureau voor de Leefomgeving (2022). Eindadvies basisbedragen SDE++ 2022, link

One commercial facility using bubbling fluidised bed gasification will be installed in Port of Rotterdam and upgraded to use for the production of Sustainable Aviation Fuel (SAF). With favourable support under Renewable Transport fuels regulations expected, the production of SAF from low-grade, post-recycling mixed waste has become an option. In light of the above – and given the capacity for Enerkem, together with Shell, to provide an end-to-end technical solution for converting hard-to-recycle waste into jet fuel by combining Enerkem's waste gasification technology and Shell's **Fischer-Tropsch technology** – the partners in the project have decided to repurpose the current project to focus on SAF production. The project would process up to 360,000 tonnes per annum of recycling rejects and produce up to 80,000 tonnes of renewable products, of which around 75% could be SAF and the remainder used for road fuels or to feed circular chemicals production.[127] Final Investment Decision has been taken in 2021.[128]

Globally, commercial deployment of these technologies is yet to occur, and the number of technology developers is limited. The largest demonstrator (115,000 tpa) is in operation in Edmonton, Canada and is fuelled by RDF for the production of methanol. The first commercial scale plant (175,000 tpa) is currently under construction in Nevada, USA and will convert RDF to FT fuels. Commissioning of this plant is expected to begin in Q3, 2021. A second commercial scale plant (165,000 tpa) to produce FT fuels from forestry residues is being constructed in Oregon, USA.[129] Plans for another commercial scale plant with a throughput capacity of 200,000 tpa have been announced for Varennes, Canada. Commissioning of the plant is scheduled for 2023.[130]

However, many of these plants have been operated in campaigns or for a limited number of operating hours and have not been operated continuously over several thousand hours. Consequently, many process control, process integration and operational issues are yet to be encountered and assessed. These will need to be resolved before stable long term operation can be achieved.

Gasification facilities can run commercially viable, however requires a significant investment and thus goes hand in hand with a high risk. The economies of scale improve with larger facilities, but this goes hand in hand with high CAPEX as well as risks involved. The experts argue that successful scale-up requires an intermediate step where the technology is developed further and economies of scale are applied, but likely not profitable at first.

On this basis, it is evident that these technologies are in the early stages of deployment and significant development of these technologies is necessary before successful commercial operation is achievable.

[127] Enerkem (2021, June 8). From Waste-to-Chemicals to Waste-to-Jet, link
[128] Shell (2021, September 16). Shell to build one of Europe's biggest biofuels facilities, link
[129] Babcock (n.d.). Open bottom bubbling fluidised bed technology designed for biomass firing, link
[130] UK Government, Department for Business, Energy and Industrial Strategy (2021). Advanced Gasification Technologies - Review and Benchmarking, link

Government intervention at this stage of the technology's development is effective

i. Cost reduction that can be achieved by scaling up, per cost category

In a study for the government of the United Kingdom, cost reduction for large-scale application for various outputs (such as hydrogen, methanol and Fischer-Tropsch fuels) is shown based on demonstration facilities. It can be concluded that large-scale application does result in a cost reduction. However, even in these facilities remain at the high end of the range, being up to approximately three times higher than the current cost of production using the established SMR of natural gas technology, significantly harming the incentive to develop the technologies further at this point. Further costs associated with the emission of CO2 will improve this business case in the near future. In general, it is shown that due to the large differential in feedstock cost, the waste plants have a significantly lower levelized cost of product (LCOX) than biomass plants.[131]

A study conducted by Poluzzi et al. (2022) indicates that, using different gasification technologies, the methanol breakeven selling prices range between 545 and 582 €/t with the current reference Denmark electricity price curve (yearly average electricity price of 38.5 €/MWh, average electricity price in the enhanced operation of 34.3 €/MWh) and between 484 and 535 €/t with the assumed modified electricity price curve of a future energy mix with increased penetration of intermittent renewables (yearly average electricity price of 30.4 €/MWh, average electricity price in the enhanced operation of 20.6 €/MWh).[132]

Experts indicate that the cost of feedstock will always be a significant part of the process. The Netherlands produces (relative) small amounts of biomass, making it unlikely that the price will drop significantly. Having some sort of carbon taxation or carbon benefit for renewable carbon would help the use biogenic residues. When creating negative emissions a double counting scheme takes place, which will truly support these new innovative technologies.

Government intervention will have deep and broad impact

Bandwidth of market size for the technology after scale up

The commercial scale systems for all of the technologies reviewed have been sized for a feedstock throughput ranging from 75,000 – 100,000 tpa for a single fluidised bed gasifier. Economics dictate that larger systems will be cheaper based on a cost per unit of product. Once technologies are demonstrated, it is likely that fluidised bed based systems can be scaled up to larger units, well in excess of 100,000 tpa.[133]

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[131] UK Government, Department for Business, Energy and Industrial Strategy (2021). Advanced Gasification Technologies - Review and Benchmarking, link

[132] Poluzzi, Guandalini, Guffanti, Martinelli, Moioli, Huttenhuis., ... & Romano (2022). Flexible Power and Biomass-To-Methanol Plants With Different Gasification Technologies, link

[133] UK Government, Department for Business, Energy and Industrial Strategy (2021). Advanced Gasification Technologies - Review and Benchmarking, link

In terms of large-scale decarbonisation, there will be insufficient waste in the UK to significantly decarbonise sectors such as the gas network or aviation. This is likely also the case for the Netherlands. In the longer term, biomass is likely to become the key feedstock, but in the short-term, economics will strongly favour waste plants due to the revenue from the waste gate fee compared with paying for biomass. While waste is considered a more difficult fuel, the research community consider that if plants capable of processing waste are developed, it is relatively straightforward to use similar technology to process biomass. It must be recognised that the reverse is not true, as biomass plants have frequently been constructed in a less robust manner as it is perceived that the fuel is better.[134]

Experts indicate that gasification is ready for scale up and can do so quickly. Reactor designs are moving in a uniform direction. Gasification is expected to be the dominant biomass processing technology, which in turn will be a major source of carbon when fossil fuels are being phased out.

Bandwidth of market size for the technology output after scale up

The output of gasification, syngas, is an intermediate product. In that sense gasification cannot be seen as an individual technology but part of a production chain from biomass-to-X. Syngas has widespread use for upgrading processes and is widely considered to be invaluable as starting point for many carbon-based processes. Experts were not aware of any gasification project that produces syngas as main output, they are all linked to other processing plants that use the syngas as feedstock.

Two distinct routes for upgraded syngas products can be distinguished, feedstock and fuel. It is likely that syngas for feedstock purposes are economically more interesting than fuel.

Applicability in number of end-user sectors after scale up

The main output of gasification, syngas, is applicable (after upgrading) as input for processes in various products, such as methanol, hydrogen and synthetic fuels. These are furthermore applicable (after upgrading) in the transport, refinery, and chemical sector.

Experts highlight the possibility of synergy with the chemical industry in the west and south of the Netherlands. Here, large quantities of oil and natural gas are processed and refined. The infrastructure to make this possible is there and could be adapted to cooperate with gasification plants.

[134] UK Government, Department for Business, Energy and Industrial Strategy (2021). Advanced Gasification Technologies - Review and Benchmarking, link

Assessment summary

Criterion	Indicators	Current assessment
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	Yes, gasification is one of two key technologies that are capable of processing biomass, the other one being pyrolysis.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes. Fluidised bed gasification is most mature and successfully demonstrated.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes. Current support schemes do not sufficiently cover last steps in innovation process for full market implementation
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes. There are some commercial plants being developed in the USA and Canada, but support in NL seems required.
Government intervention at this stage of the technology's development is effective	Cost reduction that can be achieved by scaling up, per cost category	Cost reduction is expected, though currently fossil-fuel based processes are still favourable
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Various biomass streams can be used as feedstock, benefiting scale-up.
	Bandwidth of market size for the technology output after scale up	Syngas and methanol have a broad application.
	Applicability in number of end-user sectors after scale up	Applicability (after upgrading) for transport, refinery sector, chemical sector.

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Biomass and methane pyrolysis

Scope and introduction

Specific technologies

- Methane pyrolysis — Target output: hydrogen
- Biomass (fast) pyrolysis — Target output: bio-oil

Pyrolysis is in itself not a novel technology. The reaction, anaerobic heating of feedstock materials, has been performed for centuries, for example in the production of charcoal from woody biomass.

Biomass pyrolysis involves heating solid biomass, usually woody biomass, in a similar anaerobic environment to attain a mix of gases (gas), pyrolysis oil (liquid) and char (solid). The ratio between the gas/liquid/solid outcomes is determined, among other factors, by the specific input feedstock, the operating temperature and the residence time.

A methane pyrolysis reaction involves heating methane in an anaerobic environment to produce hydrogen gas and solid carbon. Due to the solid carbon residue, the process does not emit greenhouse gasses. TNO identifies this as a key advantage that pyrolysis has over the widely used Steam Methane Reforming (SMR) method, which does emit CO_2 gas and therefore requires CCS to be carbon neutral[135]. Methane pyrolysis does require more natural gas for the same amount of hydrogen than SMR though. A literature study in combination with expert consultation was used to provide answers for the assessment framework. A summary of the final assessment is displayed in the assessment summary. The sections following this introduction will display the research and reasoning behind this assessment.

Key performance indicators of methane and biomass pyrolysis

The table below gives an overview of some key performance and cost estimates for methane and biomass pyrolysis. Data from this table will be referenced in other sections of the assessment. Do note that the table is not a full overview of all technical differences between methane and biomass pyrolysis, but a compact list of basic parameters to set the stage for further comparison.

[135] TNO, Methaanprolyse: waterstof zonder CO_2 uitstoot, link

Table 0. 7 Key performance indicators of pyrolysis[136] [137] [138]

	Methane pyrolysis	Biomass pyrolysis
Process inputs	Methane	Lignocellulosic biomass
Target process output	Hydrogen gas	Pyrolysis oil
Catalyst	Nickel, iron, carbon	None. Catalytic pyrolysis is possible using alkali metals, but it is currently not used on scale
Process heating speed	Fast (10-200K/s)	Fast (10-200K/s)
Waste outputs	Several solid carbons	Various gases: CO_2, CO, H_2, CH_4 Several solid carbons. Some waste streams can be used for additional energy generation.
Process efficiency (energy efficiency in transformation)	58%	85-90; Pyrolysis oil ~60-70% (lignocellulosic biomass)
Operating temperature	1000-1200 (without catalyst) 500-1000 (with catalyst)	500

The technology is necessary in a climate neutral society

i. Bandwidth of market share in climate neutral society

In the context of a climate neutral society, pyrolysis has not been specifically identified by the Dutch government as an important technology to produce high quality renewable energy carriers in the future. Instead, it is often grouped under the 'advanced biofuels' umbrella, where gasification technology is usually highlighted from. Scenarios by Berenschot primarily do see a role for pyrolysis in the circular economy, but primarily in the recycling of plastics[139]. Scenario analysis done by Concawe[140] does include pyrolysis as a conversion technology for energy carriers alongside gasification in its biofuel production pathways, although the report seems to favour gasification. Both of these reports concern pyrolysis of complex hydrocarbons such as biomass or plastic. Experts judge pyrolysis to be one of the two key technologies that make processing biomass viable, the other being gasification. In the chain from biomass to a high quality renewable energy carrier, pyrolysis plays a central role. Bio-oil from pyrolysis is the stepping stone and starting point for many upgrading processes down the line. In a climate-neutral society, high employment of pyrolysis ensures sufficient feedstock and a solid base for many other processes.

136 Korányi, Németh, Beck, & Horváth, A. (2022). Recent Advances in Methane Pyrolysis: Turquoise Hydrogen with Solid Carbon Production, link

137 Sánchez-Bastardo, N., Schlögl, R., & Ruland, H. (2021). Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy, link

138 Jahirul, M. I., Rasul, M. G., Chowdhury, A. A., & Ashwath, N. (2012). Biofuels production through biomass pyrolysis—a technological review, link

139 Berenschot & Kalavasta (2020). Klimaatneutrale energiescenario's 2050 – scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, link

140 Concawe (2021). Transition towards Low Carbon fuels by 2050: Scenario analysis for the European refining sector, link

When discussing methane pyrolysis as an individual technology, research points to its potential to serve as a useful transitionary technology on the road to a carbon-free energy system[141]. Until electrolysis capacity is sufficiently scaled-up, there will be a need for fossil based hydrogen production. Methane pyrolysis is technically able to create hydrogen from methane (natural gas) without emitting gaseous CO_2. Whereas SMR and gasification require energy intensive carbon capture and storage (CCS) installations, the simplicity of methane pyrolysis omits this by directly creating CO_2-free fossil-based hydrogen. However, experts highlight that methane pyrolysis is an energy intensive process in itself with a low hydrogen output compared to SMR + CCS. The question becomes whether the elimination of CO_2 in the process on the whole is worth switching from the well-known SMR + CCS to methane pyrolysis.

Another theoretical application is possible CO_2 capture through biomethane pyrolysis. Given that a biogas such as biomethane is considered carbon neutral, undergoing pyrolysis will result in 'Turquoise' hydrogen with a net negative CO_2 emission[142]. In this way, methane pyrolysis could persist as a carbon capture method. However, when assessing methane pyrolysis in the context of the full production chain, its use diminishes. Experts indicate that energetically, methane pyrolysis is not interesting. Especially so when comparing it to electrolysis technologies that are more advanced, such as Alkaline and PEM. Additionally, the methane feedstock for this process is limited. Biomethane is likely to be too valuable and scarce, that it would be a waste to convert it for its hydrogen. Biomethane has other valuable applications in our future energy mix.

The technology is ready for scale up, but needs government help to do so

i. Technology is sufficiently developed and tested in pilot-phase (y/n)

Biomass pyrolysis plants are already currently active in the Netherlands. For example, the Empyro plant in Hengelo[143] has been producing bio-oil from woody biomass since 2015. This 25 MW facility produces a mix of pyrolysis oil, electricity and process steam[144]. The Empyro plant has a TRL of 8[145]
When assessing pyrolysis based on its output, including some upgrading of the bio-oil, pyrolysis ranges between TRL 5-9. For example, pyrolysis used to produce transport fuels and marine diesel have a TRL of 7 and upgrading by co-feeding in conventional refineries at TRL 8

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141 Sánchez-Bastardo, N., Schlögl, R., & Ruland, H. (2021). Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy, link

142 Korányi, T. I., Németh, M., Beck, A., & Horváth, A. (2022). Recent Advances in Methane Pyrolysis: Turquoise Hydrogen with Solid Carbon Production, link

143 BTG Bioliquids (n.d.). Empyro Hengelo, NL, link

144 BTG (2018). Development of fast pyrolysis in the Netherlands – Technology & applications, link

145 TNO (2019). Production of pyrolysis bio-oil from solid biomass via fast pyrolysis, link

As it stands there are no methane pyrolysis demonstration plants active in the Netherlands. Recently the Monolith project in Nebraska, USA has completed the first ever large scale methane pyrolysis plant, taking the technology from concept to full scale (TRL 9)[146]. The technology is estimated to be mature enough to contribute significantly to decarbonisation in Europe as well[147], although no projects have thus far been completed.

ii. Current government support schemes for demonstration projects are insufficient (y/n)

The SDE++ covers the production of pyrolysis oil through fast pyrolysis of woody (lignocellulosic) biomass[148]. The subsidy advices a maximum capacity of 36 MW. While this subsidy aided in the completion of the Empyro plant, the SDE++ package does not seem to stimulate the emergence of more projects in the Netherlands. However, experts note that the lessons learned by Empyro have been applied in plants abroad such as in Sweden.

No other types of biomass for pyrolysis are covered by the SDE++. Other than financial support, experts indicate two other areas where the government could offer support. First, the lead time of requesting permits for pyrolysis plants in the Netherlands is a barrier. Second, the public perception of biomass is not conducive to the development of new plants.

Methane pyrolysis is not currently covered under the SDE++. The lack of SDE++ coverage in combination with there being no demonstration plants currently active in Europe suggests that there is no suitable support environment for methane pyrolysis demonstration projects.

iii. Market introduction at scale is not commercially viable, even including existing government support schemes (y/n)

Biomass pyrolysis is currently being applied in Empyro, using SDE++ subsidies. Under the SDE++ further scaling up to 36 MW is covered. However, recent analysis by PBL has advised to further analyse pyrolysis oil generation in the SDE++[149].
In addition a demand for biofuel products, such as upgraded pyrolysis oil, is in part created by mandating minimum percentages of mixed biofuels in gasoline and diesel. All in all, at this moment the demand does not seem to grow naturally, but must instead be created. Total biofuel utilisation is also limited by the relatively small supply of biomass in the future. As a result, there is relatively little development in biomass pyrolysis in the Netherlands.

Methane pyrolysis is assumed to not be commercially viable for scaling-up under the current regulatory environment, because no project has thus far been developed or initiated in the Netherlands.

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146 Monolith (2021). Taking Methane Pyrolysis from Concept to Industrial Plant, link
147 DVGW (2022). Pyrolysis – potential and possible applications of a climate-friendly hydrogen production, link
148 TNO (2021). Conceptadvies SDE++ 2022 Geavanceerde Hernieuwbare Brandstoffen, link
149 TNO (2022). Eindadvies Basisbedragen SDE++ 2022, link

Government intervention at this stage of the technology's development is effective

i. Cost reduction that can be achieved by scaling up, per cost category

According to experts, the pyrolysis process itself is more economy-of-numbers rather than economies of scale. The main driver behind this is that the pyrolysis capacity must be adjusted to the local biomass availability. As biomass availability varies per region, multiple smaller installations are favoured over large plants.
Currently there is little data available on the advantages that scaling up provides. It is highly likely however that pyrolysis-oil upgrading benefits from similar economy of scale advantages that occur for chemical processes. Experts highlight two areas where economy of scale advantages can develop. The first is in the production of pyrolysis plants. They are designed in similar fashion and costs can be reduced when they are constructed more often. Second, certain economy of scale advantages are expected in the upgrading processes that naturally follow the pyrolysis process. A logical first step is to co-feed pyrolysis oil in existing petroleum refineries.

Government intervention will have deep and broad impact

i. Bandwidth of market size for the technology after scale up

Liquid biofuels currently make up 0.028GJ for every 1 GJ of oil products supplied to the market[150]. Given the mandated mixing of biodiesel and bio-oil in traditional fuels, this usage is expected to increase. Biomass pyrolysis has the ability to play a significant part in the supply of pyrolysis-oil for biofuels, although the efficiency and cost in comparison to alternate technologies will ultimately determine its market share. Scenario analyses currently anticipate that gasification will be the dominant technology in biofuel production[151], although it remains an area of discussion.

Methane pyrolysis is, as previously stated, viewed in literature as a bridging technology towards carbon-free hydrogen. The long term market share of fossil-based methane pyrolysis in a climate neutral economy is expected to be very small. Nevertheless, such technologies to eventually reach a climate neutral economy are by no means unimportant. The carbon sink possibilities of Turquoise hydrogen put methane pyrolysis in a unique spot. The Netherlands does not have large natural carbon sink options[152]. Methane pyrolysis plants at scale will be able to provide both hydrogen and carbon storage as marketable services. While methane pyrolysis' share in the hydrogen market will be limited, it could theoretically play a role by being a controllable carbon capture method if the energy efficiency could be improved.

150 IEA Bioenergy, (2021). Implementation of bioenergy in the Netherlands – 2021 update, link

151 Berenschot & Kalavasta (2020). Klimaatneutrale energiescenario's 2050 – scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, link

152 New Climate Institute (2022). What is a fair emissions budget for the Netherlands? Link

ii. Bandwidth of market size for the technology output after scale up

The global pyrolysis oil market in 2020 was valued at $302 million. Statistics from Transparency Market Research expect a 4% CAGR for the pyrolysis oil market between 2020-2031[153].

In the medium term, the possible market share of pyrolysis oil (as a resource for biofuels) is connected to the market share of fossil fuels such as diesel and gasoline, marine fuels and kerosene. While the CAGR of biofuels is higher (8.3% estimate between 2021-2030[154]), an increase in growth in this market could reasonably translate to an increase in pyrolysis oil demand.

Hydrogen is a well-known high-density energy carrier. The IEA has identified hydrogen as a prime contender to be a promising energy carrier for a CO_2-neutral energy infrastructure[155]. In addition, large scale plans for hydrogen infrastructure are already being developed in the Netherlands[156]. Given its applicability in industry, transport and energy storage, the market size of hydrogen could reach scales similar to the current natural gas market.

iii. Applicability in number of end-user sectors after scale up

One of the uses of pyrolysis oil is to serve as an intermediate for further upgrading to biofuels[157]. Biofuel is primarily intended for use in the transport sector. There are certain sectors where electric transport is underdeveloped or sub-optimal, such as long-haul freight transport, international marine transport or aviation. Biofuels are especially useful aiding in the CO_2 reduction here, as alternatives are scarce. The chemical and refining industry are well developed in the Netherlands, but designed for fossil fuels. This infrastructure could be adapted for refining and upgrading bio-oil from pyrolysis. The Netherlands could develop a mature bio-oil processing sector. Experts indicate that traditional oil companies might be interested in such a development, but are reluctant to invest without the certainty of multi-year government guidance.

Hydrogen is applicable in a range of sectors. In industry, hydrogen-based heating installations are more easily able to replace current natural-gas based heating compared to electric solutions. In the transport sector, the high energy density of hydrogen compared to electrical battery storage gives hydrogen a distinct advantage for applications such as freight transport over roads and inland waterways. In the energy sector, hydrogen can be used as a large-scale buffer to balance supply and demand. As the Dutch electricity mix moves further away from fully flexible fossil-based production to increasing shares of variable renewables such as solar and wind, this need for (hydrogen) balancing capacity will only stand to increase.

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153 Transparency market research (2020). Pyrolysis Oil Market, link

154 Precedence Research (2020). Biofuels Market Size, Share & Growth Analysis Report, link

155 IEA (2019). The Future of Hydrogen, link

156 Gasunie (n.d.). Waterstofnetwerk Nederland, link

157 Concawe (2021). Transition towards Low Carbon fuels by 2050: Scenario analysis for the European refining sector, link

Assessment summary

Criterion	Indicators	Assessment biomass pyrolysis	Assessment methane pyrolysis
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	Yes, pyrolysis is one of two key technologies that are capable of processing biomass, the other one being gasification.	Limited use
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, several plants in the Netherlands are in use. Fast Pyrolysis=commercial Upgrading demonstrated on pilot scale	Yes, commercial scale demonstration in the USA has been developed and active.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes, experts indicated that current governmental support is too limited in scope and amount. For upgrading government support is certainly needed; demonstration projects for pyrolysis are not needed for woody biomass; residues pyrolysis based on low quality residues or non-woody sources may require support to cover the risks.	Yes, methane pyrolysis is not covered.
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes, not viable. Fast pyrolysis is commercial (wood) Co-refining in existing refineries is being introduced abroad; Support in NL desired Upgrading is at TRL 5/6, not yet ready for commercial introduction	Yes, not viable. No government support covers methane pyrolysis and no projects outside of lab scale exist in Europe.
Government intervention at this stage of the technology's	Cost reduction that can be achieved by scaling up, per cost category	Yes, due to economy of scale advantages in plant construction and process efficiencies.	Unknown, but it is likely that some reductions can be achieved in

Criterion	Indicators	Assessment biomass pyrolysis	Assessment methane pyrolysis
development is effective			scaling up, as with most technological advances in general.
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Significant market share of available biomass.	Limited use, potential market share as bridging technology on the medium term.
	Bandwidth of market size for the technology output after scale up	Bio-oil can be used to replace natural gas in industrial steam boilers with limited modifications (e.g. FrieslandCampina) Bio-oil can be co-processed with fossil fuels enabling cost-effective, and making optimal use of existing assets. In parallel stand-alone upgrading is also possible, but is less developed (TRL5-6)	Widespread adoption
	Applicability in number of end-user sectors after scale up	Transport, chemical industry, energy	Industry, freight transportation, energy

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Concawe (2021). Transition towards Low Carbon fuels by 2050: Scenario analysis for the European refining sector, link

DVGW (2022). Pyrolysis – potential and possible applications of a climate-friendly hydrogen production, link

Gasunie (n.d.). Waterstofnetwerk Nederland, link

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Jahirul, M. I., Rasul, M. G., Chowdhury, A. A., & Ashwath, N. (2012). Biofuels production through biomass pyrolysis—a technological review. *Energies*, *5*(12), 4952-5001, link

Korányi, T. I., Németh, M., Beck, A., & Horváth, A. (2022). Recent Advances in Methane Pyrolysis: Turquoise Hydrogen with Solid Carbon Production. *Energies*, *15*(17), 6342, link

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TNO (n.d.), Methaanprolyse: waterstof zonder CO_2 uitstoot, link

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Hydrogenation based and chemical and biological methanation

Scope and introduction

Specific technologies

- Hydrogenation-based catalytic methanation
  - Fixed Bed reactor
  - Honeycomb reactor
  - Fluidized Bed reactor
  - Three Phase reactor
  - Electrochemical Methanation
- Hydrogenation-based biological methanation
  - Stir tank
  - Packed column

The technology is necessary in a climate neutral society

The technologies in scope of this assessment are catalytic methanation (also called chemical methanation) and biological methanation. Both these processes use CO_x and hydrogen gas as input, using a chemical or biological catalyst to convert the gases to methane. These are other processes than biogas fermentation of biomass in biogas plants. Biogas plants are often the first step in a production chain, of which catalytic and biological methanation are a second link used to upgrade the biogas from the biogas plants. Biogas plants are a fully mature and widespread technology. Since CO2 is required for catalytic and biological methanation, it is advantageous to combine catalytic and biological methanation with the biogas plant. However, catalytic and biological methanation can also be combined with other CO_2 sources.

Bandwidth of market share in climate neutral society

Catalytic and Biological Methanation (using hydrogenation) are Power-to-Gas (P2G) technologies. P2G plays an important role in a climate neutral society, as it fulfils several crucial needs in an energy system:

- Gases are easy to transport;
- Gases are easy to store;
- General quick reaction times of P2G technologies make them suitable for providing flexibility, e.g. balancing the power grid[158]. Usually the speed of electrolysis is the limiting factor.

Green methane has two use cases in the energy transition and a climate-neutral society. Firstly it can be considered a transition fuel. It can (partly) replace natural gas, while we transition to a hydrogen dominant society. Secondly, methane is an important feedstock for industrial processes.

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158 Van Gessel, Huijskes, Juez-Larre & Dalman (2021). Ondergrondse Energieopslag in Nederland 2030–2050. Technische evaluatie van vraag en aanbod, link

Several scenario studies[159] show that energy systems with implemented P2G entail significantly lower costs than those with higher levels of electrification. In many outlooks, P2G is taken explicitly into account for its buffering capabilities and ease of transport through the current gas network[160]. TNO takes methanation and biomethane explicitly into account in their scenario study concerning Underground Gas Storage[161] and in '*Het energiesysteem van de toekoms'*[162] methanation is of increasing importance moving through the four scenarios. However, a Guidehouse study on the RePowerEU 2030 targets, specifically on the use of methane, does not mention methanation.[163]

A competitor to methane is hydrogen, because both gases can fulfil the same fuel functionalities in a climate neutral energy system. However, methanation and methane are often not explicitly considered in climate neutral scenario's, while hydrogen takes centre stage.

Hydrogen through electrolysis has several key benefits over methane from catalytic and biological methanation:

- In order to produce green methane with methanation, hydrogen from electrolysis is a feedstock. Methanation thus will always require more energy than electrolysis, making hydrogen cheaper to produce. This is even more relevant in a system with limited electricity from renewable sources.
- Burning hydrogen emits no greenhouse gasses, making it a fully renewable process as long as the input energy is green. Burning methane releases CO_2.

At the same time, methane also has several benefits over hydrogen:

- Both catalytic and biological methanation require CO or CO2 as input. They extract carbon from the environment, biomass, Synthetic Natural Gas (SNG) or from concentrated sources such as CCS[164] .
- Methane is the main part of natural gas and is currently already fed in the natural gas infrastructure, the amount limited by national guidelines. Hydrogen can also be fed into the natural gas grid, but needs to be mixed with methane[165] or be fed in at much lower percentages (3% for hydrogen to 12% for methane)[166] [167].
- Distributing hydrogen through the gas network requires high investments in the network for cleaning, replacing equipment at consumers, new compressors and new measure and control devices.
- When taking storage capability into account, methane could be up to ten times cheaper than hydrogen due to its elevated energy density[168]. However, there is ample natural

159 Van Gessel, Huijskes, Juez-Larre & Dalman (2021). Ondergrondse Energieopslag in Nederland 2030–2050. Technische evaluatie van vraag en aanbod, link
160 Netbeheer Nederland (2021). Het Energysysteem van de Toekomst, link
161 Van Gessel, Huijskes, Juez-Larre & Dalman (2021). Ondergrondse Energieopslag in Nederland 2030–2050. Technische evaluatie van vraag en aanbod, link
162 Netbeheer Nederland (2021). Het Energysysteem van de Toekomst, link
163 Guidehouse (2022). Action plan for implementing REPowerEU, link
164 Eveloy & Gebreegziabher (2018). A review of projected power-to-gas deployment scenarios, link
165 Van Gessel, Huijskes, Juez-Larre & Dalman (2021). Ondergrondse Energieopslag in Nederland 2030–2050. Technische evaluatie van vraag en aanbod, link
166 Hydrogen Europe (2020). Bijmengen van waterstof op het gasnetwerk; wat zijn de mogelijkheden? link
167 Eveloy & Gebreegziabher (2018). A review of projected power-to-gas deployment scenarios, link
168 Vogt, Monai, Kramer, & Weckhuysen (2019). The renaissance of the Sabatier reaction and its applications on Earth and in space, link

storage capacity in the Netherlands considering the vast salt caverns and former natural gas fields[169].

In an energy system with excess green energy and/or low gas storage capacity and/or high CO_2 emissions, methane could have a clear advantage over hydrogen. Even then, the cost balance for hydrogen and methane is unclear and can vary from region to region. Gasunie has started studies into the costs of implementing hydrogen and/or methane, but those studies do not yield clear conclusions yet[170]. Gasunie is preparing follow-up studies in cooperation with regional network operators. However, in a role of energy carrier, it is unlikely that methane will be used as the dominant energy carrier in a climate neutral society. Mainly because hydrogen can fulfil the same role and is significantly cheaper to produce (see Chapter 0). Methanation will owe a large part of its market share to more small scaled niche applications, where it will have an advantage over electrolysis due to:

- Limited local storage capacity;
- Local abundance of CO or CO_2, with the need to diminish it;
- Need for methane as feedstock;
- Need for flex solutions on the grid with a low response time.

The technology is ready for scale up, but needs government help to do so

Technology is sufficiently developed and tested in pilot-phase (y/n)

Both catalytic and biological methanation are not new technologies. Catalytic methanation was discovered in 1897 and has been mainly developed since to aid in the production of ammonia. CO and CO_2 pollute the catalyst. Catalytic methanation removes those gases from the process and converts them into harmless methane. The biological route has been discovered in 1906, but is less developed due to technical issues[171]. Both types of methanation are being developed further for optimization in a climate-neutral society, but both have some major caveats that hinder its wide-scale adoption.

Catalytic Methanation

The metal catalyst, usually nickel and ruthenium, used in catalytic methanation is polluted by carbon depositions as a result of its own process, reducing its efficiency[172]. Additionally, studies are being conducted into lowering the heat and pressure requirements[173] and utilizing all outputs of the process[174] namely CH_4, heat and oxygen. Finally, catalytic methanation is, compared to biological methanation, vulnerable to impurities in the feedstock[175].

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169 Van Gessel, Huijskes, Juez-Larre & Dalman (2021). Ondergrondse Energieopslag in Nederland 2030–2050. Technische evaluatie van vraag en aanbod, link

170 Netbeheer Nederland (2021). Het Energysysteem van de Toekomst, link

171 Götz, Koch & Graf. (2014, September). State of the art and perspectives of CO2 methanation process concepts for power-to-gas applications, link

172 Stangeland, Kalai, Li & Yu(2017). CO2 methanation: the effect of catalysts and reaction conditions, link

173 Stangeland, Kalai, Li & Yu(2017). CO2 methanation: the effect of catalysts and reaction conditions, link

174 Thema, Bauer & Sterner (2019b). Power-to-Gas: Electrolysis and methanation status review, link

175 Götz, Koch & Graf. (2014, September). State of the art and perspectives of CO2 methanation process concepts for power-to-gas applications, link

Catalytic methanation knows four thermochemical routes: (i) Fixed-bed reactor, (ii) Fluidized-bed reactors, (iii) three-phase fluidized-bed reactor[176] and (iv) a Honeycomb reactor. Of the four, the three-phase reactor (iii) is the most efficient and easiest to control the heat requirements[177] in a laboratory setting. In a practical setting, the fixed-bed- and honeycomb reactor are most likely to succeed. The fixed-bed reactor is applied in commercial settings, but requires a lot of energy to start the chemical process and its catalyst is easily damaged or poisoned. And although the Honeycomb reactor is still in the demonstration phase (1 MWth plant in Falkenhagen, Germany), it looks promising.

Biological Methanation

Biological methanation has two main approaches, which differ in how the hydrogen is introduced to the CO_2. The (ia) stir tank reactor and (ib) packed column reactor combine the CO_2 with the hydrogen in a separate reactor. The (ii) in-situ production introduces the hydrogen in the same tank where the CO_2 is produced, often by fermentation of biomass. In-situ production can be up to 15% less efficient than the stir tank and packed column. In the stir tank (ib), the water-microrganism mixture is continuously stirred. In a packed column (ib), the water flows down a column and the hydrogen moves up through it. Both reactors optimise the absorption of hydrogen by the water, since the main hindrance for biological methanation is the hydrogen intake by the bacteria. Hydrogen does not dissolve easily in water, making it difficult to get the hydrogen to the bacteria in the water based reactor design used for biological methanation. Modelling of reactor designs has showed, theoretically and in laboratory conditions, that biological methanation can be more efficient when hydrogen intake is not the limiting factor[178] [179]. It remains currently unclear to what degree the efficiency can be improved. However, with current reactors catalytic methanation has 20 to 50 times more yield per hour, with similar amounts of catalyst[180]. Biological methanation not only has a slower reaction time than catalytic methanation, but also requires more energy to run. This is due to the stirrers in the biological reactors, which promote the solution of hydrogen[181].

Pilots

In 2019 at least 74 methanation projects were identified in 13 countries, 34 biological and 32 catalytic (and 8 not determined) in various phases of development[182].

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176 Younas, Loong Kong, Bashir, Nadeem, Shehzad & Sethupathi (2016). Recent advancements, fundamental challenges, and opportunities in catalytic methanation of CO2, link

177 Götz, Koch & Graf. (2014, September). State of the art and perspectives of CO2 methanation process concepts for power-to-gas applications, link

178 Götz, Koch & Graf. (2014, September). State of the art and perspectives of CO2 methanation process concepts for power-to-gas applications, link

179 Thema, Weidlich,Hörl, Bellack, Mörs, Hackl, ... & Sterner (2019a). Biological CO2-methanation: An approach to standardization, link

180 Stangeland, Kalai, Li & Yu(2017). CO2 methanation: the effect of catalysts and reaction conditions, link

181 Götz, Koch & Graf. (2014, September). State of the art and perspectives of CO2 methanation process concepts for power-to-gas applications, link

182 Thema, Weidlich,Hörl, Bellack, Mörs, Hackl, ... & Sterner (2019a). Biological CO2-methanation: An approach to standardization, link

Table 0. 8 Catalytic and biological methanation projects (Thema, 2019a)

	Nb. Of projects	Installed power (in MW)	Mean installed power (in MW)	Largest installed power (in MW)	Smallest installed power (in MW)
Catalytic	32	7,447	0,35	6	0,005
Biological	34	18,371	1,31	2,5	0,001
Not reported	8	Unknown	Unknown	Unknown	Unknown

The figures for installed power are likely to be higher, since for 23 projects the installed power was not reported. These figures show that methanation is not yet deployed on a large scale, and many projects have not matured yet from their pilot-phase. Denmark has planned two catalytic 10 MW plants for 2035 and 2050 (MeGa-stoRE com 1 and 2), but other more recent initiatives have not crossed the 1 MW[183]. Noteworthy is that catalytic methanation is being considered by NASA for the production of propellant of their crafts on Mars[184].

On the biological side, some projects that aim at scaled up production have started in Switzerland and the USA (Electrochaea, 10 MW), Germany (Uniper, 1,5 MW), Switzerland (Limeco, 2,5 MW) and Belgium (Carmeuse, Engie and John Cockerill, 75 MW)[185].

In the Netherlands, various projects have started in recent years, below is an overview. Many are not an isolated process, but an upgrading process as part of a chain.

Table 0. 9 Methanation projects in the Netherlands

Name	Type	Location	Year	TRL	Capacity
Emmet Energy	Catalytic	Eindhoven	2022	5	Unknown
Eemsgas	Catalytic	Delfzijl	2024	6	13.7 MW
P2G Project (Stedin/DNV)	Catalytic	Rozenburg	2023	7	0.008 MW
W2P2G	Catalytic	Wijster	2014	7	0.4 MW
Power to Flex	Catalytic	Groningen	2016	7	Unknown
Pure methane from CO_2 hydrogenation	Catalytic	Delft	2021	2	n.a.
Ambigo	Catalytic	Alkmaar	2017	7	4 MW

183 IEA (2022). ETP Clean Energy Technology Guide, link
184 Hintze, P., Meier, A., & Shah, M. (2018, July). Sabatier system design study for a mars isru propellant production plant, link
185 IEA (2022). ETP Clean Energy Technology Guide, link

Current government support schemes for demonstration projects are insufficient (y/n)

Methanation as individual technology is out of scope of current government support, in contrast to the production of methane using fermentation processes. But there are examples of subsidies for the development of projects which demonstrate the full chain of power-to-gas, of which methanation is a part. For example, under the DEI+ schema, the Ambigo project is found as recipient. SDE+ subsidy has been granted to Eemsgas, for the production of green gases.

Market introduction at large scale is not commercially viable, even including existing government support schemes (y/n)

Most biological and catalytic methanation projects are not commercially viable at this moment[186] and require grants or subsidies to run. Some exceptions can be found when circumstances are ideal, with an abundance of green energy and CO_2 [187].

However, there are two components of the price of methane production that are expected to evolve in the next 20-30 years. This will likely lower the price of producing methane. First is the price of hydrogen and the second component is the production efficiency of catalytic and biological methanation. We elaborate further on these components in Chapter 0. These trends are expected to lower the price of methanation to such a degree, that it becomes commercially viable. Large scale investments (up to 30 GW of capacity) are planned in Europe[188]. It is likely that in one to two decades the bottleneck for methanation will shift from the price level to the use-cases of methane.

Experts indicate another barrier to commercially viable methane production, which is the availability of CO/CO_2. Currently, the commercially viable route to apply methanation is to use it in direct conjunction with classic biogas fermentation plants. The CO/CO_2 produced there is used for methanation as the next step in a system. Other sources of CO_2 of sufficient output are either not renewable (coal), expensive (pure CO_2) or not sufficiently developed (Direct Air Capture/CCS).

Government intervention at this stage of the technology's development is effective

Cost reduction that can be achieved by scaling up, per cost category

Large scale cost reductions can be expected from scaling up catalytic and biological methanation. The majority of the production costs can be explained by (i) the price of the hydrogen feedstock and to a lesser degree by (ii) the efficiency of the methanation processes. This holds true for both catalytic and biological methanation.

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186 Eveloy & Gebreegziabher (2018). A review of projected power-to-gas deployment scenarios, link

187 Younas, Loong Kong, Bashir, Nadeem, Shehzad & Sethupathi (2016). Recent advancements, fundamental challenges, and opportunities in catalytic methanation of CO2, link

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(i) Price of hydrogen

According to several studies[189] [190], the cost of electrolysis will decrease from $1.300 per kW in 2017 to $500 per kW in 2050, a decrease of 61.5%. The price of electricity is 80% of the production cost of hydrogen.

(ii) Methanation efficiency

The efficiency of catalytic and biological methanation is expected to evolve independent from each other and is usually expressed in the cost of the electrical power input. This is due to technological advances improving the efficiency of the process.

- The price of catalytic methanation is expected to drop from €800 per kW in 2017 to €130-400 in 2050, a cost reduction of 67%.
- The price of biological methanation is expected to drop from €1.200 in 2017 to €300 in 2050, a reduction of 75%.

Cost reductions for both can mainly be attributed to economies of scale and technological development[191] [192]. Experts indicate that large methanation plants can achieve almost double the cost reduction over smaller plants due to economies of scale.

Government intervention will have deep and broad impact

Bandwidth of market size for the technology after scale up

Catalytic and biological methanation can have their uses in a climate-neutral society. However, it is not logical to prioritise its scale up. Green- hydrogen and electricity are scarce and required to operate methanation in a climate-neutral fashion. Both play a more important and versatile role towards a climate-neutral society and should get first priority. When there is an abundance of green- hydrogen and electricity, it could be used in scaled up methanation.

Bandwidth of market size for the technology output after scale up

Methane is unlikely to play a role as energy carrier employed on a large scale, with hydrogen as competitor. There are several cases where methane is of added value in a climate neutral society:

- As part of a power-to-gas process that leads to the production of synthetic gases;
- Fed into the gas grid, while natural gas is still in use;
- Used as fuel for Compressed Natural Gas (CNG) engines;
- Feedstock for upgrading or industrial processes.

When scaled up, methane from methanation can be a valuable addition to methane from biogas plants. It can use the residual flow of CO_x from the biogas plants to increase its yields.

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189 Thema, Bauer & Sterner (2019b). Power-to-Gas: Electrolysis and methanation status review, link
190 Department for Business, Energy & Industry (2021), Hydrogen Production Cost 2021, link
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Applicability in number of end-user sectors after scale up

The use cases for catalytic and biological methanation differ, due to their technical differences.

Catalytic methanation is more suitable for operating on a larger scale, since it is more energy efficient and can achieve significantly higher yields. It is more suitable for a model where it is produced centrally and distributed to end-users either directly or fed-in the gas network. End users could be the energy and heating sector, catalytic industry, transport and for use as a grid stabiliser[193].

Biological methanation on the other side is more suitable for a decentralised model, where it's employed locally. The biological reactors operate on lower temperatures and are resilient to pollution in the feedstock. It can be employed at biogas and water treatment plants or for residential heating when the houses are not connected to the main gas grid.

Assessment summary

Criterion	Indicators	Current assessment Catalytic Methanation	Current assessment Biological Methanation
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	No, not in NL.	No, not in NL.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, fixed-bed reactors sufficiently developed.	Yes, stir-tanks and packed columns are sufficiently developed.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes	Yes
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	No, large scale operations are planned	No, large scale operations are planned
Government intervention at this stage of the technology's development is effective	Cost reduction that can be achieved by scaling up, per cost category	Significant cost reduction can be achieved due to (i) technological development of the process and (ii) economies of scale.	Significant cost reduction can be achieved due to (i) technological development of the process and (ii) economies of scale.

193 Ghaib & Ben-Fares (2018). Power-to-Methane: A state-of-the-art review, link

Criterion	Indicators	Current assessment Catalytic Methanation	Current assessment Biological Methanation
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	As part of P2G chain and as transition technology, methanation has a sizable use. As an individual technology, its bandwidth is limited.	As part of P2G chain and as transition technology, methanation has a sizable use. As an individual technology, its bandwidth is limited.
	Bandwidth of market size for the technology output after scale up	Use cases for methane are not sufficiently impactful to warrant major government intervention. Most of its use is for industrial, heating and fuel for mobility uses. As energy carrier, hydrogen fulfils much the same role and is cheaper to produce.	Use cases for methane are not sufficiently impactful to warrant major government intervention. Most of its use is for industrial, heating and fuel for mobility uses. As energy carrier, hydrogen fulfils much the same role and is cheaper to produce.
	Applicability in number of end-user sectors after scale up	Other technologies serve end-user sectors better, except for specific industrial uses.	Other technologies serve end-user sectors better, except for specific industrial uses.

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Mobil process (methanol to X)

Scope and introduction

The Mobil process is invented by - and named after - the company that invented it, now called Exxon-Mobil. This process converts methanol (via dimethyl ether) to gasoline. It is also known as Methanol-to-gasoline (MTG). [194] MTG was invented in the seventies of last century and has since spun off many subprocesses, each resulting in hydrocarbons of slightly different chemical content. Combined, these processes are called Methanol-to-X (MTX). Since these processes are highly similar, the focus of this assessment is on MTX.

Specific technologies:

- Methanol-to-X
  - Methanol-to-gasoline (Mobil process)
    - Adiabatic fixed-bed
    - Circulating fluidized-bed
  - TIGAS (Topsoe's Improved Gasoline Synthesis)
  - Methanol-to-Olefins (MTO)
  - Methanol-to-propylene (MTP)

The technology is necessary in a climate neutral society

Bandwidth of market share in climate neutral society

MTX requires two inputs: (i) methanol and (ii) energy for heat. In the majority of applications currently, MTX is not a renewable technology, since the methanol often is derived from natural gas and the origin of the energy is unknown. MTX can be climate neutral, as long as the input methanol and energy are green.

In a climate neutral society, MTX has limited use for wide scale application for several reasons:

1. It is an advanced upgrading technology of carbon and hydrogen atoms and therefore subject to several inefficiencies. In our energy system, carbon, hydrogen and energy from renewable sources are scarce and expensive and remain so for the foreseeable future. In such an energy system, it is not economical to use scarce resources for advanced upgrading, especially when the resource itself (i.e. hydrogen) is a capable energy carrier. And while hydrogen production can be increased, using electrolysis for example, carbon supply will be severely limited in a society that hardly emits any carbon at all. Biomass will be the main supply of carbon, but is limited in its availability. Direct-air capture is energy intensive to a degree that it is not economically interesting for the foreseeable future, and capturing carbon from water sources (such as oceans) is a novel and untested technology. So any process using carbon atoms is likely to face carbon shortages.

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[194] Keil, Frerich (1998), *Methanol-to-Hydrocarbons.process technology*

2. Hydrocarbons from fossil fuels are undesirable in a climate neutral society due to its CO_2 emission when burned, and is rightfully so not included in any green scenario.[195] [196] While they can be produced sustainably, MTX cannot produce hydrocarbons in sufficient quantities and at sufficiently low prices to completely replace hydrocarbons from fossil fuels. It can be a part of a mix of energy producers and -carriers.

MTX can play a role as part of the chain from biomass to complex hydrocarbons, as a route to upgrade gas and liquid outputs of biomass- pyrolysis and gasification. The yield of this chain is limited by the available biomass.

MTX could also be useful as a transition technology, where it supplants a part of the market share of fossil gasoline. If produced in sufficient quantities, it could speed up the fading out of fossil gasoline. In that sense, MTX has competition from the Fischer Tropsch process. Both technologies use a carbon based source as input and upgrade it to high energy liquids, albeit through different chemical processes. Compared to Fischer Tropsch, MTX has a distinct advantage though: MTX is more selective in its output, i.e. it is easier to determine what kinds of liquid are produced. Fischer Tropsch requires more post processing. [197] [198] Benefit for Fischer Tropsch on the other hand is that it skips the methanol conversion phase, saving energy.

The technology is ready for scale up, but needs government help to do so

Technology is sufficiently developed and tested in pilot-phase (y/n)

Several MTX processes are a mature technology and highly developed, such as Methanol-to-Gasoline (Mobil process), Methanol-to-Olefins and Methanol-to-Propylene. The fixed bed reactor is employed over the world and its catalysts are commercially available.[199] In China alone five major plants are operational, combined they have an output of 2.7 MTPA. [200] All these plants use fossil fuel as input for the methanol production. From a technical viewpoint, the MTX (specifically the fixed bed reactor) has been successfully scaled up. The fluidized bed reactor is not fully developed yet and needs further development to be commercialised.[201] [202]

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195 Ouden et al. (2020), *Klimaatneutrale energiescenario's 2050*

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198 Hennig, Haase (2021), *Techno-economic analysis of hydrogen enhanced methanol to gasoline process from biomass-derived synthesis gas*

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201 Jones et al. (2009), *Techno-Economic Analysis for the Conversion of Lignocellulosic Biomass to Gasoline via the Methanol-to-Gasoline (MTG) Process*

202 Almohamadi (2020), *Production of gasoline from municipal solid waste via steam gasification, methanol synthesis, and Methanol-to-Gasoline technologies: A techno-economic assessment*

It is however unclear whether the use of biomass as feedstock instead of fossil fuels to produce the methanol for MTX faces any barriers. This process has not been demonstrated yet. [203] Additionally, it is unclear to what degree MTX is vulnerable to repeated starting and stopping of the process. Experts indicate that the catalyst is MTX might be vulnerable to accelerated degradation when the process is often interrupted. Renewable electricity from wind and solar is not produced consistently and could not be a good match with MTX. More research is needed to say something definitive.

Current government support schemes for demonstration projects are insufficient (y/n)

No government schemes in recent years have been found that support MTX in Europe. The US Department of Energy has provided subsidies, for example to a pilot plant using biomass as feedstock in Des Plaines, Il with a capacity of 8 barrels per day. [204]

While no support for the individual technology has been found for MTX, several Dutch and European subsidies have been found that support previous links in the full chain. These projects advance the production of green methanol. Notably is that many of these projects focus on methanol as fuel for the shipping industry.

- Subsidieregeling R&D Mobiliteitssectoren (Project MENENS)
- SDE++ (supports methanol from lignocellulosic biomass)
- Horizon 2020 (Project LeanShips, Project FASTWATER, Project FReSMe, Project MEFCO)
- EU Innovation Fund (Project AIR (Sweden), Project C2B (Germany))

Market introduction at large scale is not commercially viable, even including existing government support schemes (y/n)

Whether MTX is commercially viable, depends on the crude oil price and the feedstock of the methanol used. The gasoline produced by MTX is in direct competition with gasoline from crude oil, which is produced cheaply. On top of that, biomass is the largest component of the price of MTX [205], making biomass based MTX not commercially viable without high crude oil prices. [206] On the global market, MTX cannot compete with crude oil. In some niche scenarios, where the price of the fuel is subservient to other considerations, MTX could be preferable to gasoline from crude oil. For example, local availability of gasoline in bad infrastructure regions, dependency on oil producing countries or local abundance of methanol and energy.

Two improvements to the process are being studied, that could reduce the production price or increase the yield. The first is the residual heat of the process, MTX is an exothermic process. This heat can be used for other applications or sold. The second is a

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[203] Jones et al. (2009), *Techno-Economic Analysis for the Conversion of Lignocellulosic Biomass to Gasoline via the Methanol-to-Gasoline (MTG) Process*

[204] Nguyen (2017), *Methanol to gasoline (MTG) as a green path to synthetic fuels*

[205] Tan et al. (2016), *Conceptual process design and economics for the production of high-octane gasoline blendstock via indirect liquefaction of biomass through methanol/dimethyl ether intermediates*

[206] Jones et al. (2009), *Techno-Economic Analysis for the Conversion of Lignocellulosic Biomass to Gasoline via the Methanol-to-Gasoline (MTG) Process*

technical improvement specifically found for MTG, unknown is whether this improvement could be applied for other MTX processes. By introducing hydrogen in the H2G process, called H_2 enhanced MTG synthesis. However, this technical improvement introduced the price of hydrogen into the price of MTG. The price of hydrogen is sufficiently high that the enhanced process will not be commercially viable. [207]

Government intervention at this stage of the technology's development is effective

Cost reduction that can be achieved by scaling up, per cost category

Few studies have been found that look into the cost reduction of MTX as individual technology, so the possible cost reduction is unclear. Some studies have been found that look at the cost reductions possible when taking the full production chain (biomass to gasoline) into account. For that chain, the biomass is a significant share of the production cost. Models show that 16% decrease in the minimum selling price of the MTG gasoline is possible due to economies of scale associated with increased production plant size. Unknown is how much the plant size needed to be increased, but it would put strain on the logistical process. The same model shows that the cost of biomass feedstock can reduce the minimum selling price with 9.6%.[208] These are theoretical figures and have not been demonstrated in practise. Whether these reduction make MTX competitive with crude oil, depends on the fluctuating price of oil. However, it is expected that the price of MTX could come in the same range as crude oil.

Government intervention will have deep and broad impact

Bandwidth of market size for the technology after scale up

While MTX could have its uses, experts indicate that advanced upgrading processes like MTX and Fischer Tropsch should not be the first priority in scaling up. The focus should be on the feedstock and the whole production chain. The chain starts at producing or importing sufficient biomass, then the first links of the chain can be scaled up. For many upgrading processes, these are pyrolysis and gasification. Additionally for MTX, fermentation is included. First, scale up those processes until they make up a solid base. Next, it makes sense to scale up the next link, the upgrading processes link MTX and Fischer Tropsch. Otherwise, upgrading processes will always be limited economically and yield-wise be the previous link in the chain.

When a stable and sizeable supply of renewable methanol is available, MTX could be implemented to produce targeted hydrocarbons.

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[207] Hennig, Haase (2021), *Techno-economic analysis of hydrogen enhanced methanol to gasoline process from biomass-derived synthesis gas*

[208] Tan et al. (2016), *Conceptual process design and economics for the production of high-octane gasoline blendstock via indirect liquefaction of biomass through methanol/dimethyl ether intermediates*

Bandwidth of market size for the technology output after scale up

Hydrocarbons from MTX processes likely have a place in the energy mix of a climate-neutral society. Carbon products are a staple of our energy system and cannot be disregarded and replaced easily. So renewable carbon products, for example from MTX (or Fischer Tropsch), will have a market size. What that market size will be, is highly dependent on developments of the (global) energy mix.

Applicability in number of end-user sectors after scale up

MTX is applicable in three major sectors in the Netherlands. (i) Oil industry, (ii) chemical industry and (iii) mobility.
The oil industry and -infrastructure in the Netherlands is rather advanced and well developed, with large plants around the harbour of Rotterdam. With the transition away from fossil fuels, oil companies are looking at renewable oil processes with increased interest. The biomass-to-liquid chain, of which MTX can be a part, makes a good fit for the existing oil infrastructure.

The chemical industry, for example in Moerdijk and Geleen, has a big presence in the Netherlands. It too has to transition to carbon molecules from a renewable source, instead of relying on fossil fuels.

Finally, the mobility industry is a big consumer of gasoline (and other complex hydrocarbons) currently. For the foreseeable future, gasoline vehicles are likely to have a place on the road. Their carbon footprint can be (partially) reduced by producing green gasoline with MTX.

Experts indicate that in the long term, carbon could become scarce. In that case, using MTX to produce hydrocarbons as feedstock for chemical processes has more economic value that to produce hydrocarbons as fuels. An exception are applications where an energy dense carrier is required that could justify the high price, such as airplane fuel.

Assessment summary

Criterion	Indicators	Current assessment
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	Limited, t is likely that in a climate-neutral society some form of high energy density fuels remain.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, fixed bed reactors are sufficiently developed.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes, no governmental support is present for MTX, only for methanol production.
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes, for MTX in a renewable route including biomass. No for the route based on fossil fuels.

Criterion	Indicators	Current assessment
Government intervention at this stage of the technology's development is effective	Cost reduction that can be achieved by scaling up, per cost category	Unknown, too few studies have been found.
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Limited size, the bandwidth of base processes upstream (such as pyrolysis, gasification and fermentation) should have a significant market share before scaling up MTX.
	Bandwidth of market size for the technology output after scale up	As transition fuel, hydrocarbons from MTX could accelerate the transition away from fossil fuels. In a climate-neutral society, its market share will be limited.
	Applicability in number of end-user sectors after scale up	Three major sectors: Oil/Energy industry, chemical industry and mobility.

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Hydrocarbon production based on Fischer-Tropsch process

Scope and introduction

Fischer-Tropsch is a process that involves the production of liquid hydrocarbons using a mixture of carbon monoxide and hydrogen. For the reactions, catalysts are used, typically at relatively mid to high temperatures (100 to 300 °C). Fischer-Tropsch processes are known in two distinct process options using very different reactor types (fixed bed and bubbling bed) and catalysts (iron and cobalt based). Fischer-Tropsch can play a similar role to MTX in a climate-neutral society. While Fischer-Tropsch requires fewer upgrading steps from biomass, its output is less selective than MTX. Thus requiring cleaning and separation processes. It could play an important role in the carbon-based process biomass-to-x. Although the resulting hydrocarbons are likely to have limited use as a fuel, they could be important for the chemical sector. Therefore, the role of Fischer-Tropsch is limited, but not insignificant.

The technology is necessary in a climate neutral society

Bandwidth of market share in climate neutral society

The Fischer-Tropsch (FT) process is a well-known and mature technology for gas-to-liquid and coal-to-liquid processes. Additionally, FT is a very promising technique to provide renewable alternatives to sectors that are difficult to decarbonise (hard-to-abate sectors). Consortia within Europe (and globally) have already announced commercial plants for the production of renewable fuels. FT here mostly builds upon processes such as gasification, pyrolysis and electrolysis. It is therefore crucial these processes provide a sufficient base for further treatment using FT. Furthermore, FT is promising for the power-to-liquid configuration, where CO2 is converted into a liquid fuel. Generally, power-to-liquid processes are costlier than biomass-to-liquid processes and further developments regarding sourcing of CO2 and direct hydrogenation of CO2 are required to make power-to-liquid mature and commercially viable.

In a quantitative study on a climate neutral energy system, Berenschot and Kalavasta assume that by 2050 the allocation of biomass to biofuels ranges from 21 PJ to 174 PJ. One important issue that was raised during the focus session is that by 2050 it will be much harder to capture and utilise carbon as no or very limited CO2 will be emitted any further. The main future source from carbon will be biomass and could be complemented by direct capture from air or water, though these processes are highly energy-intensive. It will be more likely that carbon-based products, such as those produced by FT, will be used to retain carbon (such as plastics) rather than ignition (rather than fuels).

FT could also be useful as a transition technology, for instance supplementing fossil fuels used for transportation. MTX technologies would be an alternative technology for these applications. The main benefit for FT in comparison to MTX is that no methanol conversion is required. On the other hand, MTX is more selective in its output, which is a distinct advantage compared to FT.

The technology is ready for scale up, but needs government help to do so

Technology is sufficiently developed and tested in pilot-phase (y/n)

The literature review of the ETIP Bioenergy results of several pilot and demonstration facilities were compared and analysed. It was concluded that depending on the process configuration, conversion technology, feedstock cost, plant capacity, product type (crude or upgraded), coproducts incentive and other economic assumptions, production costs of 42 – 140 €/MWh FT liquid were reported for biomass-to-liquid technologies.

A few studies have looked at the potential for power-to-liquid configuration. Hannula and Reiner indicated that depending on the carbon intensity of the electricity source, electricity price and investment cost (low and high scenarios), the estimated breakeven fossil oil prices required to match the corresponding biofuel production costs were 146–188 €/MWh (solar PV), 214–233 (solar thermal), 93–111 (onshore wind), 169–189 (offshore wind), 220–231 (nuclear), 159–170 (geothermal) 245–256 (EU-28 average), 312–323 (Germany), 197–208 (France), 152–163 (Sweden) and 181–192 (Norway). The estimated production cost range for a corresponding biomass-to-liquid plant, which assumed lower heating values conversion efficiency of 40%, was 58–74 €/MWh.

In conclusion, FT is sufficiently developed and tested in the pilot phase, both for biomass-to-liquid as well as power-to-liquid processes. Though, CO2 sourcing is another issue. The availability of biomass is generally low compared to carbon feedstocks in industry.

Current government support schemes for demonstration projects are insufficient (y/n)

There are multiple projects on a pilot, demonstration and commercial scale for both biomass-to-liquid as well as power-to-liquid processes. The following two tables present a selection of example plants, based on the literature review of ETIP Bioenergy.

One issue raised in the focus session is that FT processes might not economically or even technically be available to run intermittently, whereas current processes are designed to run continuously. This means that in future scaled-up application it needs to be made sure that a continuous flow of input (biomass and hydrogen) is available, or intermittent application of FT needs to be developed and demonstrated. This likely requires government support.

In conclusion, Horizon2020 provides opportunities for demonstration projects to be developed, depending on the level of maturity of the entire process (from feedstock to output) no additional support is needed.

Table 0.10 Selection of biomass-to-liquid facilities in Europe

Organisation	Project	Year / target	Conversion	FT technology	Finance / status	Scale-TRL	Feedstock
Essar Oil (UK), Fulcrum Bioenergy (Stanlow, UK)	Fulcrum NorthPoint	2025	TRI steam reformer	JM/BP FT technology	Estimated budget £600 million	Annual SAF production 100 million liters	Municipal solid waste
British Airways/Shell/Velocys (Immingham, UK)	Altalto	Q2 2021	TRI steam reformer, POX-Arvos Schmidtsche-Schack with Linde's oxygen burner	Velocys technology, Haldor Topsoe upgrading	planning permission granted (June 2020)	60 million liters/y (SPK jet fuel, diesel and naphtha) (commercial)	Municipal solid waste 500 ktonnes
UK (University of Manchester, Argent Energy), Netherlands (TU/e, TNO innovation for life), CSIC (Spain), vito (Belgium), Italy (CiaoTech, Siirtec Nigi), Germany (INERATEC, C&CS)	GLAMOUR	2020-2024	ATR/ gasification		EU Horizon 2020	Aviation & Marine fuels (demo)	Bio-based glycerol
Finland (VTT, AF-CONSULT OY), Germany (INERATEC, GKN, DLR EV), UniCRE AS (Czech), AMEC SRL (Italy)	COMSYN	2017-2021	DFB, steam-blown, 100 kg/h feedstock, 700–820℃, 1–3 bar	INERATEC (MOBSU)	EU Horizon 2020	Gasifier (demo), FT (lab or pilot)	Bark
Finland (VTT), Germany (INERATEC, Infraserv Höchst, ALTANA, Provadis Hochschule), Italy (Politecnico di Torino)	ICO2CHEM	2017-2021	Industrial CO2, RWGS	INERATEC microchannel reactor	EU Horizon 2020	Biogas (demo), FT (pilot), electrolysis (pilot)	Industrial CO2, electricity
Axens, CEA, IFP Energies Nouvelles, Avril, ThyssenKrupp Industrial Solutions, Total (Dunkirk, France)	BioTfueL	2021				60 t/y FTP (diesel and jet fuel) (demo)	straw, forest waste, dedicated energy crops

Table 0.11 Selected overview of power-to-liquid plants in Europe

Organisation	Project	Country	Year/target	Conversion	FT process	Production	CO2-source
Nordic Blue Crude AS, Sunfire, Climeworks, EDL Anlagenbau	Nordic Blue Crude[209]	Norway	2022	SOEC, RWGS		Commercial 8000 t/y FT	DAC, industrial
Rotterdam The Hague Airport, Climeworks, SkyNRG, EDL Anlagenbau, Schiphol, Sunfire, Ineratec, Urban Crossovers	The Zenid project[210]	Netherlands	Announced May 2019	SOEC, Co-electrolysis	Microstructures channel reactor	Demo 1000 liters/day	DAC
KIT, Climeworks, Ineratec, Sunfire	PtL test facility[211]	Germany	2019	SOEC, Co-electrolysis	Microstructured channel reactor	Pilot 10 liters/day	DAC

209 Kopernikus-Project P2X. 2022. (link)
210 Rotterdam The Hague Airport. 2022 (link)
211 opernikus-Project P2X. 2022. (link)

Market introduction is not commercially viable, even including existing government support schemes

Concluding from Tables 1 and 2, there are some facilities that run commercially viable, though others are less mature and need governmental support. This is largely dependent on process configuration, conversion technology, feedstock cost, plant capacity, location of the facility and other economic incentives

One commercial facility using gasification will be installed in Port of Rotterdam and upgraded to use for the production of Sustainable Aviation Fuel (SAF). Shell and Enerkem are expecting favourable support under the Renewable Transport fuels regulations for the production of SAF from low-grade, post-recycling mixed waste. In light of the above – and given the capacity for Enerkem, together with Shell, to provide an end-to-end technical solution for converting hard-to-recycle waste into jet fuel by combining Enerkem's waste gasification technology and Shell's Fischer-Tropsch technology – the partners in the project have decided to repurpose the current project to focus on SAF production. The project would process up to 360,000 tonnes per annum of recycling rejects and produce up to 80,000 tonnes of renewable products, of which around 75% could be SAF and the remainder used for road fuels or to feed circular chemicals production. Final Investment Decision has been taken in 2021.

Government intervention at this stage of the technology's development is effective

Cost reduction that can be achieved by scaling up, per cost category

Based on inputs from the experts advanced upgrading processes like FT should not be the first priority in scaling up. The focus should be on the feedstock and the entire production chain. The chain starts at producing or importing sufficient feedstock (biomass), so that the first links of the chain can be scaled up. This is also where potentially the highest cost reduction is expected to take place. For many upgrading processes, these are pyrolysis and gasification. First, scale up those processes until they make up a solid base. Next, it makes sense to scale up the next link, the upgrading processes like FT.

It should be noted though that the requirement regarding the availability of sufficient carbon (through biomass) and continuous availability of hydrogen are main determinants for the scalability of FT processes. Hence, these inputs are main cost determinants in a fully renewable, carbon-zero future. One would not propose intermittent operation here, since the reaction products can be many depending on operational conditions.

In conclusion, similar to gasification large-scale integrated processes are economically viable, but come with high investment costs and associated risks. Government support is thus needed to develop facilities that benefit from economies of scale, while technology is develop further.

Government intervention will have deep and broad impact

Bandwidth of market size for the technology after scale up

FT is a well-known technology for several decades and has been widely used in producing liquid hydrocarbons. Combining the technology with biomass feedstocks (after gasification and pyrolysis) and electrolysis allows for the production of net-zero synthetic fuels and chemicals. Moreover, it gives a promising option to diversify from several inputs and outputs and can thus play an important role in the future use of energy. The non-energy use is required to replace current fossil sources.

Bandwidth of market size for the technology output after scale up

The output of FT can be used widely and provide opportunity for greening hard-to-abate industries. Fuels and oils from biomass processed by FT are a promising means of replacing conventional processes and energy use. Power-to-liquid solutions (and FT processes using CCS) would in the longer term be able to produce carbon negative outputs, though significant higher energy use accompanies this process. This is also more viable when hydrogen is abundant. Simple carbonisation of biomass may be an alternative for long term sequestration of carbon in solids.

Applicability in number of end-user sectors after scale up

FT is applicable in three major sectors in the Netherlands. (i) Oil industry, (ii) chemical industry and (iii) mobility.

The oil industry and -infrastructure in the Netherland is rather advanced and well developed, with large plants around the port of Rotterdam. With the transition away from fossil fuels, oil companies are looking at renewable oil processes with increased interest. The biomass-to-liquid chain, of which FT can be a part, makes a good fit for the existing oil infrastructure.

The chemical industry, for example in Moerdijk and Geleen, has a big presence in the Netherlands. It too has to transition to carbon molecules from a renewable source, instead of relying on fossil fuels.

Finally, the mobility industry is currently a big consumer of gasoline (and other complex hydrocarbons). For the foreseeable future, gasoline vehicles are likely to have a place on the road. Their carbon footprint can be (partially) reduced by producing green gasoline with MTG.

In conclusion, FT products are of specific interest for hard to abate sectors, such as aviation, shipping and the chemical sector. According to the experts it is likely though that at some point mostly the chemical sector would make most use of FT products. Depending on the availability of carbon, and thus the price of the end products, it might also be used for sustainable air fuels.

Current assessment summary

Criterion	Indicators	Current assessment
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	Limited, but not insignificant. It is likely that in a climate-neutral society some form of high energy density fuels remain.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, Fischer-Tropsch is a mature technology.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes, Horizon 2020 supports European demonstration facilities, intermittent processes might be demonstrated. It is not sufficient for large scale implementation.
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes, mostly dependent on feedstock used, CO_2 capture, and maturity of 'chain' processes such as gasification.
Government intervention at this stage of the technology's development is effective	Cost reduction that can be achieved by scaling up, per cost category	Cost reduction is expected for the entire production of a carrier, though it will likely not take place in FT (rather gasification).
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Multiple inputs possible, could contribute to energy diversification. Highly dependent on availability of biomass feedstock as carbon input, which is likely to be limited.
	Bandwidth of market size for the technology output after scale up	FT outputs have a broad application. In a climate-neutral society, its market share will be limited.
	Applicability in number of end-user sectors after scale up	Applicability for transport, refinery sector, chemical sector (most likely).

Electrolytic Haber-Bosch ammonia production

Scope and introduction

This assessment will focus on the Haber-Bosch process itself. Hydrogen is needed for this process. The main technologies for that (electrolysis / pyrolysis) are introduced and assessed in separate technology overviews in this Annex. When needed, electrolysis will be referenced to as the standard method of hydrogen production for green ammonia, due to electrolysis' higher maturity compared to pyrolysis.

Haber-Bosch ammonia production

Ammonia is listed as a tertiary energy carrier (power-to-x technology). This implies that it needs another carrier, hydrogen, as input, which is then converted to produce ammonia. Conventionally ammonia is used in fertilizer products on a large scale. Ammonia as an energy carrier has several key benefits over conventional hydrogen. First of all, the energy density is significantly higher. Liquid ammonia has an energy density of 12.7 MJ/L, compared to liquid hydrogens' 8.5 MJ/L[212]. Secondly, the storage conditions needed for ammonia are much more lenient. Liquid ammonia is storable at -33°C, while hydrogen requires cryogenic conditions of -253 °C to achieve the stated volumetric energy density. A table of key performance indicators of EHB ammonia production is listed below.

The Haber-Bosch process uses a feedstock of hydrogen for the reaction. However, it does not matter for the reaction when or in which way this hydrogen is produced. The hydrogen production process is exchangeable, or may even be supplied externally.

Table 0.12 Key performance indicators of electrolytic Haber-Bosch ammonia production[213]

Parameter	Value
Inputs	H_2O (from water), N_2 (from air), electrical energy
Desired output	NH_3
Waste outputs	None
Process efficiency	62-65%

212 Tullo (2021). Is ammonia the fuel of the future? Industry sees the agricultural chemical as a convenient means to transport hydrogen, link

213 Smith, Hill & Torrente-Murciano, (2020). Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape. *Energy & Environmental Science*, *13*(2), 331-344, link

The technology is necessary in a climate neutral society

i. Bandwidth of market share in climate neutral society

Green ammonia production through the Haber-Bosch process is used in several ways in climate neutral scenario analyses. The Dutch climate-neutral outlook by Berenschot[214] sees roles for Haber-Bosch ammonia as both a carbon-neutral energy carrier and as a fertilizer material. Furthermore, the shipping industry sees opportunities for green ammonia as a fuel for international freight shipping, both as a fuel for ships and as a payload to transport energy over long distances[215].

Currently, ammonia serves as a vital product for synthetic fertilizers. This use case is likely to persist in a climate neutral society on some scale using green ammonia. Converting a regular fossil Steam-Methane reforming-based (SMR) ammonia plant to green ammonia primarily involves switching to green hydrogen production. The Haber-Bosch process itself is unaltered in this transition. Research indicates that the barriers for replacing SMR with electrolysis are mainly economic, not technical[216].

As an energy carrier, the market share of green ammonia is heavily dependent on the development of green hydrogen. Because ammonia uses green hydrogen as a feedstock, the technology is limited by the availability of green hydrogen. Green ammonia can find market share in areas where the efficiency loss of converting hydrogen to ammonia is worth the benefits. Areas where that might be the case are in the transport sector as a substitute for bunker fuels and in long distance transport of green energy.

Experts highlight another use case of ammonia that is relevant in a climate neutral society. When hydrogen is produced on a large scale through renewable electricity sources, for example when electrolysers are combined with large offshore windparks, large peaks of hydrogen production occur. On windy days a surplus of hydrogen can be produced, that has to be stored somewhere. Experts indicate that ammonia is an efficient storage vessel and that ammonia plants can compete with salt-cavern hydrogen storage economically. The ammonia itself can easily be stored in large tanks.

The technology is ready for scale up, but needs government help to do so

i. Technology is sufficiently developed and tested in pilot-phase

The classical Haber-Bosch ammonia production process is widely used in the fertilizer sector. Nearly all of the ammonia produced annually in the Netherlands is created using the Haber-Bosch process[217]. Naturally, this means that large scale production facilities are currently in operation. The key installations in this field are shown in Table 0.13.

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214 Berenschot & Kalavasta (2020). Klimaatneutrale energiescenario's 2050 – scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, link

215 Sveistrup Jacobsen, Krantz, Mouftier,& Skov Christiansen (March 14, 2022). Ammonia as a shipping fuel [Webinar], link

216 Planbureau voor de Leefomgeving (2019). Decarbonisation options for the Dutch fertiliser industry, link

217 Planbureau voor de Leefomgeving (2019). Decarbonisation options for the Dutch fertiliser industry, link

Table 0.13 Installed capacities of the two largest ammonia producers in the Netherlands

Plant	Installed production capacity (kton ammonia / year)	Ammonia production process	Hydrogen production process	Mton CO_2 emissions per year
Yara Sluiskil	1820	Haber-Bosch	SMR	3.2
OCI Nitrogen	1200	Haber-Bosch	SMR	2.2

The large CO_2-emissions that accompany the ammonia creation in these plants comes primarily from the hydrogen feedstock creation. Traditionally the emission-intensive Steam-Methane Reforming (SMR) is used to create the necessary hydrogen. However, SMR is not a necessary process in the Haber-Bosch reaction. Table 0.14 gives an oversight of two demonstration projects specifically targeted at EHB power-to-ammonia.

Table 0.14 Overview of EHB power-to-ammonia projects in the Netherlands

Project	Production capacity (kton ammonia / year)	Ammonia production process	Electrolysis capacity (MW)	Operational
Power-to-ammonia, Goeree-Overflakkee[218]	3.5	Haber-Bosch	27	No
Yara / Orsted, Sluiskil Power-to-ammonia[219]	70	Haber-Bosch	100	No

One area of interest that has not been studied at significant level in pilot or demonstration plants, is the reaction of Haber Bosch to intermittent operation. It is unclear to what degree Haber Bosch plants are vulnerable to repeated starts and stops of the process, set out by intermittent hydrogen supply. Experts mentioned that several large ammonia producers (Topsoe and ThyssenKrup) and power suppliers recently have started to look into the matter. The function of ammonia as large scale carbon free hydrogen storage means that intermittent operation is essential since the reason for storage is the intermittency itself. Challenges are on technological as well as economic aspects since intermittent operation implies relatively low capacity factors and therefore increased capex per output unit.

ii. Current government support schemes for demonstration projects are insufficient

The Haber-Bosch process itself is not included in the SDE++. This is no surprise, given that the Haber-Bosch is extensively used, scalable and well-understood. The support schemes necessary for EHB rely on subsidies for hydrogen electrolysis. Electrolysis is covered in the SDE++ and is also eligible for many other subsidy schemes. The adequacy of electrolysis subsidies will likely determine the growth of power-to-ammonia installations.

218 Proton ventures (December 13, 2018). Demonstratiefabriek voor groene ammoniak op Goeree Overflakkee, link
219 Yara (December 7, 2020). ESG investor seminar [Seminar], link

iii. Market introduction is not commercially viable, even including existing government support schemes

Unfortunately, hydrogen production through electrolysis is not commercially viable on scale compared to SMR, even with the current subsidy schemes. The market reflects this. SMR is being used to create hydrogen for all large scale ammonia plants. For EHB green ammonia to scale up, the key is for electrolysis-based hydrogen to come down in price[220].

The costs of electrolysis installations are an important factor in determining the resulting price of electrolyser-based hydrogen. The other important factor being the price of electricity. Irena[221] estimates that, if rapid scale-up is to take place, green hydrogen from PEM and Alkaline electrolysis will be able to compete with blue hydrogen by 2030. However, the main contributing factor to the competitiveness of electrolysis-based hydrogen was found to be the price of electricity. “cost reductions in electrolysers cannot compensate for high electricity prices” (Irena).

In order to compensate for the unprofitable top costs of scaling up hydrogen, the Dutch government provides additional subsidies through the SDE++[222]. However, the instrument has proven to be too limiting for large electrolysis scale-ups, as none have formed as of yet following the release of the subsidy.

Government intervention at this stage of the technology’s development is effective

i. Cost reduction that can be achieved by scaling up, per cost category

The Haber-Bosch process already exists on megaton scale, although not operated intermittently. Further significant cost reduction through subsidy schemes is not expected to occur, except for adaptations that come with the intermittent operation.

Alkaline and PEM electrolysis are both expected to fall in costs substantially, for details we refer to the technology overview on electrolysis.

Government intervention will have deep and broad impact

i. Bandwidth of market size for the technology after scale up

Literature shows that there are two main pathways for creating green ammonia[223]:

- Traditional SMR based Haber-Bosch with Carbon Capture and Storage (CCS)
- Haber-Bosch with green hydrogen, most likely produced through electrolysis

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220 Planbureau voor de Leefomgeving (2019). Decarbonisation options for the Dutch fertiliser industry, link
221 IRENA (2020). Green hydrogen cost reduction – scaling up electrolysers to meet the 1.5°C climate goal, link
222 Planbureau voor de Leefomgeving (2021). Conceptadvies SDE++ 2022 waterstofproductie via electrolyse, link
223 Planbureau voor de Leefomgeving (2019). Decarbonisation options for the Dutch fertiliser industry, link

The difference lies in whether it is more desirable to mitigate the negative effects of a carbon-based process (CCS), or to replace the process entirely with a carbon free option (EHB). Both pathways have their advantages and disadvantages. It is possible to add CCS installations to existing SMR installations to prevent CO_2 emissions into the atmosphere. The downside is that CCS is an energy intensive process, which will reduce the overall process efficiency. Green hydrogen through electrolysis is currently still more expensive than CCS-based blue hydrogen. Still, the supply of hydrogen is such a large component of Haber Bosch, that Haber Bosch could be conceived as a logical next step of the chain.

ii. Bandwidth of market size for the technology output after scale up

A hard limitation of EHB is the process efficiency. Being a tertiary fuel, EHB ammonia will by definition require an extra conversion step on top of hydrogen electrolysis. The process efficiency of EHB ammonia production will therefore always be lower than electrolysis by itself. Application of ammonia as an energy carrier will therefore emerge where ammonia's key characteristics (Table 0.12) are most useful.

Ammonia's higher energy density and more lenient storage conditions make it an attractive green fuel for the shipping industry[224]. Scenario analyses by DNV[225] estimate ammonia to be widely adopted in the shipping industry starting from 2037, reaching a 25% market share in 2050. In 2021, the shipping industry used 8.7 EJ in fuel. As a point of reference, this amount of energy requires 462 Mton of ammonia. Of course, fuel consumption is not expected to stay at the same level, but the order of magnitude shows that there is ample room for the scaling up of EHB green ammonia, even at a lower market share.

Additionally, ammonia's properties also allow for more energy to be stored in the same volume compared to hydrogen. When scaled up, ammonia can be a carrier of hydrogen for long distance energy importing[226]. This transportability does come with the caveat that potential Dutch green ammonia producers will have to compete with other countries which might benefit from lower renewable energy costs.

iii. Applicability in number of end-user sectors after scale up

Green ammonia as an energy carrier, as stated in the previous paragraph, is mainly expected to be used in the shipping and energy transport industries. Other (current) uses such ammonia as feedstock for industry and as fertilizer are kept out of scope, because these uses do not deploy ammonia specifically as an energy carrier

Assessment summary

Criterion	Indicators	Current assessment
The technology is necessary in a climate neutral society	Bandwidth of market share in climate neutral society	Yes, it is one of the most efficient chemical storage vessel for hydrogen, allowing

224 Sveistrup Jacobsen, Krantz, Mouftier,& Skov Christiansen (March 14, 2022). Ammonia as a shipping fuel [Webinar], link
225 Brasington, L. (November 25, 2019). Green Ammonia – Potential as an Energy Carrier and Beyond. *Cleantech Group,* link
226 Van der Ent (n.d.). (Groene) ammoniak heeft potentie als drager van waterstof, link

Criterion	Indicators	Current assessment
		easy and long term energy storage.
The technology is ready for scale up, but needs government help to do so	Technology is sufficiently developed and tested in pilot-phase (y/n)	Yes, Haber Bosch is a mature technology.
	Current government support schemes for demonstration projects are insufficient (y/n)	Yes, support for Haber Bosch is limited. Support for scaling up electrolysis and intermittent operation of Haber Bosch is needed.
	Market introduction is not commercially viable, even including existing government support schemes (y/n)	Yes, the price of green hydrogen is too high.
Government intervention at this stage of the technology's development is effective	Cost reduction that can be achieved by scaling up, per cost category	Significant cost reductions are possible in the hydrogen component of ammonia production.
Government intervention will have deep and broad impact	Bandwidth of market size for the technology after scale up	Widespread adoption in the shipping industry and hydrogen storage.
	Bandwidth of market size for the technology output after scale up	25% market share of shipping fuels by 2050, large bandwidth for hydrogen storage and other uses.
	Applicability in number of end-user sectors after scale up	Shipping, energy import and -export, energy storage and fertilizer industry.

Sources

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IEA (2019). The Future of Hydrogen, link

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IRENA (2021). Making the breakthrough – Green hydrogen policies and technology costs, link

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