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Pathways to industrial decarbonisation in the Netherlands: paper & board and steam cracking

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Summary

This report is a result of the MIDDEN+ project, a pilot project that was undertaken as an exploration of the possibilities for future developments of the MIDDEN database, especially concerning additional data for complex and impactful decision-making, facilitating the transformation to a CO_2-neutral industrial sector. The project sought to address gaps in the existing data, and areas where additional data collection and research might improve the usefulness or flexibility of the datasets, and then demonstrate the potential for analysis using the datasets. This research project has extended the MIDDEN database to better cover disruptive technologies, combinations of emissions reduction options, uncertainties related to techno-economic data and future technology cost. Two sectors – paper and board and steam cracking – were chosen for this exploratory work.

MIDDEN (Manufacturing Industry Decarbonisation Data Exchange Network), a joint project of the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Organization for Applied Scientific Research (TNO), has built a knowledge base with up-to-date information on Dutch energy-intensive industries. The MIDDEN database contains information on industrial locations, detailing their current processes and products, energy consumption and emissions, in addition to a wide variety of decarbonisation technology options that aim at deep emissions reduction for 2050, in line with the Paris Agreement. Information on current processes and products are verified with industrial companies.

Uncertainty in techno-economic data for technological alternatives in the industrial sector is an important issue. Measuring the scale of the challenge of decarbonisation hinges on good estimates of cost and energy implications of changing processes and technologies. This report aims to assess the uncertainty inherent in the techno-economic data used in energy systems analysis and industrial sector decarbonisation pathways.

Furthermore, uncertainty about techno-economic parameters increases when we consider technology learning. Future cost and performance data requires even further underlying assumptions, and the addition of a qualitative assessment of this potential in this report can aid researchers in understanding the implications and validity of their technology learning assumptions.

Beyond the uncertainties in the techno-economic data in our dataset, we have also highlighted system issues beyond the plant fence that affect the prospects for different decarbonisation pathways and technologies. Energy prices, low-carbon energy availability, and electricity grid emissions intensity can be deciding factors in the future roles of these decarbonisation options. Based on the dataset and this analysis, this report provides indicative values to the scale of systemic uncertainties and interactions, such as the availability of excess fuel gas and residual heat from steam crackers, the need for additional green electricity or green hydrogen in a number of applications, or impacts from the use of biomass, biofuels, or plastic waste.

The MIDDEN+ project and this report aim to provide additional substance and nuance to the available techno-economic data on the Dutch industrial sector, expanding and improving the MIDDEN database and indicating areas for future work.

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1 Introduction

1.1 Dutch industry in context

The industrial sector accounts for almost one fifth of Dutch GDP (CBS, 2018), and as of 2018, for almost 10% of total Dutch employment (with approximately 250,000 employees) (Berenschot, 2017a; CBS, 2018). The Dutch industry sector is also responsible for 31% (56.7 $MtCO_2$-eq in 2019) of the total greenhouse gas (GHG) emissions of the Netherlands (PBL, 2020a)**.** This is mainly due to a large energy demand, about 45% (1,392 PJ in 2019, which includes energy sources as feedstock) of the final total Dutch energy use (PBL, 2020a).

In order to lower European greenhouse gas emissions and to combat climate change, the EU endorsed the Paris Climate Agreement in 2016, with targets of reducing GHG emissions by at least 40% by 2030, and 80-95% by 2050, compared to 1990. The National Climate Agreement has a higher ambition for the Netherlands for 2030, namely to reduce GHG emissions by 49% compared to 1990 (Rijksoverheid, 2019). Moreover, the Dutch government is promoting raising the EU target to 55% for 2030 (European Commission, 2019).

To achieve the EU and Dutch targets, decarbonising the industrial sector must play an important role. There are a number of challenges, however, that the industrial sector faces on decarbonisation (Berenschot, 2017b).

1. **Heat demand**, especially high-temperature heat demand, can be costly and complex to decarbonise. Thermal energy demand makes up a large share of the total energy demand in the Dutch industrial sector.
2. **Feedstock and non-energy use** of fuels is also difficult to decarbonise, and emissions impacts occur mainly at the end of final product lifetimes, complicating incentives and policy measures aimed at these emissions.
3. **Process emissions** which result from chemical reactions in industrial production processes cannot be reduced without either carbon capture or alternative processes.
4. **Integration between sites and complexity of process equipment** can make retrofits and equipment replacement costly and complex. Many of the energy-intensive industrial sites in the Netherlands are located in clusters, with shared infrastructure and optimised energy flows; changes in one site can affect multiple others.
5. Many industrial sectors produce globally traded commodities, and for historical and geographical reasons, Dutch industry produces a large share of its products for export. **Strong global competition within these sectors and the risk of “carbon leakage”** to countries with less stringent environmental and climate regulation can make it more difficult for some industrial sectors to implement costly decarbonisation measures.
6. **Growing demand for industrial products** globally means that even as industrial processes become less CO_2- and energy-intensive, the absolute energy demand and resulting emissions continue to increase.

There are other challenges to meet the Dutch emissions reduction targets, such as the need for an affordable long-term supply of low-carbon energy carriers, such as biomass and renewable electricity. These affect the industrial sector, but cannot be solved by individual plants or sectors; system-level strategies are needed to deal with potential supply limitations. The MIDDEN and MIDDEN+ projects aim to provide publicly available, factual information on as many decarbonisation options as possible, in order to facilitate and improve policymaking and decision-making in this area. The importance of reliable datasets and the analyses based on it is underscored by the complexity of the challenge of industrial decarbonisation.

Below are the categories of decarbonisation options considered in the MIDDEN project and in the MIDDEN+ analysis (see paragraph 1.2). Some address only direct on-site emissions, while others address scope 2 and 3 emissions from energy and material inputs to the process. Industrial decarbonisation in the long term will require a combination of these strategies, dependent on site, sector, geographical, and temporal considerations.

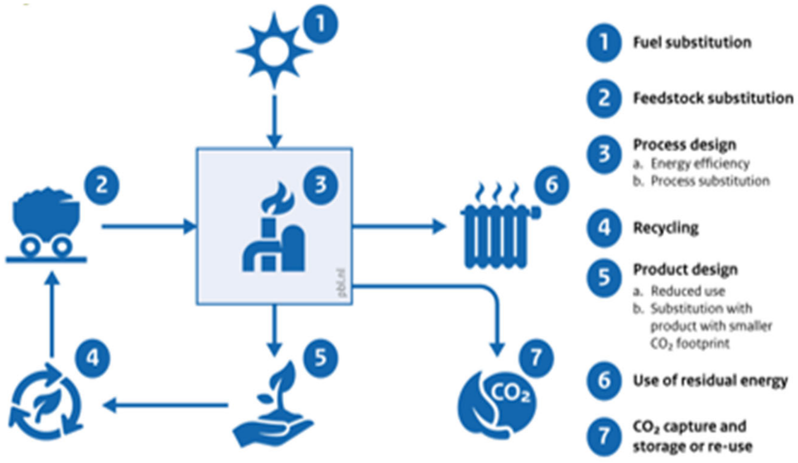

Figure 1 CO_2 reduction categories in the MIDDEN project (Schure et al., 2019)

1.2 MIDDEN and MIDDEN+ projects

MIDDEN (Manufacturing Industry Decarbonisation Data Exchange Network), a joint project of the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Organization for Applied Scientific Research (TNO), has built a knowledge base with up-to-date information on Dutch energy-intensive industries. The MIDDEN database contains information on industrial locations, detailing their current processes and products, energy consumption and emissions, in addition to a wide variety of decarbonisation technology options that aim at deep emissions reduction for 2050, in line with the Paris Agreement. Information on current processes and products are verified with industrial companies. The goal of this database is to provide a broadly accepted, publicly available, factual basis for decision making on the energy transition.[1] The strength of MIDDEN lies in its granular data on specific industrial sites and industries, developed with support and review from its network of industrial stakeholders. The MIDDEN dataset and published reports, at the time of publication, covered about 40% of emissions from Dutch industry that fall under the EU

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[1] Further information about MIDDEN, published reports, and the downloadable database can be found on the project website: https://www.pbl.nl/en/middenweb.

ETS system. When the additional reports in progress are completed, about 95% of emissions will be covered.

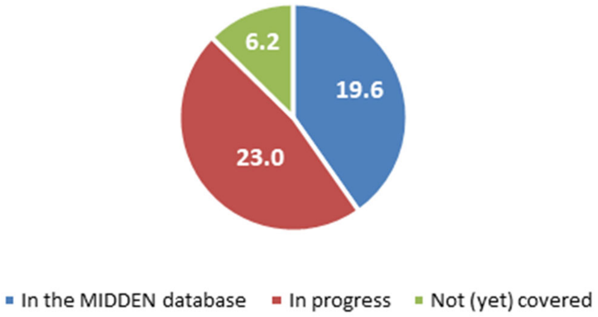


Figure 2: Amount of Dutch industrial emissions (Mt CO_2-eq) of companies that fall under the EU ETS system covered in the MIDDEN database at the time of publication (TNO and PBL, 2019)

The MIDDEN+ project is an extension of the research conducted under the TNO research program Industrial Transformation and in line with the MIDDEN project. MIDDEN+ was a pilot project that was undertaken as an exploration of the possibilities for future developments of the MIDDEN database, especially concerning additional data for complex and impactful decision-making, facilitating the transformation to a CO_2-neutral industrial sector. The MIDDEN+ project sought to address gaps in the existing data, and areas where additional data collection and research might improve the usefulness or flexibility of the datasets, and then demonstrate the potential for analysis using the datasets. These aspects were chosen as a result of an internal review of the progress in the MIDDEN project to date, and to help with defining a direction for future work for MIDDEN.

The project has extended the database to better cover disruptive technologies, combinations of emissions reduction options, uncertainties related to techno-economic data and future technology cost. This extended dataset was the basis for two sector case studies of decarbonisation pathways. The analysis was carried out by TNO researchers, while engaging key stakeholders in industry and promoting cooperation with the MIDDEN project and the use of MIDDEN data. Two sectors– paper and board and steam cracking – were chosen for this exploratory work, as test cases.

The MIDDEN project has published detailed sector reports on the paper and board (Rademaker & Marsidi, 2019a) and steam cracking (Oliveira Machado dos Santos & van Dril, n.d.; Wong & van Dril, 2020) sectors. These reports were the starting point for this research, and provided a foundation for understanding the role of these sectors in the Dutch energy system and economy, and the range of decarbonisation options available to them. The authors of these reports also built the network of stakeholders for these sectors, which provided the basis for further collaboration with them in the MIDDEN+ project. This report is intended to complement the information published in those reports.

In Chapter 2, the methodology and scope of the MIDDEN+ work is described. In Chapters 3 and 4, a brief description of the current industry and production process is given, for paper and board and steam cracking respectively, and a description of the decarbonisation technologies and combinations added to the database. These additions are then used for analysis of different decarbonisation options from three perspectives: greenhouse gas emissions, energy use, and cost. Chapter 5 includes discussion of the key findings and conclusions.

2 Methodology

2.1 Database additions

Reducing industrial emissions is not a straightforward task. To overcome existing and future hurdles and to achieve a major reduction in emissions, rapid implementation of low-carbon technologies is required. However, to select and support the right technologies, companies and policymakers need adequate publicly available, fact-based knowledge on suitable technologies at the sector, site, and process level, and reliable estimations of decarbonisation options' performance and cost. Moreover, when multiple decarbonisation technologies are implemented at the same time they may influence each other, inside and outside the site fence, making it important to take these effects into account to select a logical decarbonisation pathway.

Via the MIDDEN+ project, additional technologies and site configurations have been added to the dataset for the steam cracking and paper and board sectors. These additional technologies have been researched and selected by the project team, in consultation with industry sector stakeholders, to provide a wider range of options to decarbonise these sectors. The new data has been included in the same format as the original MIDDEN dataset, and is intended to complement and expand upon the initial sector reports. These additional options expand the possible pathways that can be described using this dataset.

- **Additional techno-economic data for disruptive or low TRL technology options**
  New options have been added to both sectors which are not currently commercialized. While low TRL technologies were already within the scope of the original reports, the MIDDEN+ project sought to dedicate additional time to gather data on technologies that may have been omitted due to lack of publicly available data during the initial projects.
- **Additional technology combinations and configurations**
  Combinations of technology options and new sectoral configurations were added in order to broaden the applicability of the database and to provide additional flexibility to the users of the database. These take into account combinations of the newly added technologies with previously included options.
- **Assessment of uncertainty**
  Emissions reductions from pre-commercial technologies and those currently at a low level of technological maturity may play an important role in the energy transition; however, interpretation of techno-economic data can be difficult. Similarly, when only limited public information is available, or validation is not possible, the uncertainty associated with the dataset increases. In order to assist users of the dataset in understand and interpreting results based on the MIDDEN+ data and making choices about their assumptions, the project team has qualitatively evaluated the uncertainty of technology data. The knowledge basis for the current techno-economic data is assessed using the pedigree matrix methodology (further discussed in Chapter 2).
- **Qualitative assessment of potential for future cost reductions from technology learning**
  The potential for cost reductions based on technology learning is also evaluated qualitatively, according to the methodology described in the following section. This allows users to better evaluate their assumptions about technology learning, and expectations of future cost developments, when no explicit data is available.

These developments in the database will provide a broader range of decarbonisation options in these sectors, and guidance for users of the MIDDEN dataset. The dataset can be used to build a variety of pathways or scenarios of decarbonisation of the industrial sector, as it does not provide normative judgements of the options. The below case studies demonstrate the potential for the additional datapoints to be used in analysis of the industrial sector, and a methodology for modellers and policymakers to interpret the inherent uncertainties in techno-economic datasets.

Each decarbonisation option offers different advantages and disadvantages. The impacts of each technology must be compared from different perspectives in order to determine the optimal choice. A full analysis from the site perspective would require more information, including process modelling and consideration of costs and benefits for the business, such as downtime, productivity effects, internal rate of return, cost of capital and priorities within the overall business strategy. From the societal perspective, again, additional information is required to make an optimal choice, including consideration of infrastructure planning, costs and benefits to consumers, subsidy expenditures, and environmental and energy policy goals, potentially utilising energy systems models to build scenarios at regional, national, or international levels as part of this process. All of this requires up to date and reliable data about current industrial processes and (future) effects of decarbonisation technologies, and the MIDDEN+ dataset is intended to provide a part of the data needs for such analysis. The full cost benefit analyses and scenario exercises discussed above are beyond the scope of the work in MIDDEN+. However, the data collected can be used to provide some limited insights and compare technologies on a few key criteria – GHG emissions, energy use, and cost – demonstrating the potential to use this dataset for analysis of decarbonisation pathways for the industrial sector.

2.2 Uncertainty assessment with pedigree matrices

In this project, quality assessment is based on a pedigree matrix, which was developed and applied in the project HyChain 3 (Kennedy et al., 2019a). This matrix was based on pedigree matrices available in literature (van der Spek et al., 2016). The pedigree matrices are defined for four quality criteria: proxy, empirical basis, methodological rigour and validation. The scores range from 0 to 4, where 4 represents the best possible quality. Low scoring data should not necessarily be interpreted as invalid or incorrect, but should be considered to have a greater level of uncertainty and require greater caution in its application. This approach allows us to assess the robustness and uncertainty of the selected indicators for the technologies and decarbonisation options in MIDDEN+. Further, it provides a high level view of where the MIDDEN+ data could be improved in the future with additional or updated data, validation, or new knowledge. The project team scored technical and economic data for each new technology collaboratively. The results are discussed in Chapters 3 and 4.

Definitions of the 4 quality criteria are based on (van der Spek et al., 2016) and adapted from (Kennedy et al., 2019b) defined as follows:

- *Empirical basis*
  Empirical basis refers to which extent direct observations, measurements and statistics are used to estimate the parameter. When the parameter is based upon good quality observational data, the pedigree score will be high. Sometimes directly observed data are not available and the parameter is estimated based on partial measurements or calculated from other quantities. Parameters determined by such indirect methods

have a weaker empirical basis and will generally score lower than those based on direct observations.

- *Proxy*
  Proxy refers to how well or closely a measure represents a quantity that cannot be measured directly. Sometimes it is not possible to represent directly the aspect of interest by a parameter, thus a proxy measure is used. Think of first order approximations, over simplifications, idealizations, gaps in aggregation levels, differences in definitions, non-representativeness, and incompleteness issues. If the parameter were an exact measure of the quantity, it would score four on proxy. If the parameter in the model is not clearly related to the phenomenon it represents, the score would be zero.

- *Methodological rigour*
  Methodological rigour refers to the norms applied by peers in the relevant disciplines for methodological quality in the process of collecting, checking, and revising the data included in the dataset. Well-established and respected methods for measuring and processing the data would score high on this metric, while untested or unreliable methods would tend to score lower.

- *Validation*
  This metric refers to the degree to which one has been able to cross-check the data and assumptions used to produce the numeral of the parameter against independent sources. When these have been compared with appropriate sets of independent data to assess its reliability it will score high on this metric. In many cases, independent data for the same parameter over the same time period are not available and other data sets must be used for validation. This may require a compromise in the length or overlap of the data sets, or may require use of a related, but different, proxy variable for indirect validation, or perhaps use of data that has been aggregated on different scales. The more indirect or incomplete the validation, the lower it will score on this metric.

The pedigree matrix used for scoring in the MIDDEN+ is shown below:

Table 1: Pedigree matrix for assessment of knowledge base (van der Spek et al., 2016)

Criterion	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Score				
4	A direct measure of the desired quantity	Controlled experiments and large sample, direct measurements	Best available practice in well-established discipline	Compared with independent measurements of same variable over long domain
3	Good fit to measure	Historical/field data, uncontrolled experiments, small sample, direct measurements	Reliable method common within established discipline; best available practice in immature discipline	Compared with independent measurements of closely related variable over shorter period
2	Well correlated but not measuring the same thing	Modelled/derived data, indirect measurements	Acceptable method but limited consensus on reliability	Measures are not independent, include proxy variables or have limited domain

Criterion ***Score***	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
1	Weak correlation but commonalities in measure	Educated guesses, indirect approximation, rule of thumb estimate	Preliminary methods, unknown reliability	Weak and very indirect validation
0	Not correlated and not clearly related	Crude speculation	No discernible rigour	No validation performed

Technology learning potential

Energy system models and the scenarios they produce often rely on estimates of future technology cost, particularly for early-stage or innovative technologies. Future cost estimates are used to improve the model results, as the cost of a pilot-scale or demonstration project is not always a good indication of future costs. Solar photovoltaic panels cost developments are a good illustration of this concept in practice (Jäger-Waldau, 2019). The cost of producing solar PV panels has fallen dramatically due to scaled-up production in recent decades, and made electricity generation from solar cost-competitive in some regions with conventional fossil fuel generation.

Researchers have observed that technology cost often falls with experience, often attributed to “learning by doing.” This can be measured in various ways, including tracking the evolution of technology cost over time as more units are installed. This data can be expressed as an “experience curve,” which represents the relationship between technology cost and some measure of experience (often cumulative production or cumulative installed capacity).

The learning curve concept was first developed in relation to the time to produce airplanes, by T.P. Wright in 1936. Wright focused mainly on labour, as this was at the time the most important cost factor in airplane production. The single-factor experience curve can be expressed in the following form:

$$C_{Cum} = C_0 Cum^m \qquad \text{Equation 1}$$

$$\log C_{Cum} = \log C_0 + m \log Cum \qquad \text{Equation 2}$$

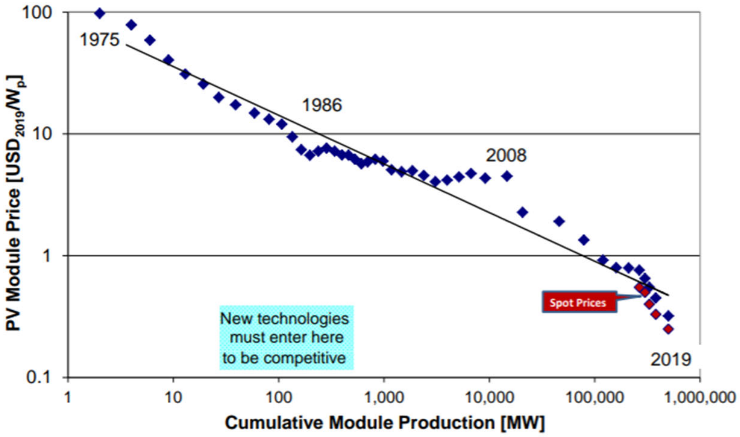
$$PR = 2^m \qquad \text{Equation 3}$$

Where C_{cum} = cost per unit; C_0 = cost of the first unit produced; Cum = the number of units produced; m = experience parameter and PR = progress ratio. The progress ratio expresses the rate at which unit costs decline for each doubling in cumulative production (Junginger et al., 2010).

In 1974, Boston Consulting Group expanded upon Wright’s work, developing the “experience curve,” which incorporates four factors of experience: learning, specialization, investment, and scale to look at the full cost of production. BCG also broadened the application of these curves to entire industries, rather than only individual companies (Junginger et al., 2010). Other improvements and variations have been proposed by researchers, such as decomposition of learning into multiple components (i.e. process, labour, materials) which may experience different rates of learning.

The applicability of this methodology to a given technology, and if so, the specific form of experience curve that is appropriate depends on the subject of the analysis and the data available. For example, as companies seek to maximize profit, this may not always translate into reductions in production cost; coal fired power plants with higher investment cost and greater flexibility may be seen as experiencing technology learning in the area of product functionality, rather than cost (Wiesenthal et al., 2012). Furthermore, there may be inherent limits to learning potential (for example, the costs of material required). Such "floor costs," however, are difficult to determine. Moreover, a breakthrough innovation can shift this floor through the invention of new materials or processes.

Despite its limitations, the experience curve is now widely used in a variety of industrial sectors, including well-known examples from the energy sector (such as the figure below, which illustrates an estimate for the cumulative production level at which PV module prices reach €1/W). Thus researchers incorporate estimates of future "experience curves" into their modelling, either using exogenous assumptions based on past experience with a given technology or related technologies, or use endogenously determined learning curves based on model results (i.e. new capacity installations). This can make model results more realistic, capturing the evolution of future costs based on learning. However, for many sectors the requisite data is not available, and progress ratios are difficult to calculate in the absence of reliable, long-term time series data. This is particularly problematic for the industrial sector, where cost and production data are often sensitive and confidential.



Source: Bloomberg New Energy Finance (BNEF) and PV News

Figure 3 Learning curve for solar PV from (Jäger-Waldau, 2019)

Empirical studies of learning rates for the paper & board and steam cracking sectors are limited. Dutton and Thomas measured progress ratios for a variety of manufacturing firms in their 1984 paper, and found a median progress ratio of 80%, though the spread was wide and they concluded that additional research was needed (Dutton & Thomas, 1984).

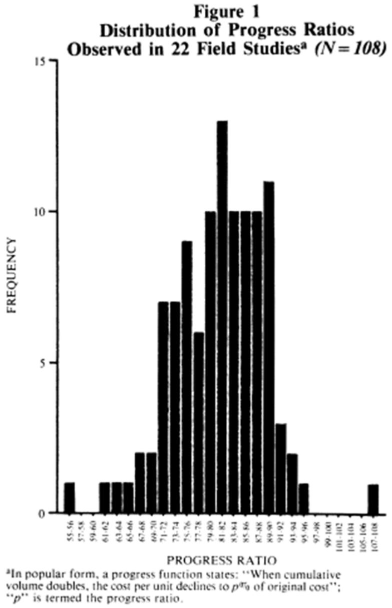


Figure 4 Progress ratios from (Dutton & Thomas, 1984)

In the MIDDEN+ project, our aim is to add useful qualitative information for researchers who incorporate these learning rates into their models for the industrial sector. We have qualitatively evaluated the potential for learning based on four main types of experience, and characterised the potential for technology learning as low, medium, or high. We focus primarily on the potential for cost reductions in these technologies, though we recognise that experience may also lead to other technological improvements, such as higher efficiency or improved product quality.

Learning by researching (R&D) refers to technology cost reductions achieved by research at a pre-commercial stage, or in labs and pilot testing of new technologies. This can occur after commercialization as well, as researchers seek improvements. We have considered available data on R&D spending (both public and private), output from R&D projects on relevant topics, and for how long R&D projects have been ongoing.

Learning by doing is the potential to reduce technology cost through experience in manufacturing. This can be achieved via small incremental adjustments in process and operations, and does not require large capital investments.

Economies of scale refer to cost reductions that come with scaling up a manufacturing process. Some potential sources of this cost reduction include lower cost for bulk purchase of materials or components, or non-linear increases in material/equipment needs for larger units.

Spillover effects refer to learning effects that come primarily from experience using related technologies, other technologies in similar applications, or similar technologies in other sectors. The potential may be higher, for example, if the technology is broadly applicable for many end-uses, and lower for specific process equipment that cannot be used for other purposes. Technology developments in another application or sector could allow a technology to achieve faster cost reductions.

Additional methodological notes

Cost reductions based on experience or technology learning are not a given. These technologies' costs will develop based on the learning factors we have discussed above, but also based on outside factors, such as global and local economic forces, policy and regulation, and broader trends in the sector. For example, hydrogen-based technologies will have a greater potential for uptake (and thus experience-based cost improvements) if the necessary infrastructure for hydrogen supply is in place near industrial facilities that may use those technologies. It is important to consider dynamics beyond the Netherlands and beyond the industrial sector.

It is also important to note that technology costs can increase in early stages of development, and do not always follow clear downward trajectories. We acknowledge this possibility, though it is not possible given the information available, to quantitatively or qualitatively assess this.

The qualitative assessments developed as part of the MIDDEN+ project represent our best evaluations given the data available, and some elements inherently include some subjective judgement. They are intended as qualitative outlooks on possible future technology cost. We recommend further empirical study of technology learning in the industrial sector, particularly for breakthrough low-emissions technologies. Data availability is the key challenge in constructing learning curves, and collaborative data collection with input from a variety of stakeholders is needed.

These assessments can be used by modellers or policy analysts to better understand the dynamics affecting each technology, in order to highlight areas where uncertainty in future costs is larger and additional analysis may be needed. The additional detail on the sources of potential learning can guide decisions on how to apply learning rates and on the coherence of scenarios. Finally, this assessment can help researchers and policymakers identify areas where caution is needed in interpreting results.

3 Paper and board

The Dutch paper and board industry had a revenue of 1.95 billion euros in 2018 and was responsible for 0.5% of the total Dutch industrial revenue (CBS - StatLine, 2018; VNP, 2018c). The amount of employees working in this sector was halved over the last 20 years, to 3,800 employees in 2017 (CBS, 2018; VNP, 2018d). In the Netherlands, 18 companies (21 paper mills) produce 3 million tonnes of different types of paper and board, of which the three most produced types are corrugated board, solid board and graphic paper (VNP, 2018d; VNP and Pöyry, 2018). The paper, pulp and print industry uses 2% of the total Dutch industrial final energy demand (IEA, 2020).

Of the 21 paper mills, 19 fall under the EU ETS system. The total amount of emissions from these mills was 1.02 $MtCO_2$ for 2019, representing 1.8% of total Dutch industrial emissions (NEA, 2020a; PBL, 2020b). Although the Dutch emission authority showed that the Dutch paper and board industry had on average in 2018 30% less emissions per tonne of product than the benchmark of the top 10% best-performing European paper mills (for the benchmark year: 2008) (NEA, 2020b), the sector still needs to make significant steps to achieve 2030 and 2050 emission goals. Currently, the sector uses mainly gas-fired CHP and boilers to meet its heat demand. In the MIDDEN database, Dutch paper and board production is categorised into eight grades. The average energy intensities and total production by grade are shown below in Figure 5.

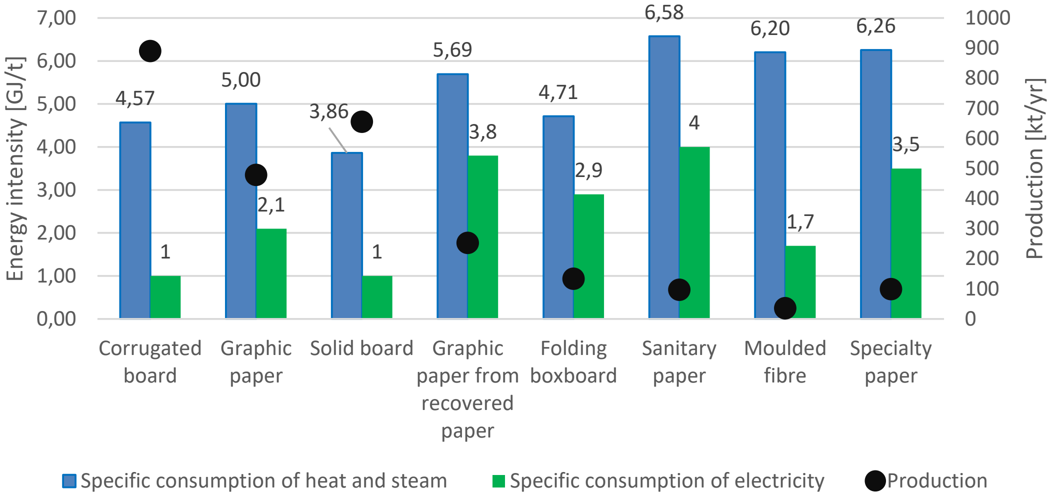


Figure 5: Dutch annual production and specific consumption of heat/steam and electricity per paper type in 2015 (Rademaker & Marsidi, 2019b)

3.1 Current paper production

The paper making process roughly consists of three parts, represented in Figure 6. Paper is made from virgin cellulose fibres or recovered paper. Virgin fibres are mostly made from wood fibres, although there is increasing interest in other feedstocks such as grass and miscanthus. With the exception of one mill that partly produces its pulp from virgin fibres, the Netherlands imports its virgin pulp or uses recovered fibre pulp.

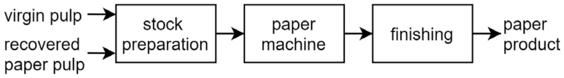


Figure 6: Block diagram of the paper production by the main process steps

Stock preparation

Before the paper can be produced, the pulp needs specific pretreatment, depending on what type of fibre is used, see Figure 7. Virgin pulp sometimes needs a refining step, where the surface of the fibres is roughened, improving its properties. Refining is currently done by rotating disks presed on a stator (Laurijssen et al., 2013). Recovered paper pulp needs more extensive cleaning than virgin pulp, to remove impurities such as staples, non-paper materials or glue. For products that require a specific brightness, recovered paper also needs de-inking. Dispersion can be required to remove impurities that were too small to be removed in earlier steps, often done by repeated compression and shearing impacts onto the fibre slurry (Rojas & Hubbe, 2004). The order of these preparation steps can vary between paper mills, and some steps might be performed more than once (Laurijssen et al., 2013).

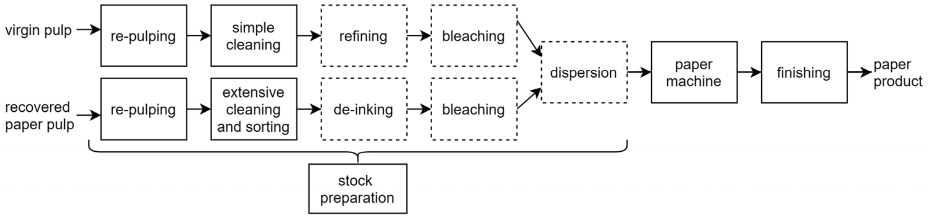


Figure 7: Block diagram of the paper production where the stock preparation phase is broken down. The exact process depends per paper mill, where dashed blocks are optional process steps

Paper machine

After the stock is fully prepared, the paper can be made. This is done in the forming phase, by spreading the pulp on a screen. A large part of the water already leaves the paper by seeping through the screen. In this phase the dry matter content (dmc) goes from 1% to 20%-25% (Laurijssen et al., 2013). Next, water is pressed out of the paper by press cylinders (reaching dmc 50%-55%) (Rademaker & Marsidi, 2019b). Mechanical dewatering requires less energy than thermal dewatering, therefore it is important to remove as much water in the pressing stage. The remainder of water is removed by heating the paper. This is done by rolling the paper web over steam cylinders, blowing hot air into the web, or by using hot air convection in tunnel drying (reaching dmc 95%) (Laurijssen et al., 2013; Rademaker & Marsidi, 2019b).

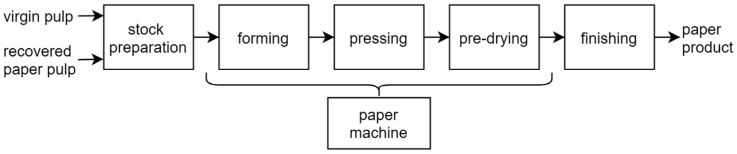


Figure 8: Block diagram of the paper production where the production steps in the paper machine is broken down. The exact process varies per paper mill

Finishing
Most paper products require finishing steps such as sizing, lamination or coating. After these steps, an additional drying step is required, called the after drying, as in these steps liquid is again added to the paper web. In the calendering step, the paper is passed through heated rolls, together called calenders, which ensures the required uniform thickness and smooth and glossy surface.

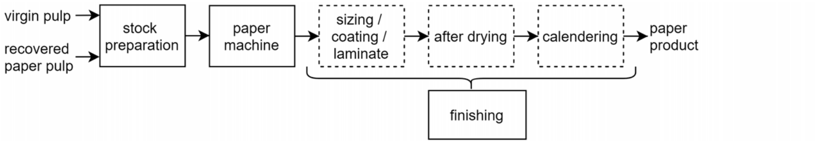


Figure 9: Block diagram of the paper production where the finishing phase is broken down. The exact process depends per paper mill, where dashed blocks are optional process steps

Additional detailed description of current paper and board production processes can be found in the MIDDEN report (Rademaker & Marsidi, 2019a).

3.2 Updates to the MIDDEN database

In order to improve our understanding of the effect of different decarbonisation technologies, we analysed different technologies and their effects on each other using the MIDDEN database and additional literature. The MIDDEN dataset already includes detailed data on alternative heat generation options for the paper and board sector. The additional technologies included for the paper and board sector are:

- **Air-laid technology**
  This dry sheet formation technique reduces energy consumption requirements for the drying step, the most energy-intensive section of a paper mill. It has a high emission reduction potential and is currently at a technology readiness level (TRL) of 5-6 (VNP, 2018a).

- **Microwave drying**
  Microwave drying uses electricity to reduce water content in paper, and reduces the thermal energy required for drying of the paper. It reduces direct emissions, and can also reduce system-level emissions if renewable electricity is used. Microwave drying is an add-on to conventional paper making and does not require a completely new production line. The Dutch association of paper and board producers (Koninklijke Vereniging van Nederlandse Papier- en Karton-Fabrieken, or VNP) indicates that this has a moderate emission reduction potential, and a TRL of >6 (VNP, 2018b).

- **Enclosing dryer hoods**
  A closed hood collects the saturated low pressure steam formed at the drying phase. The exhaust air from a closed hood has a higher temperature, reducing the overall thermal energy consumption of the dryer section as a smaller volume of air is heated. Additionally, due to a lower amount of air flow needed, the power consumption for fans is reduced. Closed dryer hoods also increase the possibilities for heat recovery from the dryer section. This is a commercial technology that is already broadly applied across the paper and board sector, which can be retrofitted in existing plants.

- **Additional information on recycling**
  Recycling paper can reduce scope 2 and 3 emissions from papermaking as the energy required to process recovered paper into recovered fibre pulp is often lower than the energy required to produce virgin pulp from wood. Recycling also has other environmental benefits, including potentially reducing deforestation and environmental pollution. An intermediate level of recovered fibre input has been included for graphic paper to represent a fuller range of potential configurations.

3.2.1 *Air-laid forming technology*

Eliminating the most energy-intensive step, the removal of water from the paper web, requires a new papermaking process, which does not use water to carry fibres and form the web. Technologies to produce paper without water are called dry sheet forming, of which air-laid technology is the most used. In air-laying, the paper is formed by creating a suspension of fibres and air, and 'laying' this onto a vacuum belt to form a web (web formation). The fibres are consolidated by thermal-bonding, chemical bonding, or a combination of these (web consolidation) (Glatfelter Corporation, 2020a). As presented in Figure 10, air-laid forming requires different steps than conventional paper machines, and therefore this technology is not a retrofit, but requires a new production line. Globally, air-laid mills had a capacity of 360 kt in 2000, with an expected rise in the following years of 120 kt, mostly in North America (Martin, Worrell, et al., 2000). More recent publicly available data on this technology is lacking in literature. For advantages and disadvantages of air-laid forming in comparison to conventional paper making, see Table 16.

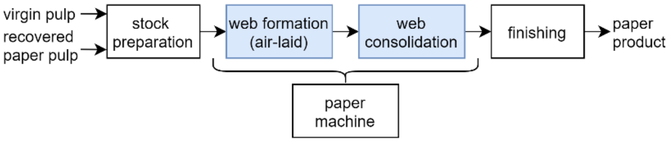


Figure 10: Block diagram of the paper production by air-laid technology

Air-laying creates a soft paper structure and is therefore used mostly for personal care products and some specialty products. Although air-laid technology has not yet been used for other, non-soft, paper types, and Martin et al. (Martin, Worrell, et al., 2000) states it is not likely it will be used in the near future for standard paper grades, the production of corrugated medium board and molding board with dry sheet forming has been demonstrated (De Beer et al., 1998). Currently, air-laid technology could be used for the production of sanitary paper or graphic paper (Rademaker & Marsidi, 2019b), which are therefore the two paper types added to the MIDDEN database for air-laid forming. Based on expert consultation, using air-laid forming for stronger paper grades on industrial scale still requires an increase in paper strength.

Currently, air-laid formation is done using fluff pulp from virgin fibres only (Glatfelter Corporation, 2020b; Rademaker & Marsidi, 2019b). However recently, CAMPEN Machinery A/S developed a new type of air-laid forming head and hammer mill system, able to process recycled fibres and biodegradable fibres (CAMPEN Machinery A/S, 2020). This opens up new possibilities on combining air-laid technology with recovered paper pulp. As discussed with an expert from VNP, whether the air-laid paper itself is recyclable depends on the binder used. The Dutch industry has focussed in recent years on optimising the value chain for enhancing recycling, where papers that require different recycling could not fit in. For sanitary paper, no binders are needed and therefore there is no loss in recyclability.

Around the year 2000, two new paper mills using dry sheet forming techniques were built with an approximate investment cost of $1,500/t paper. In Germany, a dry sheet forming paper machine with a capacity of 25 kt/yr (total cost $37.6M, planned start up in 1997) was built (Martin, Anglani, et al., 2000), and in North Carolina an air-laid plant with a capacity of 50 kt/yr was built (under construction in 2000) (Martin, Worrell, et al., 2000). The IEA estimated the investment cost in 2009 to be $1504/t paper (IEA, 2009). The investment cost of an air-laid forming mill, once fully commercialised, is expected to be 30%-50% of the cost of a conventional paper mill (De Beer et al., 1998; Martin, Worrell, et al., 2000; VNP, 2018b). The operation and maintenance (O&M) costs are also expected to be lower (De Beer et al., 1998; VNP, 2018b), due to less severe process conditions. In the MIDDEN database for air-laid forming, the same ratio between fixed O&M costs and CAPEX as for conventional paper mills is estimated (5% – 7.5%).

Electricity use is expected to increase 150-250 kWh/t, compared to conventional paper mills, to maintain the air stream and drive the equipment (De Beer et al., 1998; Martin, Worrell, et al., 2000). The dryer section of conventional paper mills, uses around 67% of the total energy required for paper making (Bajpai, 2016), which is mostly steam. This thermal energy can be reduced by 50% by air laying (De Beer et al., 1998; Martin, Worrell, et al., 2000; VNP, 2018b).

It is assumed that the required feedstocks for air-laying are the same as for conventional paper making. However, resins are added to the paper web to facilitate fibre-to-fibre bonding (De Beer et al., 1998). Publicly available information in literature on the chemical composition, quantity, and cost of required resin is currently lacking.

Table 2: Techno-economic parameters for air-laid forming

Parameter	Values	Graphic paper	Sanitary paper
CAPEX ($€_{2019}/t_{prod}/yr$)	30-50% of conventional process CAPEX	510	510
O&M ($€_{2019}/t_{prod}/yr$)	Share of CAPEX assumed to be same as for conventional process	36	56
Electricity use (GJ/t)	+ 0.5-0.9 compared to conventional process	2.8	4.7
Steam use (GJ/t)	Thermal energy for drying reduced by 50%	3.3	4.1

Note: Air-laid forming is applied only to two paper grades in the MIDDEN database where it is relevant. The values shown in the table above are for graphic paper with air-laid forming, and for sanitary paper with air-laid forming. Average CAPEX values are shown as the same here based on average data from the MIDDEN database, but investment costs for individual plants can vary significantly.

The techno-economic dataset for air-laid forming scores low in the pedigree matrix methodology (see Table 14), indicating a high level of uncertainty. The publicly available techno-economic data is generally from papers from more than 10 years ago, and papers cite each other, leading back to a few original sources. These sources base their information on a limited number of real projects, and rely heavily on estimated or theoretical values to describe the impact of the technology on the papermaking process. Some key pieces of detailed information are not publicly available; for example, the type and cost of resins used in air-laid forming is not specified in available literature. There is therefore considerable uncertainty associated with any scenario or pathway involving widespread use of this technology, which should be clearly communicated.

Furthermore, the potential for cost reductions from technology learning are estimated to be quite limited. The most promising source of potential cost reductions is in learning by doing, optimising and improving performance in a variety of product categories. Research, economies of scale, and spillover effects are unlikely to offer major reductions in technology cost, as air-laid forming is specific to the papermaking process, and must be designed as an integral part of process equipment at a new plant.

3.2.2 Microwave drying

Microwave drying is an add-on to the drying section of the paper machine, which can help in making drying more efficient and, as it runs on electricity, also reduce emissions from papermaking when using renewable electricity. Since 1966, microwave drying is one of the most well-known industrial applications of microwave energy (Kumar, 1991). Moreover, it is explored in many fields, resulting in different set-ups (Rademaker & Marsidi, 2019b). Microwave heating is volumetric, meaning it is not limited by conductive and convective heat resistances, often the case for other drying methods (Ahrens et al., 2003). Therefore microwave drying is faster, and especially suitable for high basis weight grades, which are difficult to penetrate by thermal conduction (Ahrens et al., 2003).

Microwave drying is a form of dielectric drying. The microwaves are not a form of heat themselves, but create heat through their interaction with materials, mainly by ionic conduction (oscillatory migration of ions in the materials) and dipolar rotation (Delgado et al., 2016). The latter is present for molecules with a dipole, such as water. When the microwave provides an oscillating electric field, molecules will realign to the direction of the electric field. If this is done with a high frequency, the realignment occurs fast, resulting in friction between the molecules and therefore internal heating (Delgado et al., 2016). To allow optimal absorption of microwave energy, the microwave frequency needs to be in line with the dipole moment of water. Currently, there are three microwave frequencies allowed for industrial applications: 0.915, 2.45 and 5.8 GHz, with wavelengths of 32.8 cm, 12.2 cm and 5.2 cm respectively (Ahrens et al., 2003; Linn High Therm GmbH, 2003). A higher frequency would allow a better absorption of the energy in water, according to experts.

In addition to reducing direct emissions via electrification, microwave drying can also increase efficiency. In the drying stage, the whole paper web needs to have a water content below 6%, to limit tensions in the web. As water is not evenly spread in the paper, overdrying is required in conventional paper making, and some places are heated more than necessary, and are dried down to 1.5-2% (Kumar, 1991). This is not only inefficient, it also leads to a lower quality of the paper, due to thermal degradation, especially at the outer layer of the product (Kumar, 1991; Radoiu, 2020). In the case of microwaves, the energy absorption efficiency increases with moisture content, which results in heating up of the wet spots more (Ahrens et al., 2003). This gives microwave drying the capability to efficiently use energy for the spots that need to be dried, and at the same time decrease the difference in moisture content across the web.

The microwave drying equipment can be added before, after or inside conventional drying units (Linn High Therm GmbH, n.d.-a); but note that Radoiu (2020) states that the implementation of microwave technology to any heated industrial process is not necessarily straightforward (Radoiu, 2020). Microwave drying can be used in the pressing stage to reduce the amount of water delivered to the drying stage, and it can also be used in the drying stage for preheating and complementing the existing drying cylinders (see Figure 11) (Kong et al., 2016). The greatest benefits can be realized if microwave drying is placed before or during the pressing stage (Ahrens et al., 2003). In this case, there will be an additional, second, pressing step added to already remove a large part of the water before the microwave drying and the other pressing step, see Figure 12.

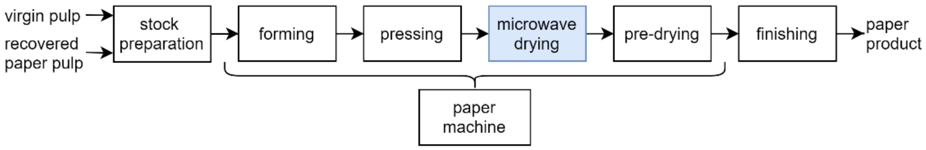


Figure 11: Block diagram of the paper production including post-press microwave drying

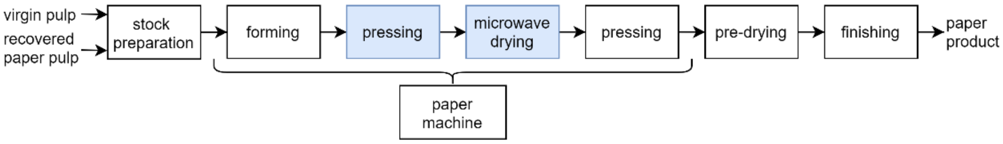


Figure 12: Block diagram of the paper production including pre-press microwave drying

Due to its efficient, selective and fast heating, microwave drying has a wide variety of improvements in comparison with conventional paper making. However, its reliance on electricity could lead to higher costs, and because of its limited deployment in the paper sector, the optimal operating parameters may still require some experimentation.

Ahrens (Ahrens et al., 2003) made a detailed cost calculation for the capital cost of a paper mill including microwave drying. He states that a waveguide of 100 kW costs $42 700, and a microwave generator $35,600 (per 100 kW generator), and 41 of each are needed for a production of 360 kt/yr for a pre-press case. Including an extra press ($2M), and a doubling of the cost for installation, this comes to an installed CAPEX of €45/t_{prod}/yr (Ahrens et al., 2003). This is compared below in Table 3 to other sources in the literature, on the same currency year basis.

Table 3: CAPEX for microwave drying systems from literature

Source	CAPEX per kW installed EUR2019/kW	Includes
(Ahrens et al., 2003)	€3156/kW	Waveguides, microwave generators, and extra press
(Radoiu, 2020)	€2456-4020/kW	Microwave generators and waveguides
(Linn High Therm GmbH, n.d.-a)	€1787-4466/kW	Microwave generators, applicators, conveyer and control system
(Datta & Anantheswaran, 2001)	€5159-9028/kW	Microwave generators, applicators, conveyer and control system
(Osepchuk, 1984)	€6062/kW	Unspecified

The main consumable, the magnetron, has a lifetime of approximately 1 year in the case of continuous operation (Ahrens et al., 2003; Linn High Therm GmbH, n.d.-b; Radoiu, 2020). A magnetron of 100 kW has a cost of $8,000 (Ahrens et al., 2003; Radoiu, 2020), which results in a fixed annual O&M cost of €1.4/t_{prod}/yr. Note that when microwave drying is added, less severe process conditions and less drying cylinders (in the Ahrens (Ahrens et al., 2003) case, 4 out of 70 cylinders are removed) are needed in the drying phase. Calculating the additional electricity use for the microwave drying from the numbers presented by Ahrens (Ahrens et al., 2003), gives an extra 0.34 GJ/t electricity demand. Ahrens states that the total drying energy will be between 0.89 – 1.05 MWh/t, in comparison to 1.13 MWh/t for the base case, resulting in energy savings between 7%-21%, with an average of 14% (Ahrens et al., 2003). Kong states that the overall energy savings of a paper mill with microwave drying are 12%, in comparison to a conventional mill (Kong et al., 2016). Assuming 0.34 GJ/t additional electricity use, and the drying section to be responsible for 67% of the total steam demand (Bajpai, 2016), the reduction in steam demand was calculated with a low, medium and high case of 21%, 14% and 7% total energy savings.

Lastly, note that in the pre-press case by Ahrens (Ahrens et al., 2003), the production increases by 31% in comparison to the base case; and this results, despite the extra cost for the microwave equipment, in an extra profit of $13.8M (for 360 kt/yr production). This potential for extra profit is not addressed in the database, as it is dependent on energy, material, and final product prices. In the MIDDEN+ database, microwave drying is included as an add-on to an existing paper mill, addressing only the cost.

Table 4: Techno-economic parameters for microwave drying as an add-on (retrofit) to an already existing paper mill

Parameter	Value estimate	Corrugated board with retrofit	Folding boxboard with retrofit	Solid board with retrofit
CAPEX (€$_{2019}$/t$_{prod}$/yr)	45 (retrofit costs)	45	45	45
Fixed O&M (€$_{2019}$/t$_{prod}$/yr)	+1.4	65.4	95.4	95.4
Electricity use (GJ/t)	+0.34	1.3	3.2	1.3
Steam use (GJ/t)	7-21% reduction in steam demand for drying	4.0	4.7	3.5

Note: CAPEX values given above are the retrofit costs only, not total plant costs. The OPEX and energy use values are for the full process after retrofit. Microwave drying is applied only to 3 paper grades in the MIDDEN database where it is relevant.

The most often mentioned drawback of microwave drying is its high CAPEX in comparison to a relatively low lifetime, and the relatively high cost of electricity (Kong et al., 2016; Radoiu, 2020). Therefore microwave drying is not yet used in paper machines (Kong et al., 2016). As mentioned above, microwave drying has, in addition to its improved efficiency, a wide variety of other advantages over conventional paper making, such as on the product quality. Therefore, it is important to assess technical and economic characteristics together when investigating microwave drying (Radoiu, 2020). Some of the improvements of microwave drying might not be relevant, such as the speed and consequent increase of production, as currently Dutch paper mills have some capacity to scale up, and if needed, there are cheaper methods to increase production (Kumar, 1991). Additionally, considering structural shifts in demand for different paper and board grades, production increases or decreases will depend on the demand outlook for a certain paper product.
The pedigree matrix in Table 14 shows that the techno-economic dataset for microwave drying has a medium level of uncertainty. The main source of technical data relies on detailed experimental measurements, which lends higher confidence to the values than theoretical estimates, though the source of experimental data is not very recent (published in 2003). To extract economic data, additional assumptions were needed. Therefore, the cost data is based on informed estimates, and not on a real-world application. Moreover, only informal consultations with stakeholders served as validation of the data for this technology.

There is potential for cost reductions for microwave drying. Microwave drying for paper applications has been investigated since the 1960s. Despite this long history of research, there is very little experience in the paper sector, and optimisation of microwave frequencies, power levels and a combination with other drying techniques is required. However, microwave drying and treatment is commercially available in the food and beverage industry, which may lead to spillover effects. Spillover effects could also be seen from household microwave ovens. Detz and van der Zwaan (Detz & van der Zwaan, 2020), found a 20% (±2%) learning rate for household microwave ovens using historical time series data.

3.2.3 *Enclosed dryer hoods*

In the pre-drying step, heat is transferred to the web by rolling the paper over steam injected cylinders. Water evaporates from the web, and is carried away by pre-heated air, forming saturated low pressure steam (Martin, Worrell, et al., 2000). The heat in this lower quality steam can still be used, reducing thermal energy demands. To make that possible, this steam needs to be captured by an enclosed dryer hood. This equipment, often implemented as retrofit of an existing paper mill, is applicable for all paper types.

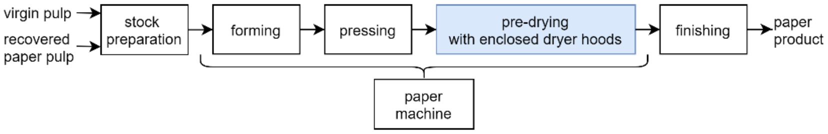


Figure 13: Block diagram of the paper production with enclosed dryer hoods

Older paper machines did not have any hoods in the drying step, causing condensed water vapour in the hall, unsafe working conditions and deterioration of the building (Ghosh, 2011). Later, dryers were covered with open canopy hoods, which was a significant improvement, but these do not get the full potential out of the low pressure steam (Ghosh, 2011). Closing the dryer hood completely does allow for this. An enclosed dryer hood collects the evaporated water so that the energy can be recovered and prevents heat and humidity to be spread in the hall (TM Systems, 2016a). The recovered heat can be used to heat the new ventilation air for the dryer, for heating process water and for heating the building (Laurijssen et al., 2010a; Rademaker & Marsidi, 2019a). To make a real impact on energy efficiency, the waste heat can be upgraded by using a heat pump or mechanical vapour recompression (MVR) (Martin, Worrell, et al., 2000). Moreover, equipping the hood with sensors allows optimal control of the drying section.

Laurijssen states that the range in drying energy for all investigated mills (3.6-6.2 GJ/t water removal) indicates a large energy efficiency improvement potential (Laurijssen et al., 2013). The dryer efficiency is the highest when the hood is fully closed, the dryer dew point is high, and the waste heat is maximally recovered (Laurijssen et al., 2013). Most large paper mills have closed hoods (Laurijssen et al., 2010b), but not all Dutch mills have adopted this best practice, leaving potential for significant energy savings (Rademaker & Marsidi, 2019a).

Paper machines with a closed hood require only 33%-50% of the ventilation air required for a semi-open hood to evaporate the same amount of water from the web (Li et al., 2012; Martin, Worrell, et al., 2000). This does not only result in a lower thermal energy demand, as less air needs to be heated, but also to a lower power consumption of the fans, approximately 66% of the power needed for the semi-open hood (Li et al., 2012). Van Deventer estimates a steam savings of 50% and an increase in electricity use of 159 kWh/t from implementing an enclosed hood with MVR (Van Deventer, 1997). Going from a semi-closed to closed drying section, can yield a steam consumption reduction of 12.9% and a power consumption of 14.2% for a specific dryer (Stenström, 2020). The waste heat recovery of the hood exhaust air in canopy air-to-air heat recovery systems is only about 15%, which can be increased to 60% - 70% using an enclosed drying hood (Martin, Anglani, et al., 2000).

Martin et al. (Martin, Worrell, et al., 2000) estimated CAPEX for the enclosed dryer hood, additional to the cost of the paper mill, earlier noted by the CADDET (Centre for the Analysis and Dissemination of Demonstrated Energy Technologies) in 1994, at $9.5/ton paper and an additional O&M cost of $0.07/ton. This results in a CAPEX cost of €16/t paper and Fixed O&M cost of €0.12/t paper. Although there may be in reality a lower cost for creating a new paper machine with an enclosed hood (due to combined design, lower engineering costs, etc.) the cost for a retrofit and new installation are assumed to be the same.

On steam and electricity savings, Martin et al. (Martin, Anglani, et al., 2000) assume a savings of 0.76 GJ/t paper and 6.3 kWh/t paper respectively (also based on the publication of the CADDET). Taking into account that mills have improved their energy efficiencies over the last years, the savings stated by Stenstorm (Stenström, 2020) of 12.9% for steam and 14.2% for electricity are assumed to be more applicable to today's situation. Assuming that 67% of the total steam use (Bajpai, 2016) and 18 kWh/t (0.065 GJ/t) of electricity (Martin, Worrell, et al., 2000) is required in the drying step, the change in required utilities can be calculated.

Table 5: Techno-economic parameters for retrofit of enclosed dryer hood to existing paper mill

Parameter	Value
CAPEX (€$_{2019}$/t$_{prod}$/yr)	16 (retrofit costs)
Fixed O&M (€$_{2019}$/t$_{prod}$/yr)	+0.12 compared to conventional process
Electricity use (GJ/t)	0.01-0.02 reduction compared to conventional process
Steam use (GJ/t)	0.3-0.8 reduction compared to conventional process

Note: This technology can be applied to plants without an existing hood, wherever the specific building configuration allows. Site-specific savings vary depending on product and current efficiency levels.

The techno-economic data on enclosed dryer hoods has a mild uncertainty, see Table 14. The main publications about this technology are based on existing projects, for retrofits of enclosed dryers. However, these are only a small number of examples, which are not recent, and these mills are located abroad. There was no validation of the data of this technology.

The potential for cost reductions from technology learning is low to medium. Learning by researching and learning by doing have a low potential, as the implementation and usage of this technology is well-known. Enclosed dryer hoods can also be used in other industrial sectors, and can experience spillover effects and benefit from economies of scale, by a higher production and implementation of closed hoods in other sectors.

3.2.4 *Recycling*

Of the 3 million tonne of paper produced in the Netherlands, 86% is made from recycled paper (KCPK, 2019), which corresponds to approximately 3.6 Mt CO$_2$/yr (calculated by the amount of carbon stored in wood pulp and recycled paper) that remains in the recycling loop (VNP and Pöyry, 2018). Increasing the recycling rate would reduce virgin feedstock requirements and also reduce scope 2 and 3 emissions by replacing the energy-intensive pulping processes. There are some limitations to increasing the amount of recycled paper, as some paper types cannot be recycled, such as paper for money or cigarettes, whereas the recycling of some types are not preferred by the paper industry, such as sanitary paper (KCPK, 2019). Moreover, fibres cannot be recycled endlessly, as they are downcycled; each cycle affects the mechanical and chemical properties of the fibres (KCPK, 2019).

The Dutch paper industry is focussing on three aspects to push the boundaries of paper recycling, which are (KCPK, 2019; VNP and Pöyry, 2018):

- Increasing the recycling rate, currently at 85%
- Reducing process losses during recycling, currently ~13%
- Keeping fibres functional through more than seven loops and increasing the functionality of the fibre, by using new materials such as grasses

Increasing recycling has large environmental benefits, which are attributed mostly outside of the papermaking process. The MIDDEN database focusses on the papermaking process, and therefore these environmental benefits are outside of scope. Nevertheless, this is an important option to take into consideration, because of its potential for reducing material and energy use, and contribution to a circular economy. In the MIDDEN database, graphic paper production from solely virgin fibre and from 90% recycled material was included, and we have added an intermediate step to represent the transition to a higher usage of recycled paper.

4 Steam cracking

4.1 Current steam cracking sector

In the Netherlands, there are six operating steam crackers with an ethylene nameplate capacity of over 4 Mt/year (Petrochemicals Europe, 2020a) (Table 6). Ethylene is one of the main products from steam crackers; however, other relevant chemicals, such as propylene, butadiene, benzene, hydrogen, and acetylene, compose the total product portfolio of these sites. Together with ethylene, they are usually called high value chemicals (HVC). This study focuses on the SABIC Geleen and Shell Moerdijk industrial sites, which together have a combined production capacity of more than 2.2 Mt/year.

Table 6: Steam cracking installations and capacities in the Netherlands in 2019 (Petrochemicals Europe, 2020b)

Steam cracker site	Nameplate capacity ethylene [kt/yr]	Number of steam crackers	Share [%]
Dow Chemical Co. Terneuzen	1,825	3	45
SABIC Europe Geleen	1,310	2	32
Shell Nederland Chemie Moerdijk	910	1	23
Total	4,045		

In 2019, the ethylene production in the European Union was around 16 Mt/year and for the Netherlands the value was 2.2 Mt/year, making the country responsible for around 14% of the European ethylene (EUROSTAT, 2020).

Figure 14 gives an overview of a conventional steam cracking process and represents both SABIC and Shell sites. The block named “Downstream units” represents the systems that process the heavier fractions from the cracked product and they differ between the two sites, delivering distinct products. For this reason, this study focuses on the three blocks (pyrolysis, compression and fractionation) that represent the units commonly present at both sites.

Naphtha, gas condensate, LPG and ethane are possible feedstocks for the steam cracking process; naphtha is the main feedstock used in Europe. The feed is diluted with low pressure steam to reduce the vapour pressure of the hydrocarbons, in order to obtain the desired product mix and to prevent coke formation in the furnace tubes. Depending on the type of feedstock used, the weight ratio of the process steam to hydrocarbon feed can vary from 0.35 to 0.70. This mixture is then fed to the pyrolysis furnaces, which are responsible for breaking the molecules in smaller chains and for promoting double bonds, resulting in light olefins (ethylene, propylene) and butadienes. The cracking process is normally performed at a high temperature (875 °C) and the furnaces are heated by combustion of (mainly self-produced) fuel gas and/or limited amounts of natural gas, making this step the main source of CO_2 emissions.

The cracked gas that leaves the furnaces must be cooled down quickly in order to prevent unwanted follow-up reactions, which is done in two steps. In the first step, the cracked gas is cooled to about 450 °C in a transfer line heat exchanger (TLE) by producing SHP (superheated high pressure) steam (>100 bar) from boiler feed water. The SHP steam is mainly used for driving compressors. The second cooling step takes place in a quench tower where the cracked gas temperature is reduced to approximately 200 °C, and partial condensation takes place. The cooling process takes place via direct contact between the cracked gas and the quench oil. In this step, a heavy stream rich in C10+ hydrocarbons is separated from the cracked gas. The C10+ stream can be further processed to be sold as by-product, and this processing can differ depending on the site. A third cooling step of the cracked gas takes place in a water quench column for primary fractionation, cooling the stream down to around 30°C. In this column, the C5-C9 fraction is separated from C4-components and also sent to downstream units for further processing.

The cracked gas from the top of the water quench column is transported to the cracked gas compressor, which is responsible for building the cracked gas pressure to the desired value. This compressor is driven by a steam turbine that uses SHP steam (>100 bar). The produced SHP steam by the cracked gas cooling is usually not sufficient and import of additional SHP is needed. The compressed gas is cooled in a number of steps in a cryogenic refrigeration unit, where the temperature can reach approximately minus 165 °C. At this temperature, nearly all hydrocarbons are condensed. The remaining gas from the cryogenic refrigeration unit contains mainly hydrogen (H_2), methane (CH_4) and small amounts of carbon monoxide (CO). The remaining stream (highly rich in CH_4) is used as fuel gas for the steam cracker furnaces. The subsequent process route for the condensate basically consists of a series of distillation systems (fractionation), which are responsible for separating the main products, respecting the quality requirements.

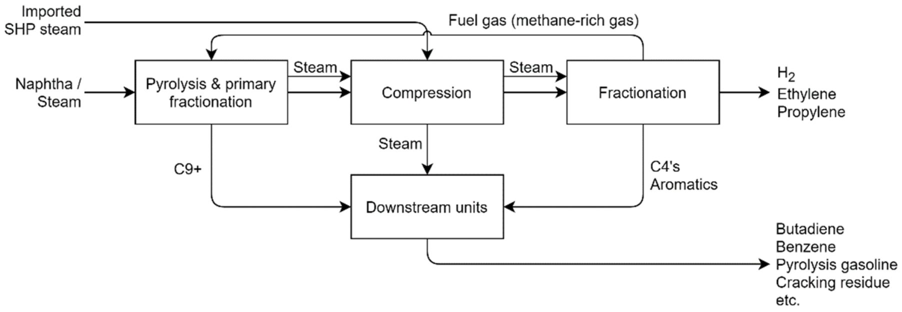


Figure 14: Simplified description of a conventional steam cracker process

ETS emissions for both sites (SABIC and Shell) were around 4 $MtCO_2$-eq/y in 2019 (NEA, 2020a), of which 71% corresponds to the pyrolysis furnaces. The remaining emissions are due to utilities production and downstream processes (e.g. ethylene oxide production in Moerdijk alone emits 0.085 $ktCO_2$/y).

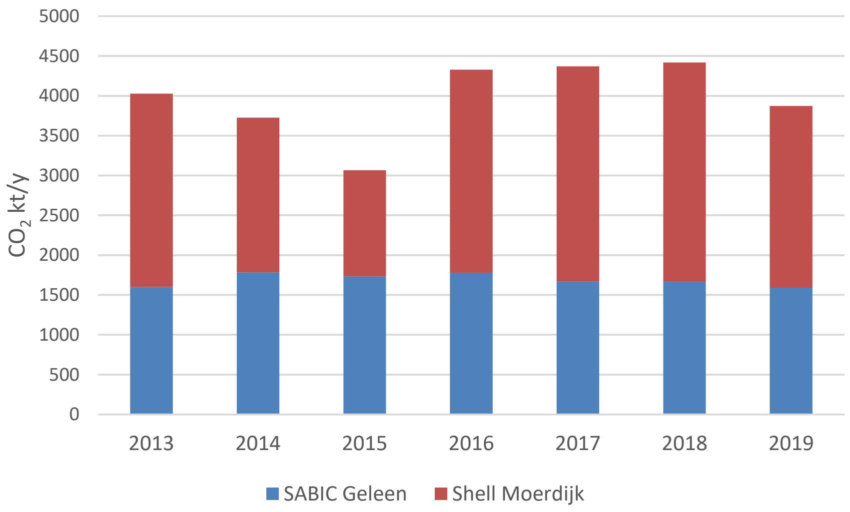


Figure 15: Total direct CO_2 emissions from Shell Moerdijk and SABIC Geleen steam crackers based on (NEA, 2020a) Shell Nederland Chemie B.V., vest. Moerdijk BKG 1-8 and 70% of combined emissions points Chemelot BKG 01 and Chemelot BKG 02. The emission point Chemelot BKG-02 includes also the Swentibild CHP, owned by USG (Utilities support group), therefore, its emissions were not included in this graph since they are not under SABIC's process.

4.2 Updates to the MIDDEN database

In order to provide insights into the effects of different decarbonisation options in the steam cracking sector, a set of technologies was analysed considering both their standalone application and possible combinations. The original MIDDEN datasets for SABIC and Shell already include information on post-combustion CCS, hydrogen furnaces, distillation with mechanical vapour recompression (MVR), miscellaneous efficiency measures (e.g. heat-integrated distillation columns), full electrification of furnaces, bio-naphtha as feedstock substitution and methanol to olefins. The additional technologies included are presented in the following sub-sections.

4.2.1 Partial/full electrification of furnaces (30%-100% electrification of thermal demand)

The full electrification of pyrolysis furnaces was evaluated in both SABIC's and Shell's MIDDEN reports, however, the intermediary configuration was not assessed on these studies. Since it is probable that the cracking furnaces electrification will take place step-wise, the evaluation of this option can be quite relevant for the sector.

In this study, four configurations were considered: electrification of 30%, 50%, 70% and 100% of the total thermal demand of the cracking furnaces. In practice, the gas-fired furnaces would be substituted by electrical tubular cracking furnaces. This technology is still under development (TRL 1-2) (Römgens & Dams, 2018).

Electric furnaces present significant potential to reduce energy related emissions. Electricity-based processes can use electric currents (resistance heating) or electromagnetic fields (induction and dielectric) to heat materials. Most of the electrical heating methods can be subdivided into direct (inductive/dielectric) and indirect (resistance/arc/infrared) heating technologies. Direct technologies generate heat within the target without the need for a heat transfer medium, whereas indirect heating takes place outside the heating target and heating occurs with the aid of a heat transfer medium.

Electric heating is already widely used in industry, however none of the known technologies have been applied yet in steam cracking processes. The technologies for electrical industrial heating that were identified with significant potential application in furnaces, are direct and indirect resistance heating and arc heating.

Direct resistance heating is composed by an electric current driven through a material, which heats up due to its electrical resistivity. Indirect resistance heating, instead, is defined by an electric current driven through a resistor, which heats up, and, through convection and radiation it heats up a surrounding fluid or gas. Electric arc systems heat up materials with the generation of a high-density electric current between two electrodes (electric arc). The heated materials can be solids, gases and liquids. This technology is more commonly used in the steelmaking industry and it could be applied to hydrocarbon cracking systems via the Plasma Arc Heating technology, as discussed with specialists from TNO.

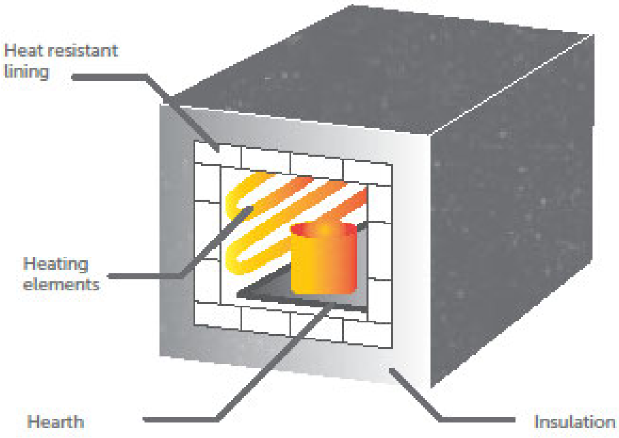


Figure 16: Overview of indirect electrical resistance heating (Beyond Zero Emissions, 2018)

A conventional steam cracker pyrolysis furnace has two main sections: the radiant and the convection section. Naphtha mixed with steam is pre-heated with hot flue gas by a heat exchanger in the convection section. The mixture enters a fired tubular reactor where its temperature reaches around 875 °C and the cracking reactions take place; this tube is located in the radiant section. The cracked gas needs to be cooled just after reaction in order to prevent degradation of certain products that are highly reactive. This cooling process happens in the transfer line heat exchanger (TLE), which uses high pressure boiler feed water (60-120 bar). The cooling process produces high pressure steam (60-120 bar), which is superheated in the convection section of the furnace with the remaining heat from the hot flue gases. Figure 17 illustrates a typical cracking furnace and presents the energy shares found in literature (Ullmann, 2002), based on fuel gas intake. The heat losses indicated in the picture concerns the stack losses (5%) and losses via the furnaces walls (1.5%).

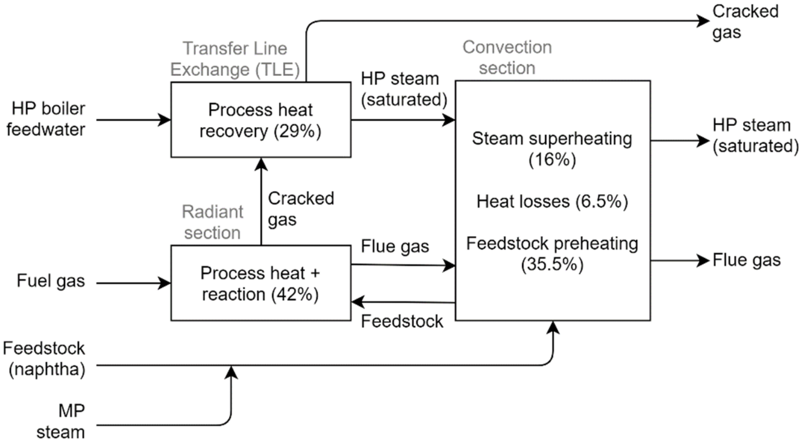


Figure 17: Heat distribution in a conventional cracking furnace based on (Ullmann, 2002)

Figure 18 illustrates the proposed configuration option. The key points when looking into this technology application are the following:

- Excess of fuel gas due to reduction of combustion demand;
- Higher electricity demand;
- Massive changes on site considering cabling and substation installation

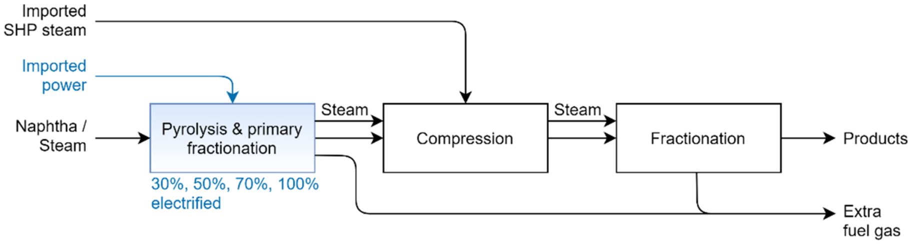


Figure 18: Simplified representation of technology option: partial/full electrification of pyrolysis furnaces

For the evaluation of electrical furnaces, the following assumptions were made:

- The stack losses are considered to reduce linearly with the electrification level (30%, 50%, 70% and 100%) of the furnaces. Since the combustion of fuel gas does no longer takes place, it was assumed that the electrical cracking would present higher thermal efficiency (98.5% vs. 93.5%);
- The actual heat delivered to the system remains unchanged and it is based on the current cracker's situation, the calculation can be described by:

$$Heat\ delivered\ = (Fuel\ gas\ input_{conventional\ cracker}) \cdot 93.5\%$$

- Based on (Wong & van Dril, 2020), the fuel gas input for Moerdijk site is around 19.2 PJ/yr and the input for Geleen is 31 PJ/yr (Oliveira Machado dos Santos & van Dril, n.d.);
- The electricity demand is calculated based on the calculated heat delivered combined with the electrification share (30%, 50%, 70% and 100%) and the thermal efficiency (98.5%), as indicated by the following:

$$Electricity\ demand = (Heat\ delivered) \cdot \frac{Electrification\ share\%}{98.5\%}$$

- The cracked gas cooling via TLEs still happens and the superheating of high pressure steams is possible via electrical heating. For this reason, it is assumed that the amount of superheated high pressure steam produced in the cracking section is the same as in the conventional process;
- It is assumed that the cracking products yields are equivalent to the ones from the conventional process.

Table 7 presents the main changes in the system considering the aforementioned assumptions.

Table 7: Techno-economic characteristics for the electrification of cracking furnaces

Parameter	**Unit**	**Moerdijk**				**Geleen**			
		30%	**50%**	**70%**	**100%**	**30%**	**50%**	**70%**	**100%**
Inputs									
Electricity	PJ/yr	5.5	9.1	12.8	18.2	8.8	14.7	20.6	29.4
Fuel gas	PJ/yr	13.4	9.6	5.8	0	21.7	15.5	9.3	0
Outputs									
Fuel gas surplus	PJ/yr	5.8	9.6	13.4	19.2	9.3	15.5	21.7	31
CO_2 Emissions (furnaces) [a]	kt/yr	839	599	359	0	1176	840	504	0
Economic parameters									
Electric furnaces capacity (input)	MWe	173	289	405	578	280	467	653	933
Electric furnaces capacity (output)	MWth	171	285	398	569	276	460	643	919
CAPEX [b]	M€$_{2019}$	270-386	387-552	489-699	628-897	378-540	541-772	684-977	878-1255
CAPEX	M€$_{2019}$/ MW$_e$	1.6-2.2	1.3-1.9	1.2- 1.7	1.1- 1.6	1.4- 1.9	1.2- 1.7	1 -1.5	0.9- 1.3
OPEX (Fixed)	M€$_{2019}$/yr	5.4-7.7	7.7-11	9.8-14	12.6-17.9	7.6-10.8	10.8-15.4	13.7-19.5	17.6-25

[a] The emission factors for the fuel gas considered are 62.4 kg CO_2/GJ for Moerdijk (Wong & van Dril, 2020) and 54.2 kg CO_2/GJ for Geleen (EMJV, 2016)

[b] The CAPEX values are based on (Römgens & Dams, 2018) and a scaling factor of 0.7 was used to adjust the CAPEX figures to the electrical furnace capacities suggested. The OPEX values are considered to be 2% of CAPEX (Römgens & Dams, 2018)

4.2.2 *Full electrification of compressors*

Normally, there are at least four compressors on a steam cracker site, which are: cracked gas compressor, methane, ethylene and propylene compressors. These equipment are driven by steam turbines, which are responsible for the largest share of the total steam consumption in a steam cracker.

The compressors in a steam cracking process are usually driven by back-pressure turbines, which use steam (super-heated-high, high, medium or low pressure steam) and exhausts a lower-pressure steam or condensate. The energy delivered by the steam is converted to rotational energy by means of rotor blades, which are coupled to the compressor's shaft. This energy is, therefore, used to run the compressor.

The steam that leaves the turbine is normally used to i) run other steam turbines and ii) as heating media to other processes on site (e.g. heat exchangers, reactor's regeneration, etc.). This makes the compression system quite relevant for the overall steam network. The replacement of the compression system by electrical compressors would reduce significantly the steam consumption of both sites. However, the SHP steam produced by the cracking furnaces would no longer be used by this compressor’s steam turbine. For this reason, it was assumed that the heat demand by the fractionation section and by the dilution steam added to the furnaces would be partially met by this heat excess. Because the cracked gas compressor is determinant to keep the steam network on site balanced, once it is replaced by an electrical compressor, the high/medium steam header will suffer a decrease in supply. For this reason, the import of steam under these qualities are needed (see Table 8).

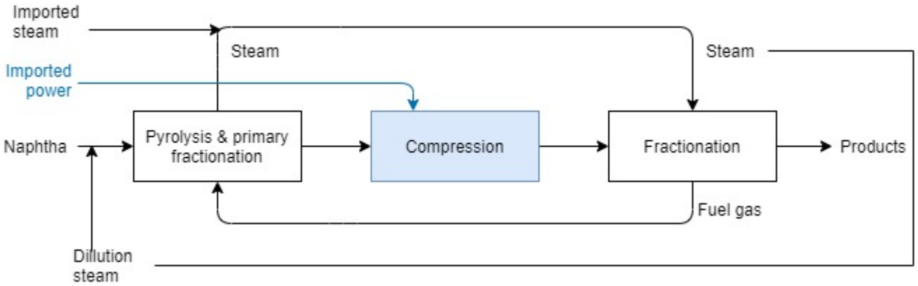


Figure 19: Simplified representation of technology option: electrification of compressors

Electrical compressors are already commercially available (TRL 9) and they are mostly applied to air compression systems. Electrical motors are well accepted in the industry for having less maintenance requirements and for producing less noise and vibration than gas-fired or steam driven ones (IPIECA, 2020). They also present improved operational efficiency, however, the capital costs and the energy costs can be higher for an electric motor compared to those for a steam/gas driven engine (EPA, 2011).
For the evaluation of this option, the following assumptions were made:

- Literature indicates that the energy use by the cracked gas compressor is around 15% of the energy use of a steam cracking process composed by cracking reactions+ compression+ separation (Ren, 2010). The derived value for the energy use by compression is 2.8 PJ/y for Moerdijk and 5 PJ/y for Geleen;
- An average efficiency of 90% (range of 87-92%) was considered for the electrical compressors (Kaser compressors Autralia, 2017);
- As Figure 17 indicates, 29% of the fuel gas input to the furnaces is recovered as steam in the TLEs and 16% of the fuel is superheats the steam produced in the TLEs. In total, 3.1 PJ/yr (Moerdijk) and 5.6 PJ/yr (Geleen) of heat would be available once the compressors are electrified. It was assumed that this heat would be used for the fractionation section and as the dilution steam added to the naphtha feedstock;
- Literature indicates that 20% of the energy use in the overall steam cracking system refers to the fractionation energy use, resulting in 3.7 PJ/yr (Moerdijk) and 6.7 PJ/yr (Geleen). It was considered that the fractionation section thermal efficiency is around 80%, which was used to derive the heat input to this section: 4.7 PJ/yr (Moerdijk) and 8.3 PJ/yr (Geleen);
- It was assumed that the dilution steam is a medium pressure steam of 18 bar and 300˚C (3 GJ/t), which is translated to 4.6 PJ/yr (Moerdijk) and 6.1 PJ/yr (Geleen) as heat demand for the system. In terms of mass, the dilution steam is half of the naphtha intake;
- As no modification on the steam consumption of the fractionation section and downstream processes was considered and the compressor’s steam turbine would no longer provide high/medium pressure steam, it was estimated that the steam needed by boilers/CHP would be around 5.3 PJ/yr (Moerdijk) and 2.4 PJ/yr (Geleen). This estimate also considers the steam demand from the units MEG and SMPO in Moerdijk

and by the benzene extraction, butadiene and MTBE units in Geleen. However, the current superheated steam provision by boilers/CHP to the cracked gas compressor would no longer be needed;

Based on the points raised above, the following technical and financial figures were calculated:

Table 8: Techno-economic characteristics of electrical compressors

Parameter	Unit	Moerdijk	Geleen
Electricity demand electrical compressor (import from the grid)	PJ/yr	3.1	5.6
Electrical compressor capacity	MWe (input)	99	177
Steam demand from fractionation section	PJ/yr	4.7	8.3
Steam for feedstock dilution	PJ/yr	4.6	6.1
Steam for downstream processes (e.g. benzene extraction)	PJ/yr	4.7	1.9
Heat available from TLEs and superheating from furnaces	PJ/yr	8.6	14
Steam needed from boilers/CHP	PJ/yr	5.3	2.4
CAPEX	M€$_{2019}$	207-413	370-740
CAPEX[a]	M€$_{2019}$/MWe	2.1-4.2	2.1-4.2
OPEX (fixed)[b]	M€$_{2019}$/yr	4.1-7.4	8.3-14.8

[a] CAPEX figures based on an electrical compressor of 10 MWe capacity (Römgens & Dams, 2018), no scaling factor was applied since this technology is already commercialized and the values found in literature for different compressors capacities are covered by the mentioned range

[b] OPEX is considered to be 2% of CAPEX (Römgens & Dams, 2018)

4.2.3 *Plastic waste oil as feedstock (co-processing of 5-10%wt of total feed)*

Plastic solid waste (PSW) can be used as feedstock in steam crackers via pyrolysis, a process that converts the waste into an oil that can be upgraded to naphtha level. Pyrolysis is a non-catalytic treatment of plastic solid waste in the presence of a large amount of heat under controlled temperatures and in an inert atmosphere (Al-Salem et al., 2017). The plastic is thermally cracked due to rapid heating in the absence of oxygen, reducing the plastics long polymer chains into much shorter hydrocarbons. The process takes place in four stages which are: initiation, transfer, decomposition and termination, resulting in the production of vapours and char. Among all thermolysis of plastics routes, pyrolysis has shown significant advantages over the others, mainly because it produces less gaseous pollutants due to the absence of oxygen in the process (Fivga & Dimitriou, 2018).

The pyrolysis reaction results in three main streams: condensable vapours, char and non-condensable gases. The condensable vapours are composed by cracked hydrocarbons, which form the plastic waste oil. Char is a solid by-product rich in carbon and it is used as fuel to produce heat for the pyrolysis reaction. Literature reports that char has calorific value of around 18.84 MJ/kg and low sulphur content, characteristics that make it suitable to be used as fuel (Anuar Sharuddin et al., 2016). The second by-product is a gas which composition depends on the mixture of plastic waste that is pyrolysed; however, some studies mention that the main gas components are hydrogen, C1, C2, C3 and C4 hydrocarbons. If PVC is included in the mix, hydrogen chloride is also produced and chlorine removal is required before this gas can be used. The non-condensable gases typically have a calorific value between 42 and 50 MJ/kg, depending on the waste material being processed, but in general this stream can be used as fuel for heat production (Anuar Sharuddin et al., 2016).

The general flow scheme for pyrolysis of plastic waste is presented at Figure 20. The process is basically composed by reaction and separation systems. The combustion step is optional if both gas and char by products are produced in significant amounts. A process model from a plant in the UK, presented by Fivga et al. (Fivga & Dimitriou, 2018) shows that the heat obtained from the combustion of gas and char is sufficient to meet the energy needs from the pyrolysis step, whereas the excess heat can be exported.

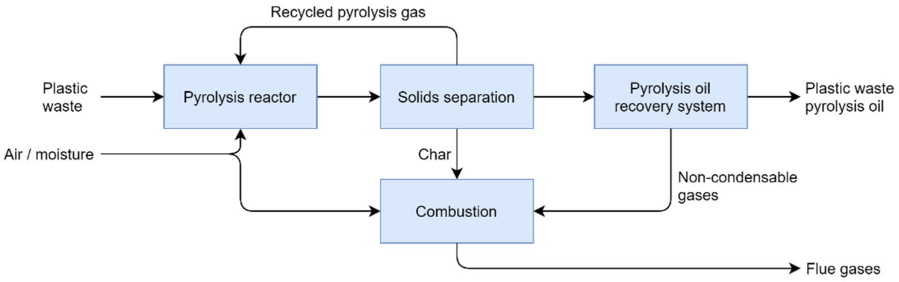


Figure 20: Simplified representation of plastic waste oil production via pyrolysis

Several studies have been done on this topic and different types of reactors have been applied (fixed bed, fluidised, batch and semi-batch). Although some studies are still at lab scale, there are already some industrial projects for plastic pyrolysis, such as the system built by BP during the 1990s in Scotland with the capacity to process 25 kt/yr of plastic waste. The plant was established in a refinery complex (Tukker et al., 1999). BASF also constructed a pyrolysis plant (15 kt/yr) in Germany, which started running in 1994, however, the unit stopped operating in 1996 because no long-term agreement between BASF and the waste supply company could be reached (Al-Salem et al., 2009).

As no major modifications on the current steam cracker systems are expected, for co-processing up to 10%wt, the focus of the analysis is on the production process of the plastic waste oil. The main assumptions for the evaluation of this technology are:

- The production of plastic waste oil is self-sufficient in energy due to combustion of both char and residual gas. Moreover, there is an excess of heat to be exported to external parties;
- The composition of plastic waste oil does not change significantly the steam cracking products yields if the co-processing with naphtha is done up to 10%wt;
- The pyrolysis plastic waste oil can be directly co-processed up to 10%wt with naphtha in the steam crackers without previous upgrades.

A general plastic waste composition was assumed, therefore, differences in the pyrolysis oil were not evaluated in this study. Fivga et al. (Fivga & Dimitriou, 2018) considered a plastic waste mixture of polypropylene, polyethylene and polystyrene; 50, 25 and 25%wt, respectively.

Table 9 summarizes the inputs and outputs of the production of plastic waste oil via pyrolysis of plastic waste. The values were derived considering the process model presented by Fivga et al. (Fivga & Dimitriou, 2018) and the supposed demand for plastic waste oil when co-processing it with naphtha in the crackers of both Shell Moerdijk and SABIC Geleen.

Table 9: Techno-economic characteristics for plastic waste oil production and co-processing with naphtha

Parameter	Unit	Moerdijk		Geleen	
		5%wt	10%wt	5%wt	10%wt
Inputs					
Platic waste	kt/yr	175	350	233	466
Electricity	PJ/yr	1.8	3.6	2.4	4.8
Outputs					
Plastic waste oil	kt/yr	150	300	200	400
Heat to export	PJ/yr	5.8	11.6	7.8	15.5
CO_2 Emissions [a]	kt/yr	72.5	145	96.7	193.4
Economic parameters					
CAPEX [b]	M€$_{2019}$	99	148	99	174
CAPEX	M€$_{2019}$/kt plastic waste oil/yr	0.66	0.49	0.58	0.44
OPEX (Fixed) [b]	M€$_{2019}$/yr	0.22	0.15	0.19	0.13

[a] Direct CO_2 emissions based on the combustion of char and non-condensable gases, with heating value of 38.1 MJ/kg mixture (Fivga & Dimitriou, 2018) and emission factor of 73.3 kg CO_2/GJ (assumption).

[b] CAPEX and OPEX figures based on (Fivga & Dimitriou, 2018) and adjusted considering scaling factor of 0.7.

4.2.4 *Bionaphtha production*

One of the options to decarbonise the steam cracking sector is to replace its feedstock (naphtha) with a renewable feedstock. In this analysis, a partial replacement of naphtha with bionaphtha, in range of 5 to 10 wt%, was chosen. As the impact of coprocessing these two feedstocks on the technical performance is unknown, we assumed that the downstream processing (cracking and separation) would remain identical to current steam crackers. The changes happen outside the system boundaries of the crackers, and thus would not contribute to direct emissions reductions for steam crackers, though they would reduce emissions at the system level. This analysis is focused on different technologies for producing bionaphtha. This is additional to the already existing data in MIDDEN, where only the impacts of substituting the feedstock on the cracker's site were assessed and the upstream possible technologies and configurations for producing bionaphtha were not considered.

The technologies selected in this study for producing bionaphtha are as follows: i) upgrading of tall oil, ii) hydrogenated vegetable oil, iii) lignocellulosic biomass pyrolysis and upgrading, iv) lignocellulosic biomass gasification and syngas conversion (Fischer Tropsch) into bionaphtha. These technologies were selected to represent the utilisation of residual streams from other industries, the use of feedstocks derived from crops (vegetable oils), and the use of second generation technologies for feedstock production.

For all biobased technologies the amount of bionaphtha to be produced is determined by the blending level (5wt% or 10wt%) with fossil naphtha and the steam cracker site capacities. In this study, two sites were considered: Moerdijk and Geleen, with annual naphtha processing capacities of 3,000 and 4,000 kt, respectively. The analysis presented in this study corresponds to the production of bionaphtha to cover 5wt% and 10wt% blending for both Moerdijk and Geleen crackers. It is assumed that the total production of bionaphtha can be covered in a single plant (for each case). Scalation of mass and energy flows were assumed to be linear and CAPEX scaled using the sixth tenth rule of thumb with a scaling factor of 0.7 for the entire plant. A fixed OPEX was calculated in all cases as 5% of CAPEX. In general fixed OPEX fluctuates between 2.5 and 5% in chemical processes, and used in MIDDEN database for most processes. Thus we followed here the most conservative approach This approach applies for all bionaphtha production systems described below.

4.2.4.1 *Upgraded tall oil as feedstock (co-processing of 5-10%wt of total feed)*

Crude tall oil (CTO) is a co-product of the soft kraft pulping industry which can be used as an in-situ energy carrier in mills or that can also be used as feedstock for biochemicals and biofuels (Aryan & Kraft, 2020). The upgrading of tall oil to produce bionaphtha as feedstock for olefins production has been extensively studied in the past (Adjaye & Bakhshi, 1994; Coll et al., 2001; Sharma & Bakhshi, 1991). However, only recently has there been growing interest in the valorisation of CTO, given that policies have been adopted to promote its use for chemicals and fuels rather than its in situ use (Aryan & Kraft, 2020). Most of the studies reported in literature on the upgrading of vegetable oils focus on technical aspects. Although the technology is known to be commercial, to the knowledge of the authors, there is little public available data reporting its techno-economic and environmental performance.

For this study, output and input information related to the technology performance was gathered from (Rajendran et al., 2016), and CAPEX was gathered from (Hilbers et al., 2015). The upgrading of CTO consists of hydrotreatment in which hydrogen enriches the quality of the oil to yield a paraffin and olefin rich liquid (Anthonykutty et al., 2015), which can be co-processed with naphtha for olefins production. Figure 21 provides a simplified flow diagram of crude tall oil upgrading and its integration with steam crackers. Table 10 provides an overview of main inputs and outputs of bionaphtha production by tall oil upgrading, and economic parameters for the production of bionaphtha using crude tall oil as feedstock.

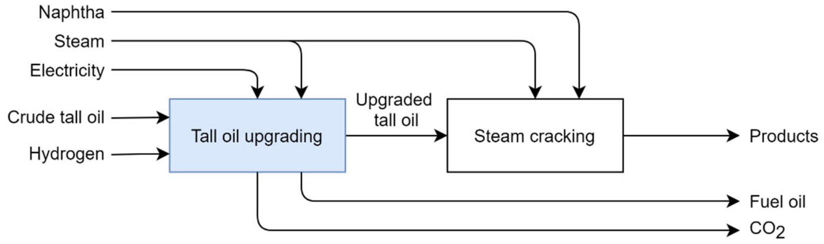


Figure 21: Simplified representation of tall oil upgrading for bionaphtha production

Table 10: Techno-economic parameters for tall oil upgrading

Parameter	Unit	Moerdijk		Geleen	
		5%wt	10%wt	5%wt	10%wt
Inputs					
Tall oil	kt/yr	251	502	335	669
Electricity	TJ/yr	52	103	69	137
Steam	TJ/yr	542	1085	723	1446
Hydrogen	kt/yr	7	14	9	18
Outputs					
Bionaphtha	kt/yr	150	300	200	400
Fuel oil	kt/yr	93	186	124	248
CO_2 Emissions [a]	kt/yr	14	29	19	38
Economic parameters					
CAPEX [b]	M€$_{2019}$	122	199	149	243
CAPEX	M€$_{2019}$/kt bionaphtha/yr	0.8	0.7	0.7	0.6
OPEX (Fixed)	M€$_{2019}$/yr	6	10	7	12

[a] Considered as biogenic

[b] CAPEX source 370 MUSD$_{2015}$ for a capacity of 1192 kt/yr palm oil. CAPEX calculated in € using 2015 average exchange rate and updated to 2019 using the CEPCI

4.2.4.2 *Hydrotreated vegetable oil as feedstock (co-processing of 5-10%wt of total feed)*

Similar to the case of CTO, vegetable oils can also be used as source for bionaphtha production. Vegetable oils are currently a cornerstone for oil-based biorefinery concepts for producing a suite of products such as fuels, lubricants, and products for food applications such as cooking oils (Rincón et al., 2014). In this case, we have chosen the use of palm oil as a source for further upgrading into bionaphtha. The process is analogous to that of tall oil upgrading, where hydrotreatment with hydrogen yields a hydrocarbon-rich liquid (Hilbers et al., 2015). Inputs and outputs, as well as CAPEX, of the technology where gathered from (Hilbers et al., 2015), and adapted to the capacities required to meet the needs of steam crackers in Moerdijk and Geleen. Figure 22 provides a simplified flow diagram of palm oil upgrading and its integration with steam crackers. Table 11, provides main input and outputs, as well as economic parameters of the upgrading of vegetable oils.

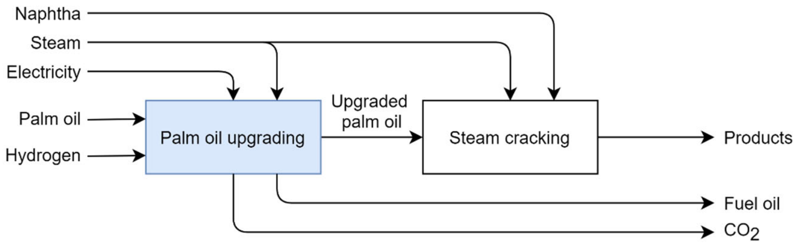


Figure 22: Simplified representation of vegetable oil upgrading for bionaphtha production

Table 11: Techno-economic parameters for vegetable oil upgrading

Parameter	Unit	Moerdijk		Geleen	
		5%wt	10%wt	5%wt	10%wt
Inputs					
Palm oil	kt/yr	183	367	244	489
Electricity	TJ/yr	38	75	50	100
Steam	TJ/yr	396	792	528	1056
Hydrogen	kt/yr	5	10	7	13
Outputs					
Bionaphtha	kt/yr	150	300	200	400
Fuel oil	kt/yr	68	136	90	181
CO_2 Emissions [a]	kt/yr	5	9	6	12
Economic parameters					
CAPEX [b]	M€$_{2019}$	98	159	120	195
CAPEX	M€$_{2019}$/kt bionaphtha/yr	0.7	0.5	0.6	0.5
OPEX (Fixed)	M€$_{2019}$/yr	5	8	6	10

[a] Considered as biogenic

[b] CAPEX source 370 MUSD$_{2015}$ for a capacity of 1192 kt/yr crude tall oil. CAPEX calculated in € using 2015 average exchange rate and updated to 2019 using the CEPCI.

4.2.4.3 *Upgraded pyrolytic bio-oil as feedstock (co-processing of 5-10%wt of total feed)*

Lignocellulosic biomass is seen as an important feedstock for biorefineries as it can be used to produce important platform chemicals such as syngas, pyrolytic oil, carbohydrates, among others for their further conversion into fuels and chemicals (Moncada et al., 2016). In literature, there is a vast amount of studies investigating the production and upgrading of oil derived from the pyrolysis of biomass for producing chemicals and fuels (Adjaye & Bakhshi, 1994; Dai et al., n.d.; Yao et al., 2014; Zhang et al., 2014). The pyrolysis process is a thermochemical conversion of biomass into oil fractions and vapours. The oil fraction is generally hydrotreated to reduce the oxygen content of the oil and increase its quality towards hydrocarbons. This can be done in multiple configurations including one or two hydrogenation steps, and/or combining water soluble and water insoluble fractions of the oil prior to upgrading (Sharifzadeh et al., 2015). Figure 23 presents a simplified diagram of the production of pyrolysis oil and upgrading, and its subsequent integration with steam crackers. Table 12 provides main input and outputs, as well as economic parameters of the production of bionaphtha from lignocellulosic biomass. Base case input and outputs, as well as economic parameters were gathered from (Sa et al., 2011) and scaled to the cases presented in this study.

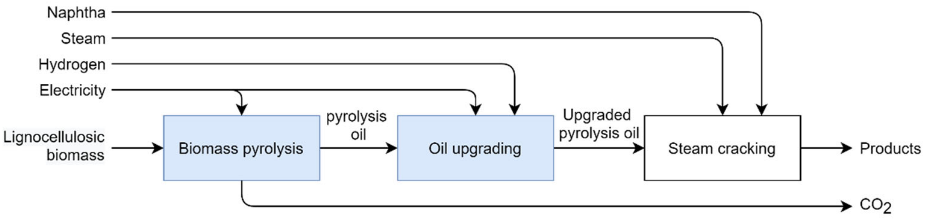


Figure 23: Simplified flow diagram of pyrolysis oil and upgrading for bionaphtha production

Table 12: Techno-economic parameters for upgraded pyrolysis oil

Parameter	Unit	Moerdijk		Geleen	
		5%wt	10%wt	5%wt	10%wt
Inputs					
Wood chips	kt/yr	273	546	364	729
Hydrogen	kt/yr	19	38	25	51
Electricity	TJ/yr	264	528	352	704
Outputs					
Bionaphtha	kt/yr	150	300	200	400
CO_2 Emissions [a]	kt/yr	102	204	136	272
Economic parameters					
CAPEX [b]	M€$_{2019}$	138	224	169	274
CAPEX	M€$_{2019}$/kt bionaphtha/yr	0.9	0.7	0.8	0.7
OPEX (Fixed)	M€$_{2019}$/yr	7	11	8	14

[a] Considered as biogenic

[b] CAPEX source 332 MUSD$_{2010}$ for a capacity of 773 kt/yr woodchips. CAPEX calculated in € using 2010 average exchange rate and updated to 2019 using the CEPCI.

4.2.4.4 *Fischer Tropsch liquid as feedstock (co-processing of 5-10%wt of total feed)*

As mentioned above, lignocellulosic biomass can serve as feedstock for important platform chemicals for a variety of applications in industry. One important platform is syngas as it can be converted into a large group of chemicals and fuels (Moncada et al., 2015). In this case, biomass gasification was adopted as technology for producing syngas which was later converted into Fischer Tropsch liquids for paraffins and olefins production. Both, gasification and Fischer Tropsch (FT) have been extensively studied in literature. However, literature focuses the most on FT liquids for fuels production such as diesel, kerosene and gasoline and not as much on olefins. Nevertheless, there are a couple of studies in literature dealing with FT liquids for naphtha production, mostly focused on technical aspects (Cheng et al., 2016; Oschatz et al., 2016; Pedersen et al., 2018).

Figure 24 presents a simplified diagram of the production of FT liquids and upgrading, and its subsequent integration with steam crackers. Table 13, provides main input and outputs, as well as economic parameters of production of bionaphtha from lignocellulosic biomass via Fischer Tropsch. Base case input and outputs, as well as economic parameters were gathered from (Sa et al., 2011) and scaled to the cases presented in this study.

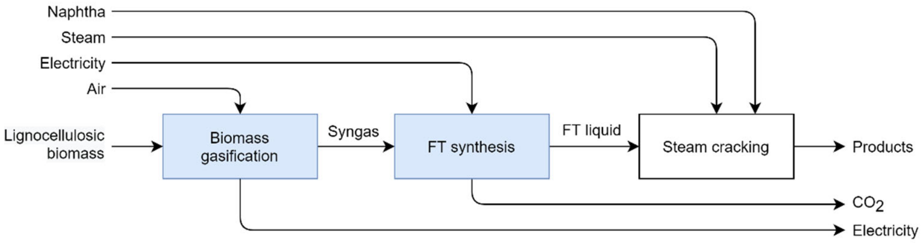


Figure 24: Simplified flow diagram of biomass gasification and Fischer Tropsch for bionaphtha production

Table 13: Techno-economic parameters for biomass gasification and FT synthesis

Parameter	Unit	Moerdijk		Geleen	
		5%wt	10%wt	5%wt	10%wt
Inputs					
Wood chips	kt/yr	649	1299	866	1732
Outputs					
Bionaphtha	kt/yr	150	300	200	400
CO_2 Emissions [a]	kt/yr	243	485	323	647
Electricity	TJ/yr	627	1255	836	1673
Economic parameters					
CAPEX [b]	M€$_{2019}$	289	469	353	574
CAPEX	M€$_{2019}$/kt bionaphtha/yr	1.9	1.6	1.8	1.4
OPEX (Fixed)	M€$_{2019}$/yr	14	23	18	29

[a] Considered as biogenic

[b] CAPEX source 379 MUSD$_{2010}$ for a capacity of 773 kt/yr woodchips. CAPEX calculated in € using 2010 average exchange rate and updated to 2019 using the CEPCI.

5 Results

5.1 Uncertainty

Uncertainty is a theme throughout the MIDDEN+ research. When gathering techno-economic data on industrial technology, particularly innovative or disruptive technology, this is inevitable. Major uncertainties and unknowns remain in this space. We have discussed this in the context of specific technology and configuration examples, but it is also worthwhile to look at the general findings. Below in Table 14, the pedigree matrix scores for each of the new technologies is shown. Broadly, the scores are rather low; this is a direct result of the lack of publicly available, direct measurements of quantitative technology information for this set of technologies. This is to be expected for pre-commercial technologies, particularly in the industrial sector where technology data is often kept confidential for competitiveness reasons. Generally, scores are higher for technical information than economic, for similar reasons. The validation process scores lowest of any category, pointing to both the challenges and the importance of collaboration and industry sector involvement in such research to validate quantitative information. These low scores do not necessarily indicate that the data are poor, but rather that the data are uncertain.

Table 14: Pedigree matrices for all technologies described in this report

Technology	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Paper and board				
Air-laid forming – technical	2	1	2	1
Air-laid forming – economic	2	1	2	0
Microwave drying retrofit – technical	3	3	2	1
Microwave drying retrofit – economic	2	1	2	0
Enclosed hoods retrofit – technical	2	3	2	0
Enclosed hoods retrofit – economic	2	1	2	0
Steam cracking				
Steam cracker furnace electrification – technical	1	1	1	1
Steam cracker furnace electrification – economic	1	1	2	0
Steam cracker compressor electrification – technical	3	2	3	2
Steam cracker compressor electrification – economic	3	2	2	2
Plastic waste pyrolysis oil as feedstock – technical	2	3	3	2
Plastic waste pyrolysis oil as feedstock – economic	2	2	2	2
Upgraded tall oil as feedstock – technical	2	2	2	1
Upgraded tall oil as feedstock – economic	1	1	2	0
Hydrotreated vegetable oil as feedstock – technical	3	2	2	2
Hydrotreated vegetable oil as feedstock – economic	2	2	2	1
Upgraded pyrolytic bio-oil as feedstock – technical	3	3	2	2
Upgraded pyrolytic bio-oil as feedstock – economic	3	2	2	2
Fischer Tropsch liquid as feedstock – technical	2	2	2	1
Fischer Tropsch liquid as feedstock – economic	1	1	2	0

Note: 0 indicates less certain data (knowledge basis is weaker) and 4 indicates more certain data (knowledge basis is stronger). See Chapter 2.2 for more details on the pedigree matrix methodology.

The report also highlights areas where the authors are aware of uncertainties flowing from assumptions. For example, we assume that the electrification of the furnaces does not affect the products yields. However, because electrical crackers are expected to differ considerably from the conventional gas-fired furnaces in design and heat distribution, this may not be realistic. Currently little information about this aspect is found in publicly available literature. We have made simplifying assumptions in our analysis of other technologies, which are described in the report. These assumptions are taken into account in our scoring of the technologies in Table 14.

Users of the MIDDEN+ dataset can conclude that the technology data should be interpreted cautiously, and continually updated and re-evaluated against new information and literature. Particularly for economic data, sensitivity analysis would be useful in order to validate models and determine the sensitivity to changes in the values given in this report.

5.2 Future technology cost

Future costs are also an important area of uncertainty. As shown below in Table 15, there is considerable uncertainty about the evolution of the costs of the technologies in this report. Particularly where the potential for technology learning is judged to be “low” in several categories, modellers and data users should be cautious when applying general progress ratios or learning rates to the dataset. Note that these are indications of long-term potentials, and does not account for increasing cost estimates as technologies commercialize and more detailed and accurate cost assessments are completed.

Table 15: Technology learning potential for all technologies described in this report

	Learning by researching (R&D)	Learning by doing	Economies of scale	Spillover effects
Paper and board				
Air-laid forming	Low	Medium	Low	Low
Microwave drying retrofit	Low	High	High	High
Enclosed hoods retrofit	Low	Low	Medium	Medium
Steam cracking				
Steam cracker furnace electrification	High	High	Medium	Medium
Steam cracker compressor electrification	Low	Medium	Low	Low
Plastic waste pyrolysis oil as feedstock	Medium	High	High	Medium
Upgraded tall oil as feedstock	Medium	High	High	Low
Hydrotreated vegetable oil as feedstock	Medium	High	High	Low
Upgraded pyrolytic bio-oil as feedstock	Medium	High	High	Low
Fischer Tropsch liquid as feedstock	Medium	High	High	Low

Based on the assessment of potential cost reductions from technology learning, some technologies must be treated with caution when applying learning rates. Air-laid forming, for example, because of its integrated nature and TRL level, is unlikely to experience large cost decreases. Compressor electrification for steam crackers also has limited potential for cost reductions, as electric compressors are a mature, commercial technology. Others see higher potential for future cost reductions from learning, such as alternative bio-based naphtha feedstock production; these are new processes for which there is room for improvement via research, implementation and scale-up of equipment.

Most long-term cost reduction potential is based on learning by doing and economies of scale, rather than R&D or spillover effects. This stems partially from the choice of technologies for inclusion in the dataset. The group of technologies researched was limited, and only technologies with sufficient publicly available information could be included. Data typically becomes publicly available when there is already a large body of research about a given technology.

Nonetheless, the variety of ratings even among a small group of technologies, indicates that applying a uniform learning rate to all industrial technologies could lead to inaccurate results and misleading conclusions. Further research is needed to determine whether broad trends within industrial sectors or types of processes can be identified.

5.3 Examples of sectoral decarbonisation analysis

Via the MIDDEN+ project, ten new technologies have been added to the database for the paper and board and steam cracking sectors. These additions provide new options for users of the MIDDEN dataset and can broaden the scope of analysis of decarbonisation pathways. These additional technologies and configurations are further described and discussed in Chapters 3 and 4.

Below, we provide examples of the kind of analysis made possible using the additional dataset. These are not intended to be comprehensive analyses, but rather a demonstration of the potential of the MIDDEN and extended MIDDEN+ datasets. The aim is not to provide a recommendation or normative conclusion, but rather to illustrate insights that can be gained from the dataset, and advantages and disadvantages of different technologies and combinations based on the data collected. Using the MIDDEN+ data, we aim to highlight the key factors influencing technology choices, to aid users of the dataset.

5.3.1 Decarbonisation pathways for the Dutch paper and board sector

Here, we aim to illustrate the advantages and disadvantages of the different technologies and configurations for the paper and board sector, based on the data collected. Table 17 compares advantages and disadvantages of the full set of technology options considered for paper and board manufacturing in MIDDEN+. Here the analysis is focused on energy use, costs, and GHG emissions. Some examples will be further discussed in the following sections.

Table 16: Benefits and challenges for the decarbonisation options for the paper and board sector

Technology	Benefits	Challenges
Air-laid forming	• Lower fuel use in paper forming (up to 50% of energy used in the drying section) • Softer paper • No waste water treatment needed • Direct investment cost reduced to 30%-50% that of a conventional mill • Operation and maintenance costs expected to be reduced	• Increased electricity use in paper forming (+150-250 kWh/t) • Less uniform paper thickness • Lower sheet strength • Reduced smoothness • Lower production rate for standard paper grades (1,500 m/min vs 6,000 m/min for conventional mills)
Microwave drying (pre-press)	• Increased paper machine speed • Increased fibre strength and less thermal degradation of the product • Energy consumption savings of 12%-20% compared to conventional paper making, due to moisture selectivity • Reduced floor space requirements • Uniform product • Immediate on-off process heat control • Lower overall investment costs for new machines • Lower operation and maintenance costs due to less drying cylinders and less severe process conditions	• Difficult to manage the paper web temperature in case of a paper break • Difficult to find the optimal values for operating parameters like frequency, power, and assistive drying techniques • High upfront investment cost of equipment with high replacement cost for microwave generators • Dependency on electricity prices and availability
Enclosed hoods (retrofit)	• Less ventilation air need per tonne of evaporate water (by 33%-50%) • Lower thermal energy demand • Lower power demand • Prevents heat and humidity from spreading in the hall, leading to improved safety and less degradation of the hall	• Cost of retrofitting the hood and associated downtime

Sources: Air-laid forming (Bajpai, 2016; Martin, Worrell, et al., 2000); Microwave drying (Ahrens et al., 2003; Delgado et al., 2016; Kong et al., 2016; Kumar, 1991; Linn High Therm GmbH, n.d.-b; Radoiu, 2020; VNP, 2018b); Enclosed hoods (Martin, Worrell, et al., 2000; TM Systems, 2016b)

5.3.1.1 *Greenhouse gas emissions*

In terms of greenhouse gas emissions, multiple configurations of technologies can reduce or eliminate the direct CO_2 and other GHG emissions from paper and board production. In some cases, technologies can or must be combined to provide emissions reductions. Many of these combinations rely on electrification to reduce scope 1 emissions. If scope 2 emissions from electricity generation are included, the picture changes.

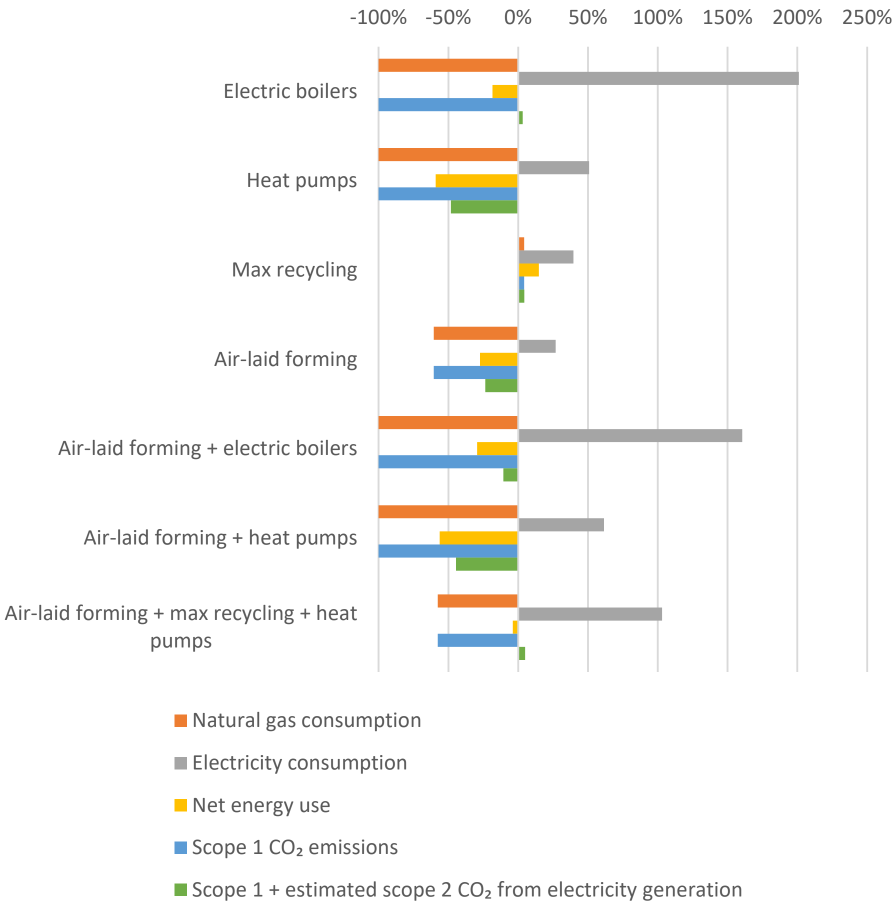


Figure 25: Total effect, relative to the base case, for graphic paper production in the Netherlands (800 kt capacity)

Note: The base case considers a paper mill with a CHP and auxiliary natural gas boiler. Alternative heat supply options replace both CHP and gas boiler. Heat pumps require the installation of enclosed hoods at all remaining plants. CO_2 intensity of grid electricity is based on 2020 values from the Klimaat- en Energie-Verkenning 2019 (Planbureau voor de Leefomgeving (PBL), 2019) – additional reductions in grid intensity beyond 2020 have not been assumed (though some of the presented options will become available later). Air-laid forming for graphic paper production has not yet been commercialised, and its use with recycled fibres is still being researched, so these options should be considered only as potential options after commercialisation.

Figure 25 shows the effects in terms of cost, energy and emissions, if 800 kt of graphic paper production capacity in the Netherlands were replaced with various other configurations including electrified utilities. Electric boilers, heat pumps, air-laid forming and increased recycling increase electricity consumption for graphic paper production, while reducing direct CO_2 emissions from the site. When including estimated scope 2 CO_2 emissions from electricity generation, based on today’s grid intensity, some of these electrification options become less attractive from an overall CO_2 emissions perspective. For example, electric boilers in particular could even increase total emissions if used in isolation from other efficiency options, and could more than double electricity consumption for graphic paper production.

Combinations of technologies could mitigate this effect; if efficiency measures are applied, the process electricity requirement can be reduced. Air-laid forming increases electricity consumption relative to the base case, but also reduces the steam requirement in the drying section; thus air-laid forming in combination with heat pumps counterbalances the increase in electricity consumption resulting in less net energy use and emissions.

Without a system-level scenario analysis, it is impossible to tell which is the optimal configuration; in fact, the optimal configuration may not be the same for all 800 kt of capacity. It also may change over time, as other elements of the system, such as product demand, waste management systems, and electricity generation, evolve. Further, not all of the technologies shown below are currently commercially available, and many other options could also be considered. However, this hypothetical case highlights the importance of considering emissions impacts beyond the plant fence.

It is not possible to estimate emissions from other parts of the value chain (scope 3) based on the MIDDEN+ dataset for paper and board; additional information and potentially a full life cycle assessment (LCA) would be needed. The use of biomass, biogas, or hydrogen could also lead to emissions elsewhere in the system, which should not be neglected in analysing decarbonisation pathways. Material inputs to the papermaking process would also have upstream and downstream effects on emissions, energy consumption and environmental pollution.

5.3.1.2 Final energy consumption

Energy consumption and energy efficiency are important elements of this analysis as well. Below, the comparison of total final energy consumption in the same hypothetical cases is presented, relative to the base case (2015 production levels and average energy intensity).

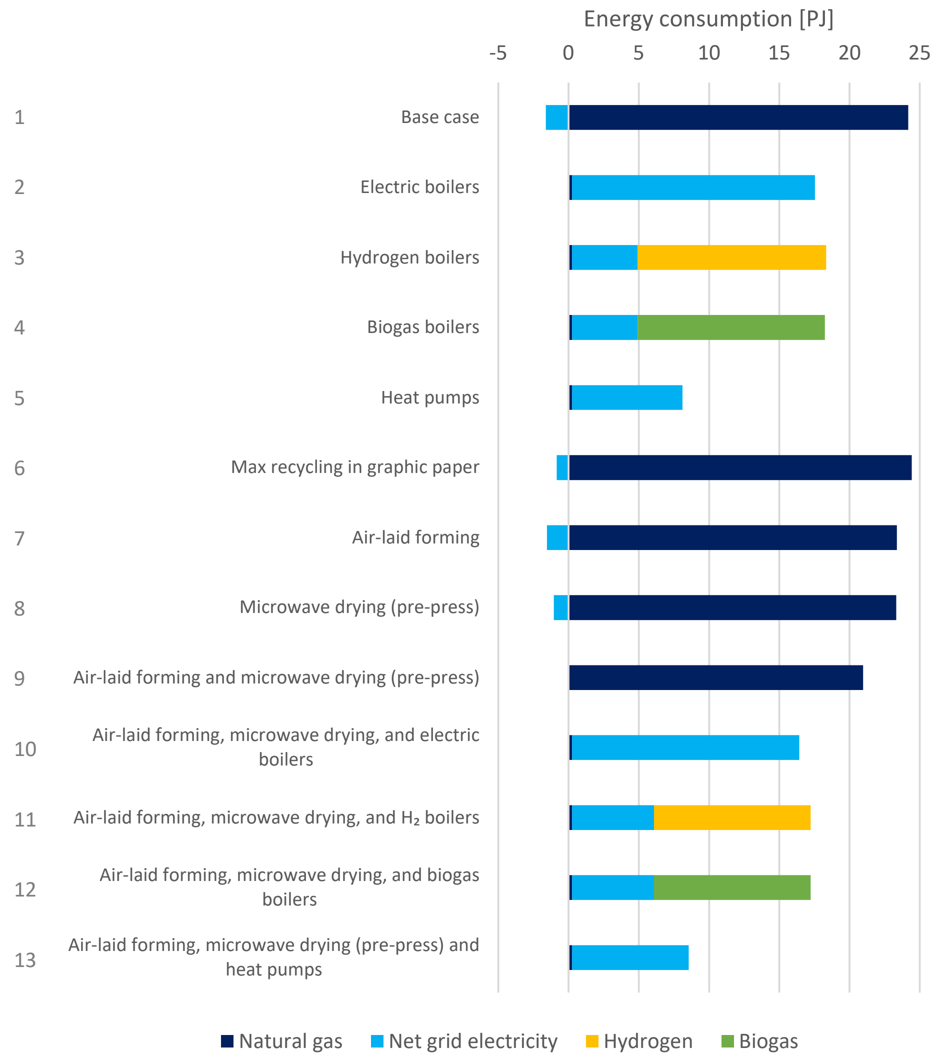


Figure 26: Total paper and board sector final energy consumption (PJ) in different configurations

Note: For each configuration, the full paper and board sector energy use is included, based on 2015 production levels from the MIDDEN database. Air-laid forming, microwave drying, and higher temperature heat pumps have not yet been commercialised for the relevant sectors. In this figure, air-laid forming is applied to low basis weight grades (graphic and sanitary paper), and microwave drying is applied to corrugated board, folding boxboard, and solid board. Heat generation options are applied in all paper and board grades. Net grid electricity consumption considers that surplus electricity generated at CHP units can be sold into the grid in the base case and other cases where alternative utilities are not included (cases 1, 6, 7, 8 and 9). Energy consumption is calculated on the basis of MIDDEN data for the paper sector, which considers the average energy intensity level for all production, and uses production values for 2015. This figure does not include all possible configurations.

Energy intensity could potentially be reduced considerably with alternative drying processes and alternative heat generation technologies, with effects on both the total energy consumption of the sector and the energy mix. Alternative fuels for boilers, such as biogas and hydrogen, could also shift the energy mix. Combinations of these processes and technologies could lead to significantly different energy demand in the paper and board sector in the future.

Cases 6, 7, 8 and 9 consider alternative processes that reduce energy intensity, but without a change in the utilities. These cases would reduce CO_2 emissions, but without a major change in the energy mix of the sector. If the existing CHPs are replaced with a boiler with a low-carbon fuel, as in cases 2-5 and 10-13, energy use and emissions can be reduced further via efficiency gains and fuel shifts. However, these changes in utilities may not have beneficial effects on operating cost, as these low-carbon energy sources are typically more costly than natural gas, and the sales of electricity to the grid would be lost. Considering both utility and process technology options together is important, as process changes affect capacity and investment needs for utilities and future variable costs.

These combinations illustrate a few of the possibilities in the paper and board sector, but of course many more potential combinations exist. The graph above assumes the full potential of each option will be reached, which in reality is unlikely. More likely is a combination of different pathways and energy carriers based on site-specific considerations. The MIDDEN+ dataset allows users to combine these technologies to construct coherent scenarios.

5.3.1.3 Cost

Cost is, of course, one of the most important considerations for technology investments. High up-front investment costs can be a barrier to low-carbon technology adoption, especially in a sector that has faced a turbulent market and shifting product demand in recent years. For European producers, which have increased exports to outside the EU in recent years, facing rising demand for raw materials, and rising energy prices, costs play a pivotal role in remaining competitive globally (Berg & Lingqvist, 2019; European Commission, 2013; Kallio et al., 2015).

Air-laid forming for sanitary paper production provides an instructive example; investment costs for this technology are expected to be considerably lower than a greenfield conventional paper mill, when commercialised (Figure 27). However, given the current economic situation and market dynamics in the paper and board sector, the context of the investment decision is important. In the case of decarbonising existing sanitary paper production, greenfield conventional mills are not the best choice for comparison purposes; if the CAPEX of a new air-laid forming-based paper mill is compared only to the relevant utility investments in different decarbonisation configurations, the CAPEX then far exceeds other potential decarbonisation pathways. In the case where new sanitary paper capacity is being built, then the full CAPEX would be considered, and air-laid forming is more attractive. In this case, air-laid forming also reduces CAPEX for utilities, as their capacity can be reduced to meet only the reduced process steam demand.

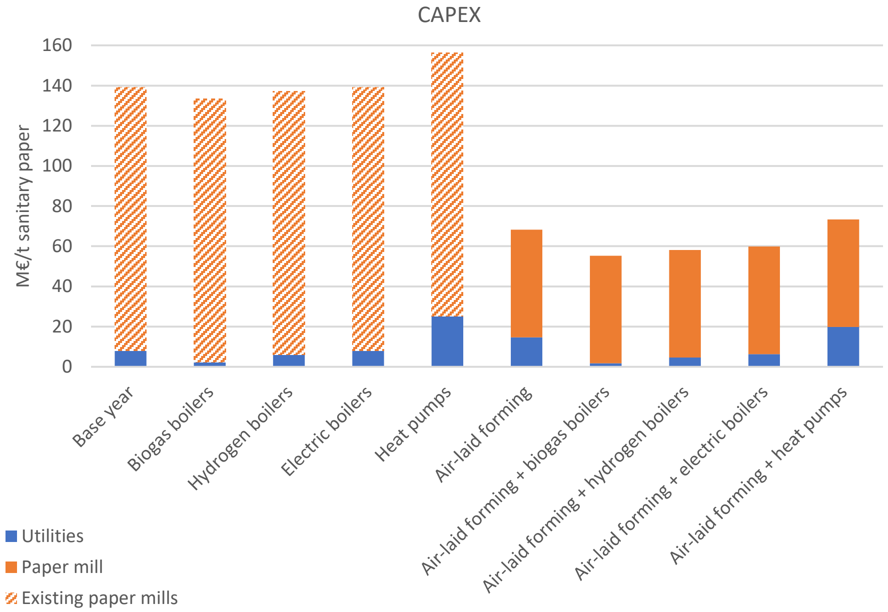


Figure 27: CAPEX for sanitary paper mills in different configurations

Note: In all cases where utilities are specified, they replace the existing CHP and natural gas boilers, with capacity scaled to meet process steam demand. Microwave drying is not compatible with production of sanitary paper and other low basis weight paper grades, and is therefore excluded from this example.

With a number of low-carbon technologies relying heavily on electricity, electricity prices will be an important determining factor of the payback times and economic viability of these decarbonisation strategies. In Figure 15, the levelised cost of production for the hypothetical case of a 100 kt corrugated board mill is shown, relative to the baseline. The first graph considers the 2020 CO_2 and natural gas prices from the KEV2019 (Planbureau voor de Leefomgeving (PBL), 2019). Here we see that the conventional paper mill with CHP has a lower levelised cost of production at electricity prices of about €40/MWh and above. Microwave drying combined with CHP does not achieve a lower levelised cost at any electricity price below €90/MWh. However, in combination with electrified utilities, it can begin to compete with the paper mill with conventional steam drying, because of the efficiency gains and reduced CO_2 costs.

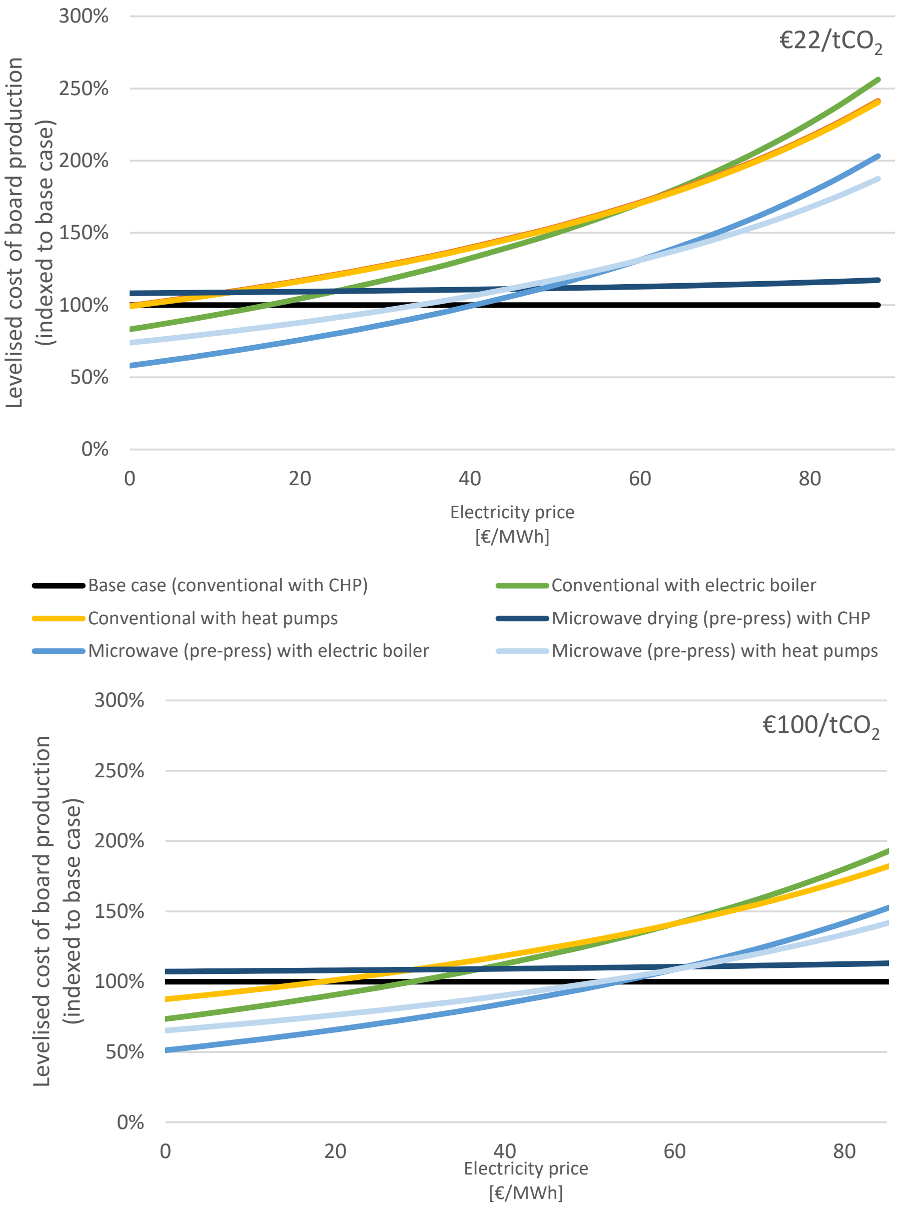


Figure 28: Levelised cost of production for a 100 kt capacity corrugated board mill with various configurations, relative to average performance conventional production

Note: Levelised cost of production is indexed to the base case, which considers an average CAPEX, OPEX, and energy intensity of corrugated board production in the Netherlands in 2015. All cases consider a natural gas price of €0.19/m^3 (about €6.7/GJ). It is assumed that surplus electricity generated by the CHP can be sold at the same market price indicated on the horizontal axis. The assumed cost of recovered fibre input is €129/t.

Taking the same hypothetical case, if we increase the CO_2 price to a high level (€100/tCO_2), we then find that the levelised cost of production with microwave drying and electrified steam generation becomes competitive with the base case, at electricity prices up to just more than €50/MWh, and reducing the cost gap at higher electricity prices. Such a hypothetical case must be interpreted with caution, of course, as there are limitations of levelised cost as an indicator for profitability, and the assumptions may not be representative of the situation in many paper mills (see notes below Figure 28). It also includes annualised capital charges in the base case, whereas in reality many existing mills may have paid off the initial capital cost, and thus have much lower levelised costs for continued operation. Furthermore, the comparison of levelised cost does not consider other potential barriers to investment in new technologies, such as the availability of capital and the lost profits during a shutdown for a retrofit.

Nonetheless, it indicates the sensitivity of the competitiveness of microwave drying to variable operating costs, specifically electricity price and CO_2 price. This sensitivity is important to consider in evaluating decarbonisation pathways for the paper and board sector. The technology choice that makes sense at today's CO_2 prices may no longer be the optimal choice at the CO_2 prices of 2030 or 2050. Further, policymakers can work to close this gap by analysing and targeting the specific areas of high cost for low-carbon technologies. In the case of microwave drying, electricity price is an important factor to consider.

5.3.2 *Decarbonisation pathways for the Dutch steam cracking sector*

Decarbonisation options for the Dutch steam cracker sector have been divided in two main types of technologies: i) electrification technologies, ii) feedstock production technologies. Here, we aim to illustrate the advantages and disadvantages of the different technologies based on the data collected and presented in the previous chapter, and how it can be used to guide users on its utilisation for further analysis. Table 17 compares advantages and disadvantages of the full set of technology options considered for steam crackers in MIDDEN+. Here the analysis is focused on energy use, costs, and GHG emissions. Some examples will be further discussed in the following sections.

Table 17: Benefits and challenges for the decarbonisation options for the steam cracking sector

Technology	Benefits	Challenges
Compressor electrification	• Mature technology • Intermediate step for full electrification • Higher efficiency than compressors driven by steam turbines • May reduce scope 1 emissions when the SHP steam is partially delivered by a CHP on site	• Excess heat from cracked gas cooling • Significant infrastructural costs • Impact on site's steam network that may lead to import of high/medium pressure steam • May affect only scope 2 emissions • Renewable electricity dependency • Dependency on electricity price
Partial furnace electrification (30%-70%)	• Reduction of scope 1 emissions • Higher thermal efficiency • Intermediate step for full electrification	• Low TRL (1-2) • Significant infrastructural costs • Renewable electricity dependency • Dependency on electricity price • Unknown impacts on cracking product quality and yields
Full furnace electrification	• High reduction of scope 1 emissions • Higher thermal efficiency	• Low TRL (1-2) • Significant infrastructural costs • Renewable electricity dependency • Large amount of extra fuel gas available • Unknown impacts on cracking product quality and yields

Technology	Benefits	Challenges
Pyrolysis plastic waste co-processing feedstock 5-10%wt	• Reduction of naphtha intake • Circular economy option • Technology in demo phase (TRL 6)	• Uncertainty on waste plastic supply • No reduction on scope 1 or scope 2 emissions • Unknown impacts on cracking products
Bionaphtha as co-processing feedstock 5-10%wt, upgraded tall oil	• Substitution of fossil naphtha intake • Technology at commercial stage	• Technology dependent on availability tall oil • Not certain on maximum blending capacity with naphtha • Requirement of significant amounts of hydrogen for upgrading • Uncertainty on hydrogen source • Impacts (costs, GHG emissions) happening outside steam cracking gate
Bionaphtha as co-processing feedstock 5-10%wt, Hydrotreated vegetable oil	• Substitution of fossil naphtha intake • Technology at commercial stage • High efficiency on carbon balance	• Technology dependent on vegetable oils • Debate about sustainability of first generation feedstock use for fuels and chemicals • Requirement of significant amounts of hydrogen for upgrading • Uncertainty on hydrogen source • Uncertainty around maximum blending capacity with naphtha • Impacts (costs, GHG emissions) happening outside steam cracking gate • Scope 3 emissions need to be monitored as first generation bio-oils are used
Bionaphtha as co-processing feedstock 5-10%wt, fast pyrolysis and upgrading	• Substitution of fossil naphtha intake • Technology at demo phase (TRL 5-6)	• Technology dependent on supply of lignocellulosic biomass • Uncertainty around maximum blending capacity with naphtha. • Requirement of significant amounts of hydrogen for upgrading • Uncertainty on hydrogen source • Impacts (costs, GHG emissions) outside steam cracking sector/plant gate
Bio naphtha as co-processing feedstock 5-10%wt, Gasification and FT	• Substitution of fossil naphtha intake • Technology at pilot phase (TRL 4) • Electricity produced as co-product	• Technology dependent on supply of lignocellulosic biomass • Uncertainty around maximum blending capacity with naphtha • Low carbon efficiency into bionaphtha • High CAPEX compared to other options

5.3.2.1 *Greenhouse gas emissions*

Combined electrification of furnaces and cracked gas compressor
The electrification of both furnaces and cracked gas compressors was chosen for further analysis, as it results in the highest electricity demand among the technologies studied.

In this example, it is assumed that the cracking furnaces are fully electrified and the compressors are replaced by electrical compressors. Figure 29 gives an overview of the proposed technology configuration. Considering that the compressor would no longer provide high and medium pressure steam to the fractionation section and to the downstream processes, it is expected that this demand would need to be covered by boilers/ CHP. The impact on the total electricity demand would be quite significant for both sites.

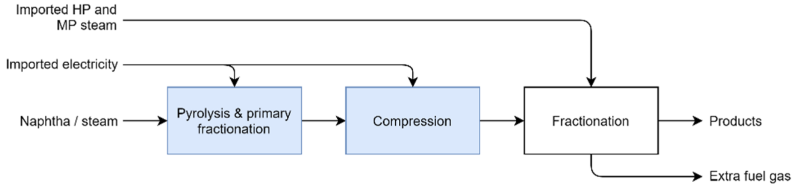


Figure 29: Full electrification of cracking furnaces and cracked gas compressor

For the assessment of this configuration, the following assumptions were taken into account:

- Fuel gas consumption from the pyrolysis furnaces is reduced by 100%;
- The heat recovery via TLEs in the furnace would still take place because the cracked gas needs to be cooled down for further processing, however, the superheating step would no longer happen since no exhausted gas from combustion in the furnaces would be available. For this reason, it was considered that the heat from the TLEs (4.4 PJ/yr for Moerdijk and 8.5 PJ/yr for Geleen) would partially cover the heat demand from the fractionation section (4.7 for Moerdijk and 8.3 for Geleen) and the steam demand for feedstock dilution (4.6 for Moerdijk and 6.1 for Geleen) and for downstream processes (4.7 for Moerdijk and 1.9 for Geleen).
- The current steam use from boilers/CHP (medium and high pressure steam) would be 9.5 PJ/yr for Moerdijk and 7.8 PJ/yr for Geleen to cover the heat demand of the fractionation section, the downstream processes and the feedstock dilution steam.
- Considering that electrification of crackers would be available after 2030, the projected emission factor for the electricity grid for this year was used (0.09 kg CO_2/kWh) (Planbureau voor de Leefomgeving (PBL), 2019) to estimate the emissions related to electricity import;
- For the steam use, an emission factor of 0.104 kg CO_2/MJ (Wernet et al., 2016) was considered

The figures for the current situation were based on the MIDDEN reports for Moerdijk (Wong & van Dril, 2020) and Geleen (Oliveira Machado dos Santos & van Dril, n.d.). Table 18 summarises the CO_2 emissions, electricity and steam imports for each site considering the assumptions already mentioned and the information collected from the MIDDEN reports.

Table 18: CO_2 emissions, electricity and steam imports for both the current situation and the proposed configuration

Topic	Current situation		Full electrification	
	Moerdijk	Geleen	Moerdijk	Geleen
CO_2 direct emissions (Mt/yr)	2.356	1.688	1.158	0.008
Electricity from the grid (PJ/yr)	1.3	1	19.73	36.02
Steam from boilers/CHPs (PJ/yr)	5.1	7	9.5	7.8
CO_2 energy related emissions (Mt/yr)	0.563	0.753	1.485	1.720

Figure 30 shows the total CO_2 emission for both sites, and compares the current and the proposed configurations. Around 1 Mt/yr of CO_2 emissions (scope 1 and 2) could be avoided if this configuration is implemented in 2030, considering the extra grid electricity and steam from boilers/CHPs. However, the steam demand is a rough estimate, because the steam network is site-dependent and the effects of replacing the current cracked gas compressor might not be fully covered in the estimation. Therefore, the calculated avoided emissions are probably optimistic. The elimination of fuel gas combustion is the only factor responsible for the direct emissions reduction because the reduction in steam consumption reduces indirect emissions.

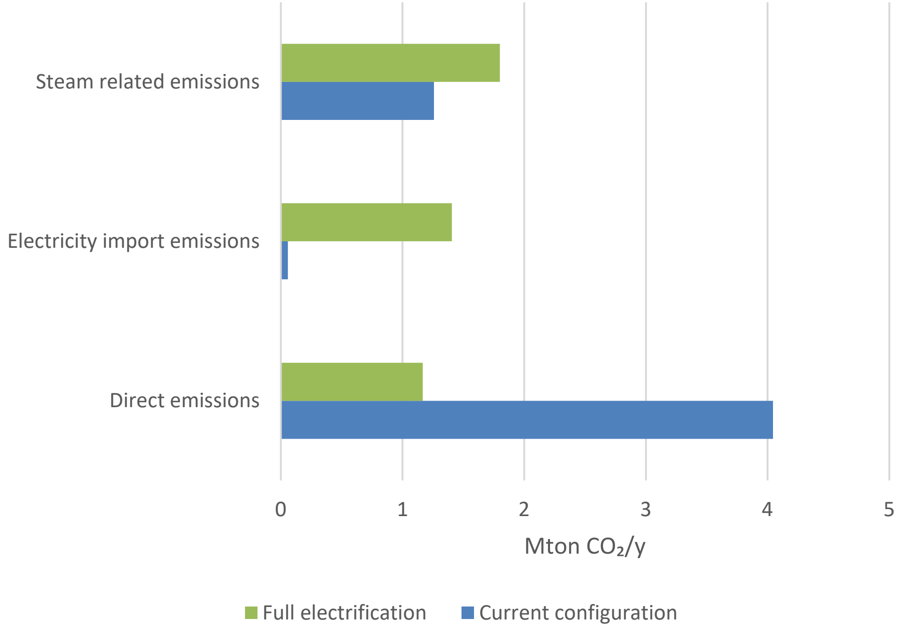


Figure 30: CO_2 emissions comparison between current situation and full electrification configuration (electricity grid emission factor: 0.091 kg CO_2/kWhe and steam emission factor: 0.104 kg CO_2/MJ)

Since the electricity demand is more than 25 times higher for this technology configuration than for the current system, the emission factor of the electricity grid is determinant for the avoided emissions. Figure 31 gives an impression of how the grid's emission factor influences the emissions analysis for the full electrification option. The emission factors between 2018-2030 were extracted from the Klimaat- en Energie-Verkenning 2019 (Planbureau voor de Leefomgeving (PBL), 2019) and the values for the following years were extrapolated until 2050.

Considering the extrapolation of the electricity grid emission factor, the avoided emissions could reach a maximum of 2.1 Mt CO_2/yr in 2050, which represents a 52% reduction when compared to the current situation. Nevertheless, a reduction in total emissions (direct + indirect) would be possible only after 2032 with an electricity grid emission factor of 0.078 kg CO_2/kWhe. Before this year, the emissions (scope 1 and 2) for both sites together would increase 0.1-3.8 Mt CO_2/yr.

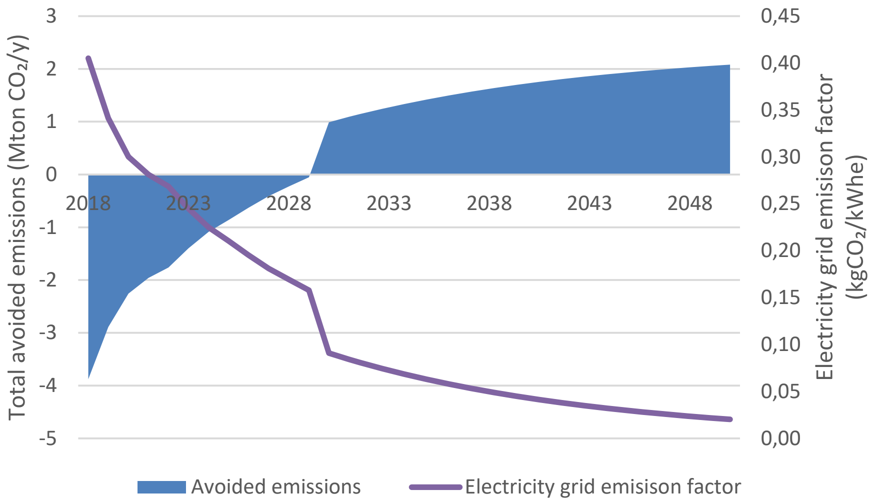


Figure 31: Avoided emissions for the full electrification configuration for different grid CO_2 intensity factors

Bionaphtha production

Table 19 shows scope 1 emissions of both steam cracking sites (excluding downstream processes). The impact of replacing fossil feedstock with a renewable feedstock can be reflected in scope 1 emissions only if the emissions related to the use of the renewable feedstock are considered biogenic, and are thus not accounted. As the effects on process conditions and steam cracking downstream processing are unclear, we have assumed that steam cracking will perform identically as when the feedstock is only fossil naphtha. Therefore, we have assumed that the reduction in emissions is linear to the blending composition. Figure 32 presents site-level emissions, considering different blending levels. The reduction in emissions is not very large and the effects on scope 1 emissions could be increased when combining feedstock substitution with other technology options, such as electrification.

Table 19: Site scope 1 emissions for steam crackers (Oliveira Machado dos Santos & van Dril, n.d.; Wong & van Dril, 2020)

Steam cracker site[a]	Total site's scope 1 emissions ($kt\ CO_2/yr$)
Moerdijk	1127
Geleen	1576

[a] Emissions only related to steam cracker unit.

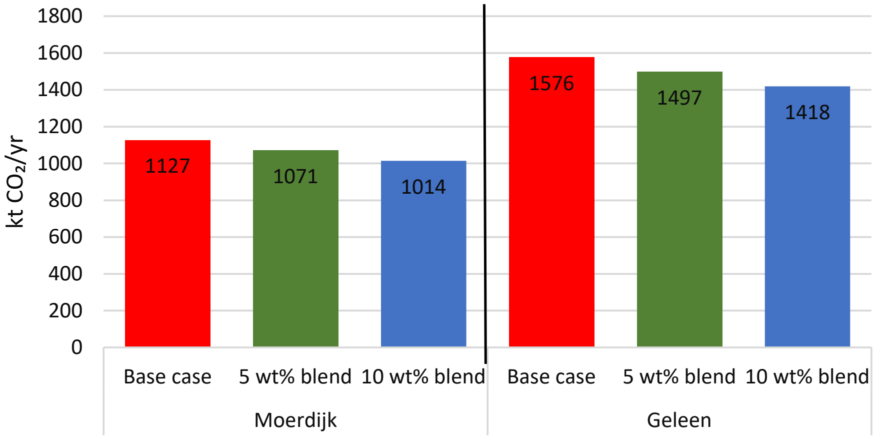


Figure 32: Scope 1 emissions of steam cracker sites when considering different blending levels of bionaphtha with naphtha for steam cracking

It is worth mentioning that the impacts of substituting the feedstock happen outside the steam crackers' plant gate. Thus, it is very important to identify and understand the trade-offs of using biobased feedstock in steam crackers versus the impacts of producing the bio-feedstock itself.

The following analysis focusses on emissions related to the technologies selected to produce bionaphtha. Direct emissions (scope 1) from biogenic sources are excluded. Consequently, the main impacts in emissions terms of producing the feedstock are related to the generation of electricity and steam, and in some of the cases, the use of additional inputs such as hydrogen. These should be compared to the Scope 2 emissions of fossil-based naphtha production in the refinery sector.

Figure 33 presents estimated scope 2 emissions (energy related emissions from steam production and electricity) for the bionaphtha production technologies, compared to emissions saved in steam cracking if bionaphtha replaces naphtha by 5wt%. Figure 33 shows that energy use in producing bionaphtha actually plays a very important role in the total GHG emissions intensity. For instance, steam use in both crude tall oil upgrading and vegetable oil upgrading has a significant impact on scope 2 emissions of the technologies producing bionaphtha (assuming that steam is produced from natural gas). Emissions are reduced in those two technologies by using of fuel oil (co-product) to replace a fraction of the heavy fuel oil. However, in the case that the fuel oil was not used as a replacement, scope 2 emissions (electricity and steam use only) would overshoot the savings in steam crackers' scope 1 emissions. This shows a clear trade-off that needs to be carefully assessed before deciding on which process to use for bionaphtha production. This underpins the need to assess emissions on a system level rather than on a technology level. In the case of upgrading of vegetable oils, further attention to the decarbonisation of energy use in biorefineries would be required, as this can also have a significant impact on the overall environmental performance of biobased systems. This also exposes the need to understand in more depth, relevant system aspects of biorefineries, rather than simply assuming bio-feedstock is carbon-neutral due to its biogenic origin.

In the case of pyrolysis oil production and upgrading, scope 2 emissions are fully related to electricity use. Nevertheless, production emissions for bionaphtha from pyrolysis oil upgrading do not overshoot emission savings in scope 1 emissions of steam crackers.

In the case of the Fischer Tropsch route, scope 2 emissions become negative as the energy efficiency of the technology is high and electricity is produced as co-product.

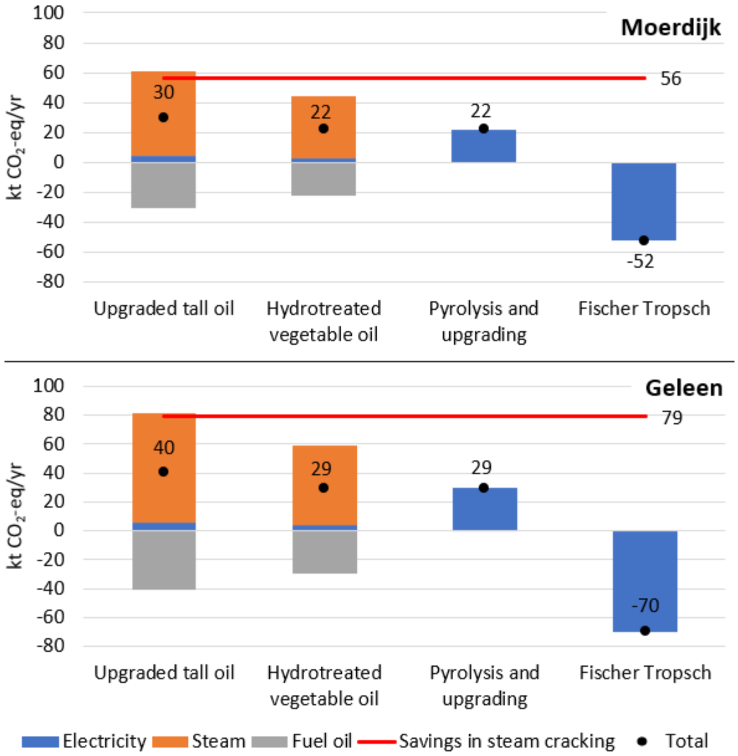


Figure 33: Estimated scope 2 GHG emissions of producing bionaphtha to be blended with naphtha at 5wt% for the Moerdijk and Geleen sites. Emission factors: electricity 0.3 kg CO_2 eq/kWh (Planbureau voor de Leefomgeving (PBL), 2019), steam 0.104 kg CO_2 eq/MJ, fuel oil 0.329 kg CO_2 eq/kg (Wernet et al., 2016). Emissions estimated as the system was expanded, assuming that electricity produced would replace electricity from the grid and that fuel oil can replace heavy fuel oil.

Regarding scope 3 emissions, a similar analysis was done here but only comparing emissions related to hydrogen use and feedstock production of the technologies for producing bionaphtha (part of scope 3 emissions). This does not constitute a full life cycle assessment; the intention of presenting these figures is to see the order of magnitude differences in (some) aspects of scope 3 emissions. Figure 34 shows emissions related to feedstock and hydrogen use (part of scope 3 emissions) for the technologies for producing bionaphtha, compared to emissions saved in steam cracking if bionaphtha replaces naphtha by 5wt%. There is a clear difference in emissions from raw material use when using tall oil and vegetable oil, in comparison to the routes using lignocellulosic biomass (wood residues) as feedstock for producing bionaphtha (Figure 34). The large impacts of feedstock can be explained by two aspects. First, the conversion of oils into bionaphtha produces a side stream product (fuel oil) which reduces the overall efficiency of the process in the conversion of oil into bionaphtha. The second and most important aspect is related to the emissions in the production of the feedstocks themselves. This figure clearly shows that the use of palm oil as feedstock for bionaphtha is not beneficial from a system perspective, given that its production emissions overshoot by a factor of 12 the direct emissions saved at the steam cracking sites. In the case of pyrolysis and upgrading, hydrogen-related emissions play an important role. In this figure, hydrogen is considered to be produced from fossil sources. In the case that hydrogen with lower GHG emissions is used (i.e, blue and/or green), emissions can be further reduced. As discussed above, these are important system-level impacts to be accounted for when making a decision about which process alternatives to focus on.

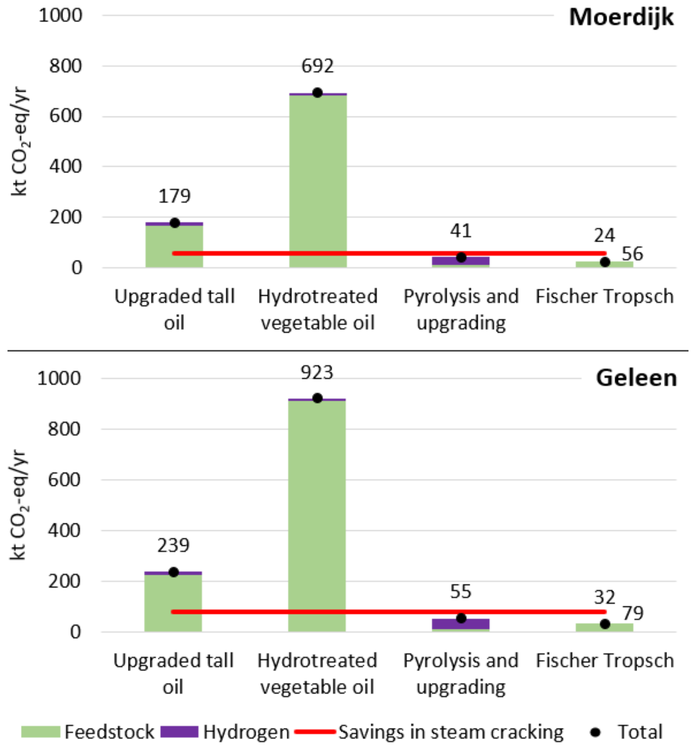


Figure 34: Scope 3 GHG emissions of producing bionaphtha to be blended with naphtha at 5wt% for the Moerdijk and Geleen sites. Emission factors: hydrogen 1.61 kg CO_2 eq/kg (from natural gas), crude tall oil 0.67 kg CO_2 eq/kg, crude palm oil 3.73 kg CO_2 eq/kg, woodchips 0.037 kg CO_2 eq/kg

Figure 35 presents the aggregated, estimated scope 2 and scope 3 emissions for bionaphtha production. The results show that in all cases except the FT route, emissions are higher than the potential savings in scope 1 emissions in steam crackers. This implies that the decarbonisation pathway of using bionaphtha might not be beneficial in terms of CO_2 emissions from a system point of view, and hence the sustainability of upstream activities needs to be considered as well. In the case of FT, total emissions remain negative, as the electricity produced during gasification can be used to replace electricity from the grid. The results show what type of analysis can be done using MIDDEN data, however, it is important to mention that with more knowledge about the technologies presented here, data can be finetuned and the results could change. For instance, a small shift in the energy-intensity of the FT route could shift it from having net negative to net positive emissions.

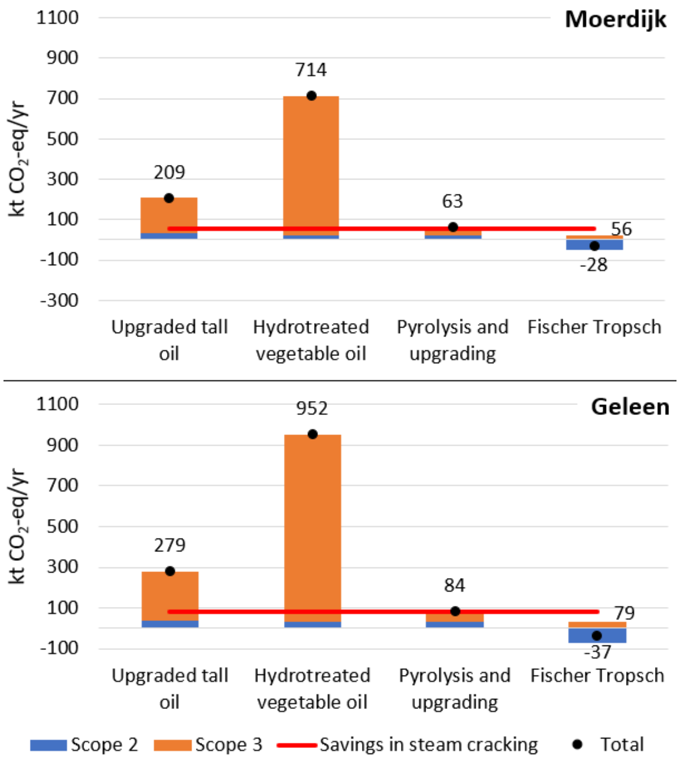


Figure 35: Scope 2 and scope 3 GHG emissions of producing bionaphtha to be blended with naphtha at 5wt% for the Moerdijk and Geleen sites. Comparison of emissions with savings in scope 1 emissions of steam crackers when using 5wt% blend with bionaphtha as feedstock

5.3.2.2 *Energy consumption*

Combined electrification of furnaces and cracked gas compressor

Table 20 summarizes the changes in energy use when furnaces and compressors are electrified. Figure 36 highlights the differences compared to the conventional process. The reference consumption for the current situation was extracted from the MIDDEN reports for both Moerdijk (Wong & van Dril, 2020) and Geleen (Oliveira Machado dos Santos & van Dril, n.d.).

Table 20: Fuel gas, electricity and steam imports for both current situation and proposed configuration

Topic	Current situation		Full electrification	
	Moerdijk	Geleen	Moerdijk	Geleen
Fuel gas consumption (PJ/yr)	25.6	31.0	6.4	0
Electricity import (PJ/yr)	1.3	1	19.73	36.02
Steam from boilers/CHPs (PJ/yr)	5.1	7	4.8	5.9

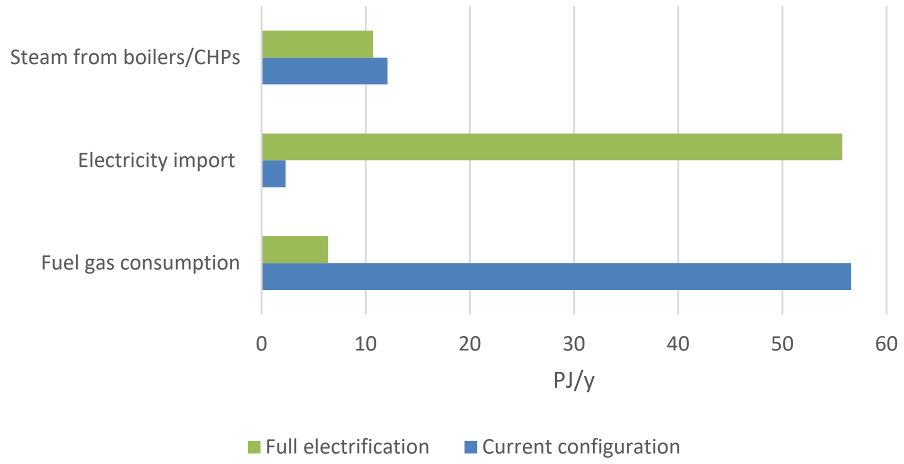


Figure 36: Energy consumption comparison between the current situation and the full electrification option

As shown in Figure 36, the excess fuel gas for the electrified process is around 50.2 PJ/yr and the extra demand for electricity from the grid is 53.4 PJ/yr. Since the fuel gas is a by-product from the cracking reactions, it is important to find a sustainable use for it. Blue hydrogen production could be an alternative; however, this option is very dependent on CO_2 capture, transport, and storage infrastructure. Considering the intake of gas for blue hydrogen production of 175 GJ/t H_2 (IEAGHG, 2017), the extra fuel gas from both crackers could theoretically be used to produce 0.3 Mt H_2/yr. The composition of the fuel gas can vary significantly among the sites, which may result in different efficiencies for the hydrogen production. Regarding the demand for electricity in the full electrification option, if only green electricity is used, around 968 wind turbines of 4 MW with 4000 full load hours per year would be required to meet the additional demand.

Bionaphtha production

As previously discussed in the GHG emissions section, energy use and GHG emissions are strongly correlated. Figure 37 presents the additional energy use, when considering the production of bionaphtha as addition to the conventional steam cracker facilities, for both Moerdijk and Geleen at the different blending rates. Steam use in both crude tall oil upgrading and vegetable oil upgrading has a significant impact on overall system energy consumption. The results also show that there is a strong correlation of energy use with the bionaphtha production capacity required to meet blending levels. In the case of pyrolysis oil production and upgrading, energy use is related to electricity supply. For the case of pyrolysis, energy consumption is lower than that of the cases for upgraded tall oil and vegetable oils upgrading by 39%-56%. In the case of the Fischer Tropsch route, energy consumption is negative, as electricity is produced as co-product.

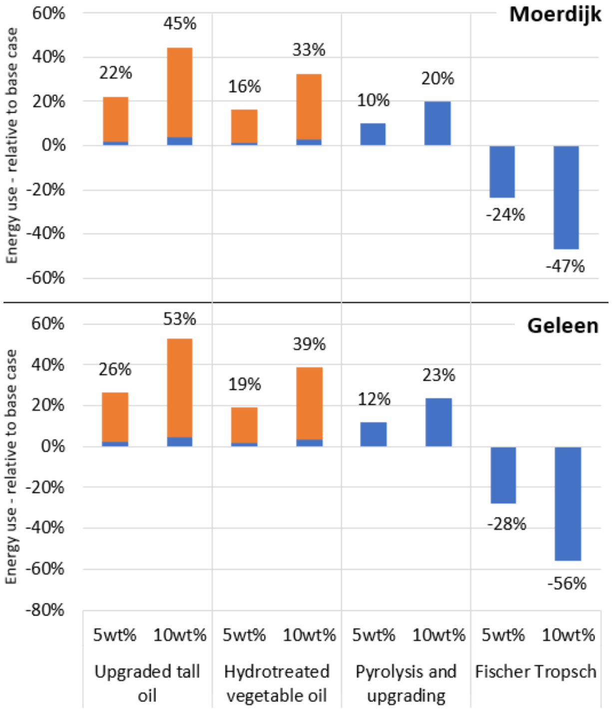


Figure 37: Energy use in bionaphtha production relative to energy use in steam cracking sites. a) Moerdijk, b) Geleen

5.3.2.3 *Cost analysis*

Bionaphtha production

Figure 38 presents bionaphtha production costs, and in all cases, these surpass the current price range of fossil naphtha (250-500 €/t). For both blending rates, the major contributor to cost is feedstock. In the case of upgrading in the pyrolysis system, hydrogen price also plays a major role on costs for both blending targets. One can expect that given the energy consumption levels described in the previous sections, cost of energy can be significant. However, the prices of energy in the Netherlands are currently low (Planbureau voor de Leefomgeving (PBL), 2019). Bionaphtha production costs are a factor 1.1-3.3 higher than the costs of fossil naphtha. Although there are small differences in costs when considering a capacity for 5wt% to those of 10wt%, the difference is not significant to derive a robust conclusion.

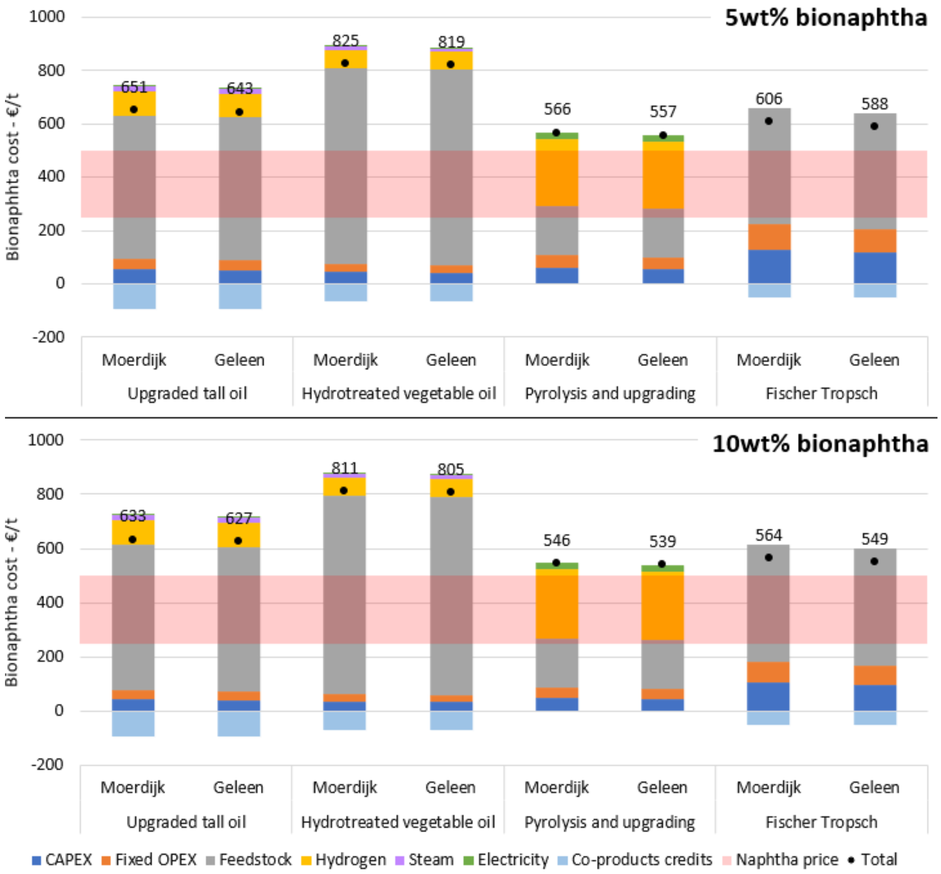


Figure 38: Bionaphtha production costs for 5wt% and 10wt% co-processing. The price of fossil naphtha is in the range of 250-500 €/t

To provide a better understanding of the aspects that affect costs the most, a sensitivity analysis was carried out on feedstock, hydrogen and electricity prices. Results of the sensitivity analysis are presented in Figure 39. When looking into the results of the sensitivity analysis, in the case of crude tall oil upgrading (see Figure 39a), the price of crude tall oil needs to be between €80-230/t in order to make bionaphtha comparable to fossil naphtha, whereas prices below that range would allow a benefit over fossil naphtha. In the case of palm oil, the price needs to be between €120-320/t. In the case of lignocellulosic biomass prices (see Figure 39b), for Fischer Tropsch, biomass price needs to be below €75/t, which is a reduction of 25% compared to the costs assumed in the analysis. In the case of pyrolysis the maximum biomass price that allows bionaphtha to be comparable to fossil naphtha is €60/t. In terms of hydrogen costs, a price below €1500/t (see Figure 39c) would be required for the pyrolysis route. However, this price seems challenging to achieve for hydrogen from low-carbon sources (International Energy Agency, 2019; Mulder et al., 2019). It is important to note that this analysis consists of varying one parameter at the time. Finding optimal prices that allow these systems to be competitive was out of the scope of this study.

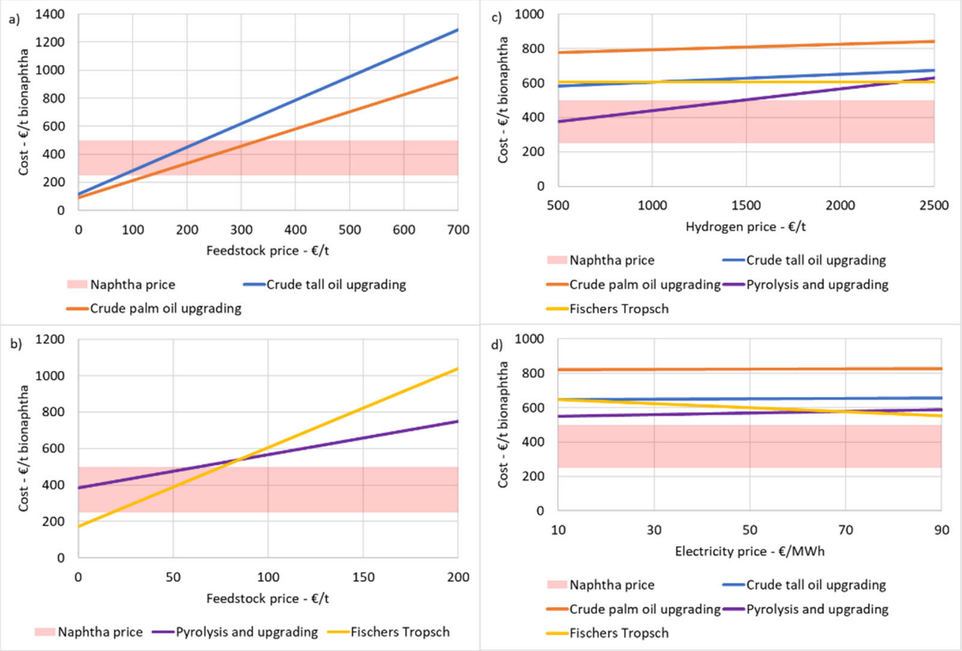


Figure 39: Bionaphtha production costs (5wt%) for the Moerdijk case as a function of: a) feedstock price (tall oil and palm oil), b) feedstock price (woodchips), c) hydrogen price, d) electricity price. The price of fossil naphtha is in the range of €250-500/t

6 Discussion and conclusions

6.1 Key findings

This report covers a broad range of technologies, processes, and configurations in two industrial sectors, but some common insights can nonetheless be drawn from the MIDDEN+ project research. Many of the technologies discussed above face common barriers and challenges, and have common advantages and disadvantages. Many of the important considerations for the industrial sector are common to many sectors.

Uncertainty in techno-economic data for technological alternatives in the industrial sector is an important issue. Measuring the scale of the challenge of decarbonisation hinges on good estimates of cost and energy implications of changing processes and technologies. This project aims to start assessing the uncertainty inherent in the estimates used in energy systems analysis and industrial sector decarbonisation pathways. It is clear from the MIDDEN dataset that some key technologies require additional research and careful consideration in the context of these analyses.

Furthermore, uncertainty about techno-economic parameters increases when we consider technology learning. Future cost and performance data requires even further underlying assumptions, and the addition of a qualitative assessment of this potential can aid researchers in understanding the implications and validity of their technology learning assumptions.

Process integration may create additional challenges in both sectors. For example, because the steam cracking process is normally integrated with other downstream units, modifications in the cracking furnaces and in the compression may considerably impact those other units, which can create barriers for the implementation of new technologies. Changes to the drying section of a paper or board mill may also affect the full production line, requiring adjustments and creating additional costs and risks.

The way that companies and sites deal with these challenges can be the deciding factor for the viability of implementing a new technology. For example, because pyrolysis reactions in the steam cracking sector are held under high temperatures (> 800^{o}C), heat recovery is a key factor for the overall site’s energy efficiency. Once electrification technologies are in place, a lot of excess steam will be available for use. In this study, only one option was suggested as alternative use for this steam (electricity generation via steam turbine), but a more comprehensive analysis should be done including site-specific aspects, which can determine the overall business case.

Beyond the uncertainties in the techno-economic data added to the MIDDEN dataset, we have also highlighted uncertainties beyond the plant fence that affect the prospects for different decarbonisation pathways and technologies. Energy prices, low-carbon energy availability, and electricity grid emissions intensity can be deciding factors in the future roles of these decarbonisation options, as highlighted for the inputs for bionaphtha production and for electrified processes in both steam cracking and paper & board production. Infrastructure may also prove to be a determining factor in some cases, either within a cluster or at a larger scale. Some of the highlighted technologies can mitigate such uncertainties or risks; for example, efficient alternative papermaking routes like air-laid forming can reduce the overall energy intensity of the process, reducing the burden for low-carbon utilities. For others, these uncertainties are amplified: in the case of steam cracking, electrification requires rethinking the design of the on-site steam network and fuel use as well as connections to other sites and supply infrastructure. A broad techno-economic dataset cannot determine the optimal solution for a given site or process, but it can improve the results when used in combination with other tools. This can highlight the most important points, and underline where additional research and sensitivity is needed. Over time, these uncertainties can shift to different areas or technologies.

Based on the dataset and our analysis in this report, we can give indicative values to the scale of systemic uncertainties and interactions. Issues raised in this report, like the availability of excess fuel gas and residual heat from steam crackers, the need for additional green electricity or green hydrogen in a number of applications, or impacts from the use of biomass, biofuels, or plastic waste, can only be addressed with a more systemic view that takes into account geographical and infrastructural constraints, connections between sites and sectors, and potential future developments in Dutch industry. The industrial products that are demanded today may not be the same as products that are required in 2050. Technology development and economic trends in these sectors will also be influenced by these long-term trends. No one can predict exactly how the industrial sector will develop, but insights into these questions are best addressed by combining analyses from different perspectives and levels. The MIDDEN+ dataset provides one such perspective, to complement and improve other analyses of the industrial sector.

6.2 Recommendations for future research and data collection

The continuous update and maintenance of techno-economic datasets on industrial decarbonisation is important; model outputs and scenarios reflect the quality of their inputs. Future data collection should focus on improving the pedigree matrix scores shown above, and on reflecting the state of the art knowledge in the sector, to the extent that is possible using publicly available data. Technology cost and efficiency are key parameters that can develop quickly over time, and which can see considerable spread across different projects and sites. Additional validation of datasets with industrial sector stakeholders would also be valuable, and provide insights for potential improvements and changes to the database in the future.

Developing datasets at this level, or at a more detailed level, requires time and creativity. Publicly available literature can only take the research so far, and going beyond existing literature requires finding creative ways of using new sources of information, good collaboration with the relevant industrial stakeholders, and investment in the time it takes to build an understanding of the sector. However, despite the limitations, interesting results and insights into the potential pathways towards lower-emissions industry can be obtained from this sort of analysis, even with imperfect information. Finding the main sources of error and uncertainty can even be interesting results in themselves.

Additional technologies could also be included as they develop and become relevant, both for these two sectors and the others included in the broader MIDDEN project. New areas could be explored, such as including additional circular economy options and material qualities, in order to better put industrial technologies and industrial products in context and make it possible to more easily see links between sectors and processes. Using the data collected in system-level research on decarbonisation pathways would also be an important step. Such analysis, perhaps via LCAs or scenarios developed with energy systems models, would provide insight into the key parameters and determinants of the chosen pathways, and the most important contributors to cost, emissions, and energy use. These analyses could more comprehensively account for path-dependencies, full system costs of technology options, competition for resources and economic feedback effects, among other relevant issues.

The choice of modelling tool or methodology is highly dependent on the research question, the level of analysis, and perspective. Developing modelling tools that are suited to the most pressing research questions, both from policymakers and industry, as well as to the available data, is an important next step. For example, including a detailed technology representation of these sectors in an optimization model, along with the best available public data, could allow us to provide insights on such topics as effects on prices and availability of energy carriers and fuels, and the impacts of technological shifts on the broader regional, national, and international energy markets.

Furthermore, through the use of the dataset and continuous feedback, the techno-economic information can be iteratively and collaboratively improved. Dialogue based on the conclusions from such systemic analysis about the strategic, policy and regulatory decisions affecting industrial decarbonisation, and eventually, better informed choices for industrial transformation are the ultimate goal of the project.

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A Methodological annex

A.1 Prices and general assumptions

All costs presented in this report are given in euros (€) 2019, unless otherwise stated. These have been calculated on the basis of official statistics.(European Central Bank, 2020; Federal Reserve Bank of Minneapolis, 2019)

In this report, production costs were estimated by adding up annualized CAPEX and OPEX. Annualized CAPEX was estimated using Equation 4, where plant life time (*t*) and interest rate (*i*) are input parameters. A plant lifetime of 20 years and interest rate of 3% was assumed for all cases.

$$Annualized\ CAPEX\ \left(\frac{€}{year}\right) = CAPEX\ (€) \cdot \frac{i}{1-\frac{1}{(1+i)^t}} \qquad \text{Equation 4}$$

The operational expenditure (OPEX) of each technology option is composed by the costs of main feedstock, additional materials (e.g. hydrogen), energy inputs, fixed and co-products credits. Data for CAPEX and fixed OPEX was gathered from the additions to MIDDEN databases as presented in previous sections.

Table 21: Prices used for assessing bionaphtha production costs

Feature	Price	Unit	Reference
Tall oil	320	€/t	Price based on (Aryan & Kraft, 2020)
Oil	600	€/t	Price based on (Aryan & Kraft, 2020)
Biomass	100	€/t	(Moncada et al., 2018)
Hydrogen	2000	€/t	Average fossil H_2 price
Electricity	0.045	€/kWh	(Planbureau voor de Leefomgeving (PBL), 2019)
Steam	11	€/t	(Planbureau voor de Leefomgeving (PBL), 2019)
Natural gas	5.7	€/GJ	(Planbureau voor de Leefomgeving (PBL), 2019)
Fuel oil	150	€/t	Assumed as black liquor price

Note: All prices are assumed to be applicable for 2019.

B Summary of technology learning potential

Potential sources of cost reductions are discussed below. These qualitative discussions of technology learning can help dataset users understand the uncertainties surrounding future technology cost, and the contexts and factors influencing this parameter. See Appendix A for methodology.

B.1 Air-laid forming

Learning by researching (R&D) (low potential)

- Air-laid forming is already commercially applied for soft paper products; its main limitation is in the technology's ability to produce higher strength paper with uniform thickness. (VNP 2018).
- While breakthroughs and improvements through research are always possible, this technology is at TRL 5-6, beyond the traditional phase of research and development.

Learning by doing (medium potential)

- As mentioned above, air-laid forming is already commercially applied for soft paper products, but it has not yet been commercially applied in for graphic paper or other paper types. Improvement in its performance in terms of paper strength and thickness could lead to application for other paper grades with basis weight at the low end of the range.
- Furthermore, broader application of the technology could lead to cost reductions based on experience. It cannot be retrofitted to existing plants, so this potential may be limited by the investment cycles and growth of the sector.

Economies of scale (low potential)

- As air-laid forming is an intrinsic part of the papermaking process, it cannot be applied as a retrofit to an existing plant. The application of air-laid forming requires new construction (or rebuilding of a paper machine) designed for air laying, rather than the conventional water-based process. Because of the engineering process and customization of paper machines, they are unlikely to benefit from economies of scale.

Spillover effects (low potential)

- Air-laid forming is specific to the paper and board sector, and thus has very little potential for cost reductions based on technology development for other processes and sectors.

B.2 Microwave drying

Learning by researching (R&D) (low potential)

- Paper drying applications investigated since the 1960s (Bechtel/Varian)
- Goerz Jr., D.J. and Jolly, J.A. (1967), “The Economic Advantages of Microwave Energy in the Paper Industry”

Learning by doing (high potential)

- Despite long history of research, very little experience in the paper sector and optimization is needed with respect to microwave frequencies, power levels, and combination with other drying techniques.

Economies of scale (high potential)
- Commercially applied in food and beverage industry, but so far not broadly scaled up
- Regulatory guidelines differ, and commercial applications are limited primarily to Europe and the US
- Limited to niche processes, for example: thawing of frozen ingredients and sterilization of packaged prepared foods and ready-to-eat meals

Spillover effects (high potential)
- Detz and van der Zwaan (Detz & van der Zwaan, 2020) found a 20% (±2%) learning rate for household microwave ovens using historical time series data
- Ubiquitous application in household microwave ovens (1.1 TW capacity installed by 2020)
- Commercial application in food & beverage applications could also provide insights for industrial applications
- Other high-frequency drying processes also have potential – synergies between these technology groups

B.3 Enclosed dryer hood

Learning by researching (R&D) (low potential)
- Not a complicated technology, and will therefore not experience a lot of advantages from researching. More so when applied in combination with heat pumps or mechanical vapour recompression

Learning by doing (low potential)
- It is expected that once installed this technology will not be improved a lot by doing, as it is a relative simple technology

Economies of scale (medium potential)
- When more hoods are produced, this technology can experience medium cost benefits due to economies of scaling

Spillover effects (medium potential)
- The enclosed dryer hoods can also be used in other sectors involving drying. Therefore it is expected that learning from spillover effects has a medium potential

B.4 Furnace electrification

Learning by researching (R&D) (high potential)
- Technology in early development phase with low TRL (1-2)

Learning by doing (high potential)
- No demonstration that steam cracking via electrical furnaces is technically feasible and more will be understood once this technology is available on the market

Economies of scale (medium potential)
- For larger thermal cracking capacities, this technology can experience medium cost reduction, however, the energy and infrastructure costs are still the most relevant factors to allow this technology to be economically feasible

Spillover effects (medium potential)
- Electrical furnaces are already used in other industrial processes such as in the steel sector, therefore, some insights could come from the current applications
- The steam cracking process differs significantly from the sectors that use electrical heating, for this reason the potential is not high.

B.5 Compressor electrification

Learning by researching (R&D) (low potential)
- Technology already commercially available

Learning by doing (medium potential)
- Despite the fact that electrical compressors are widely available in the market, its application in steam crackers for the compression of the cracked gas is not broadly done. For this reason, there is still room for improvement when looking to this specific application

Economies of scale (low potential)
- The investment costs for electrical compressors do not vary significantly among the capacities available in the market

Spillover effects (low potential)
- Electrical compressors are also used for air and industrial gases compression processes and this application is already fully developed, therefore, there it is expected little future improvement for this technology. For this reason, the spillover effects are limited.

B.6 Plastic waste oil co-processing

Learning by researching (R&D) (medium potential)
- Technology still under development phase, there is potential for improvement specially when looking into larger scales production of the plastic waste oil
- For larger co-processing amounts, it is unknown the effects in the steam cracking process and whether upgrading processes are needed, therefore, there is still room for research regarding this aspect.

Learning by doing (high potential)
- Few demo plants were constructed so far worldwide with this technology, thus, a big potential for learning by doing is expected; especially in the co-processing part.

Economies of scale (high potential)
- The costs can change significantly with the production capacity, specially due to the equipment costs.

Spillover effects (medium potential)
- General pyrolysis processes have some similarities with the plastic waste oil production , however, there are some specific challenges that this technology faces which are quite relevant to make it both technical and economical feasible (e.g. plastic waste supply, co-processing level in the crackers).

B.7 Upgraded tall oil as feedstock

Learning by researching (R&D) (medium potential)
- Technology is commercial, however, there is potential for improvement specially when looking into larger scales production of tall oil upgrading and research into improved possibilities for upgrading
- For larger co-processing amounts, it is unknown the effects in the steam cracking process and whether further pretreatment is required

Learning by doing (high potential)
- Few plants are running worldwide, thus, if more installations are coming from this technology potential for learning by doing is expected.

Economies of scale (high potential)
- The costs can change significantly with the production capacity, specially due to the equipment costs and integration with already existing technologies, such as wood biorefineries and paper mills.

Spillover effects (low potential)
- Although this technology can be impacted by aspects such as capacities of steam crackers, there is very low potential from applying the technology in other fields with completely different purposes for producing fuels and chemicals. The technology is very specific and spillover effects are not expected.

B.8 Hydrotreated vegetable oil as feedstock

Learning by researching (R&D) (medium potential)
- The analysis is analogous to tall oil upgrading. Technology is commercial, however, there is potential for improvement specially when looking into larger scales production of upgraded vegetable oil and research into improved possibilities for upgrading
- For larger co-processing amounts, it is unknown the effects in the steam cracking process and whether further pretreatment is required

Learning by doing (high potential)
- Few plants are running worldwide, thus, if more installations are coming from this technology potential for learning by doing is expected.

Economies of scale (high potential)
- The costs can change significantly with the production capacity, specially due to the equipment costs and integration with already existing technologies, such as oil extraction, biodiesel plants, bio jet fuel plants.

Spillover effects (low potential)
- Although this technology can be impacted by aspects such as capacities of steam crackers, there is very low potential from applying the technology in other fields with completely different purposes for producing fuels and chemicals. The technology is very specific and spillover effects are not expected.

B.9 Upgraded pyrolytic oil as feedstock

Learning by researching (R&D) (medium potential)
- Technology is still at development stage. There is potential for improvement specially when looking into larger scales production and research into upgrading pathways and strategies (e.g., one step hydrotreatment, two step hydrotreatment)
- For larger co-processing amounts, it is unknown the effects in the steam cracking process and whether further pretreatment is required

Learning by doing (high potential)
- Plants still at demo phase, thus if more installations are coming from this technology potential for learning by doing is expected.

Economies of scale (high potential)
- The costs can change significantly with the production capacity, specially due to the equipment costs and integration with already existing technologies.

Spillover effects (low potential)
- Although this technology can be impacted by aspects such as capacities of steam crackers, there is very low potential from applying the technology in other fields with completely different purposes for producing fuels and chemicals. The technology is very specific and spillover effects are not expected.

B.10 Fischer Tropsch oil as feedstock

Learning by researching (R&D) (medium potential)
- Technology is still at development stage for olefins production from biomass. There is potential for improvement specially when looking into larger scales production and oil quality for olefins.
- For larger co-processing amounts, the effects in the steam cracking process and whether further pretreatment is required are unknown.

Learning by doing (high potential)
- Plants still at demo phase, thus if more installations are coming from this technology potential for learning by doing is expected.

Economies of scale (high potential)
- The costs can change significantly with the production capacity, specially due to the equipment costs and integration with already existing technologies.

Spillover effects (low potential)
- Although this technology can be impacted by aspects such as capacities of steam crackers, there is very low potential from applying the technology in other fields with completely different purposes for producing fuels and chemicals. The technology is very specific and spillover effects are not expected.

C Stakeholder workshop notes/comments

To get feedback on the work in MIDDEN+ and to engage with the MIDDEN network, two webinars were organised. Preliminary results and methodology were discussed with 18 experts and key stakeholders from research, industry, and government organizations during these webinars, held on 6 October 2020 and 20 October 2020. Topics discussed ranged from technical aspects of the decarbonisation technologies to impacts beyond the plant fence, such as policy, regulatory, financial, infrastructure and social considerations. Moreover, additional bilateral meetings were held for supplementary feedback. Some key conclusions and discussion points from those workshops were:

<u>MIDDEN database</u>
The database is valuable to the expert panel for a wide variety of purposes, including: validation of other data, using it as a screening tool to find industrial sub-sector decarbonisation options, and advising the government on feasible decarbonisation options. Adding pedigree matrices on the quality of the data, and qualitative assessments of learning potential can improve the understanding of the state, quality and uncertainty of data and help with estimations on future performance and cost. The MIDDEN database focusses on scope 1 emissions. However, for a full analysis of the impact of a decarbonising technology, the whole value chain, including scope 2 and 3 emissions, needs to be taken into account.

<u>Barriers for implementation of decarbonisation technologies in industry</u>
A number of barriers to implementation were identified and discussed, including:

- Efficient use of excess heat, as heat cannot be transported far away or stored efficiently
- A sufficient and stable electricity supply and impacts on the grid
- Need for more coordination and collaboration between industrial sites, as flows are shared
- Valuable and sustainable usage of the excess fuel gas (in the case of an electrified furnace)
- Regulatory barriers to alternative feedstock use and difficulty of targeting scope 3 emissions.

<u>Decarbonisation pathways</u>
Decarbonisation is expected to (and probably must) happen via combinations of sustainable technologies, focussing on (but not limited to) low-carbon feedstocks and low-carbon energy use simultaneously. Decarbonisation will happen in steps, first partly and later up to the maximum technical potential. The specific combinations used will depend on the sector and site-specific context, but also on which technologies will be supported by policy/regulations.

For more information about this work, or to provide feedback or comments, please contact Kira West (kira.west@tno.nl).