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ENERGY EFFICIENCY OPTIONS IN THE DUTCH MANUFACTURING INDUSTRY

Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN)

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MIDDEN

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Energy efficiency options in the Dutch manufacturing industry

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MIDDEN project coordination and responsibility

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TNO Energy & Material Transition has a twofold mission: to accelerate the energy transition and to strengthen the competitive position of the Netherlands. TNO conducts independent and internationally leading research and we stand for an agenda-setting, initiating and supporting role for government, industry and NGOs.

This report has been reviewed by Dick van Dam (PBL) and Martin Scheepers (TNO). PBL and TNO are responsible for the content of the report. The decarbonisation options and parameters are explicitly not verified by companies.

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Summary

This report gives an overview of the energy efficiency measures and potentials across the Dutch manufacturing industry. The measures and potentials are based on the MIDDEN database and reports, literature review and interviews with companies. The report also compares the findings with the findings from the Project 6-25 technology validation study (P6-25), which is a recent study that looked into innovative energy efficiency measures for the Dutch manufacturing industry and their potential to reduce CO_2 emissions in a cost-effective way by 2025. The P6-25 project ambition is to reduce industrial CO_2 emissions by 6 million tonnes by 2025.

Energy efficiency policy for the manufacturing industry in the Netherlands has centered around voluntary agreements or covenants (‘meerjarenafspraken’) that were in place from 1990 up to 2021. The agreements resulted in large-scale voluntary collaboration of businesses, institutions, and governments. The most recent covenants resulted in average energy savings of 1.1% and 1.8% per year over periods from 2005 and 2009 up to 2020. Since 2019, energy efficiency policy has shifted from voluntary agreements to obligations.

Many energy efficiency measures have been identified in the MIDDEN reports, both generic and sector specific measures. At the larger energy-intensive industries such as chemicals manufacturing, refining, and iron and steel production, process optimization and energy efficiency improvements, like upgrading rotating equipment and the use of residual heat, are common practice. Further incremental improvements in energy efficiency are expected, yet estimates for remaining technical potentials are limited. Larger gains in energy efficiency require larger changes to the plants, such as the replacement of older furnaces with more energy efficient new furnaces. At integrated production sites, large adaptations for the reduction of CO_2 emissions (e.g. electric cracking) can create opportunities to reevaluate the plant energy balance and improve overall energy efficiency. On the other hand, the application of new technologies for decarbonization such as CCS, electrolysis and material recycling may require additional energy and lead to a net increase in energy use. As these technologies are introduced there will be new opportunities for improving energy efficiency of the technologies, creating new potentials for energy efficiency.

Most frequently mentioned energy efficiency measure in MIDDEN is waste heat use, either directly or by using industrial heat pumps or mechanical vapour recompression (MVR) to increase the temperature to a more useful level. For many sectors in MIDDEN the technical energy savings potentials of heat pumps and mechanical vapour recompression have not been estimated.

During the course of this study, it has proved challenging to quantify energy efficiency potentials. While companies shared insights with us in the interviews, these insights were more often of a qualitative than a quantitative nature (e.g. that an estimate is overestimated, but not by how much). The complexity of industries in terms of scale and variety makes it difficult to establish from general data how much energy can be saved. An accurate estimation requires data on the energy and mass balances of plants, sources of waste heat and suitable sinks, quality of insulation on equipment, etc. all of which requires significant site-specific study to quantify. The MIDDEN data provides a start, but is not sufficient by itself to conduct such detailed analyses. Often even the companies do not have a complete overview of savings potentials as they apply a more project-based approach for energy efficiency measures.

Only a handful of interviews could be conducted for this study and they were focused on the largest industries which may or may not paint an accurate picture for the rest of the smaller industries.

Every sector, industrial site, and plant is unique in operation, construction and business plans. For many sectors the measures identified by MIDDEN have not been checked with industry and have been merely summarized in this report. Additionally, estimating technical potential savings is not prioritized by the companies mostly due to the reason that they are focused on the practical and achievable savings.

The P6-25 validation study contains a number of measures that have also frequently been identified in the MIDDEN project, such as improved electromotors, heat recuperation, mechanical vapour recompression and heat pumps. Insulation was not mentioned often in the MIDDEN reports, but according to P6-25 it provides a significant energy savings potential. The application of membranes was limited to a specific use-case in the P6-25 study, yet we see the application of membranes also for other sectors in MIDDEN, particularly in the food and beverages sector. The P6-25 study identified a significant potential for electric boilers. Electric boilers were excluded from the scope of our study since it is often not seen as an energy efficiency measure per se. We therefore do not have a savings potential to compare to the estimate based on the P6-25 study. Electric boilers are mentioned frequently in MIDDEN reports, indicating that there is indeed significant potential for their application.

The major difference with MIDDEN is that the P6-25 study focuses on innovative technologies and therefore excludes most of the equipment upgrade potentials (except for electromotors). Yet based on the MIDDEN data and interviews with large industrial parties, we observe that there is a large potential for energy savings through improvements to existing assets (such as furnaces and rolling mills). This is also in line with earlier findings from the covenants.

The P6-25 study also has limitations due to scoping and the necessary generalisations that have to be made across industrial sectors. While the P6-25 study corrected for many of the generalisations and performed checks with industry, the general sentiment from industry that we have spoken to for this project is that the potentials for the innovative technologies have been overestimated. The qualitative nature of the answers received during the interviews was often not sufficient to establish by how much it was believed the potentials were overestimated by the P6-25 study.

An overview of the findings from MIDDEN and a comparison to the analysis based on the P6-25 study is given in Table 1. For the paper and board sector the estimates are most comparable as they are both largely based on the potential from mechanical vapour recompression and heat pumps. The MIDDEN estimates for the fertilizer, iron and steel and organic chemistry are all based on continued yearly incremental improvements to energy efficiency and cover a wide variety of possible measures, including the replacement of existing assets with more efficient ones. These incremental improvements are not included in the P6-25 scope. The P6-25 estimates include some measures that according to the sectors have already been implemented. For the refinery industry we could not make an estimate based on the MIDDEN data and interviews.

Table 1
Total technical energy savings potentials (PJ/y) for 2030, assuming similar production levels as in 2020. Estimates based on MIDDEN and P6-25 (excluding e-boilers to align with the scope of this report).

Sector	Final energy consumption in 2020 (CBS)	Technical Potential Estimate MIDDEN	Technical Potential Estimate P6-25	Comments
Organic chemicals/ Steam crackers	176.7	16.9	13.0	MIDDEN estimate based on 1% annual improvement 2020-2030. P6-25 estimate includes measures that have already (partially) been implemented according to the sector.
Paper and Board	20.6	8.2	10.4	Both estimates mostly based on the potential for heat pumps and MVR.
Food and Beverages	80.8	At least 6.7 PJ	20.3	MIDDEN estimate only for vegetable oil and fats (3.7 PJ) and dairy industries (3 PJ). P6-25 covers all food industry, but excludes beverages.
Other industries	118.9	At least 5.3 PJ	n/a	MIDDEN estimate only for building materials. No estimate based on P6-25 excluding e-boilers. Including e-boilers the estimated savings potential is 16.6 PJ/y.
Iron and Steel	29.6[1]	5	5.3	MIDDEN estimate based on 1% annual improvement 2020-2030 (including on the use of production arising gases in the steel production process). The reduction of final energy consumption will be smaller. P6-25 estimate includes measures such as insulation for which TSIJ sees less potential, but excludes measures such as upgrades to furnaces.
Fertilizer	30.9	0.3-0.6	2.9	MIDDEN estimate based on 0.1-0.2% annual incremental improvements 2020-2030 covering many energy efficiency measures. P6-25 estimate includes measures that have already (partially) been implemented according to the sector.
Wider chemical industry	69.1	n/a	17.5	No estimate for MIDDEN. Largest potential from P6-25 estimate from heat pumps, MVR and heat transformers.
Refineries	128.3[2]	n/a	16.1	Largest potentials from P6-25 estimate from heat integration and insulation. The estimate for heat recovery in MIDDEN is much higher (57-83 PJ) but it is expected that much of this has already been implemented.
Industrial gases	17.1	n/a	1.7	P6-25 estimate for motors, flue gas recuperation and ICT process optimization. These measures were also identified by MIDDEN, but no potential estimated.

This report has focused on the technical energy efficiency potentials because economical potentials are dependent on factors such as energy prices and the costs of measures, both of which are more

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[1] Excludes use of production arising gases during the steel production process. Total energy use including these gases is estimated by MIDDEN at 52.2 PJ per year for the production of 7.05 million tonnes of crude steel per year (Keys, van Hout, & Daniëls, 2019).

[2] Refers to own energy use.

uncertain and change over time. There are also various barriers that limit the measures that can be implemented in practice. These limitations were frequently mentioned during the interviews conducted for this project. Main barriers identified in the interviews are: financial constraints, shortages in the labor force, knowledge and skills, energy efficiency not being a priority for the managers, validation of technology, and timing issues regarding turnaround. While energy efficiency has recently received additional attention due to an increase in energy prices, interviews with companies indicate that this does not automatically make energy efficiency projects accelerate. Practical issues such as investment cycles, implementation time, labor shortage and turnaround planning remain significant limiting factors than can outweigh the savings from the application of the energy efficiency measures.

Introduction

This report describes the options and preconditions for energy savings in the manufacturing industry in the Netherlands. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Scope

The scope of the project is the whole manufacturing industry of the Netherlands that have already been a part of the MIDDEN project database, as listed on https://www.pbl.nl/en/middenweb/publications. The energy efficiency measures that are discussed are only related to process efficiencies, that is within the site limits. To limit the extensiveness of the report, efficiency measures in the value chain are excluded from the study. These measures relate to the efficiency of the whole production chain from raw material to end use, including the energy supply (Abeelen, 2019). The export of excess residual heat to external parties (industrial, residential or other) is not included as an energy efficiency measure in this report. Renewable energy use is not seen as an improvement in energy efficiency. This report purely focuses on the technological aspect of energy efficiency improvements in industrial processes, and does not account for policies, implementation trajectories, barriers, or economic issues. These issues are reflected on in the discussion (Chapter 5).

The MIDDEN database contains many decarbonization options, such as CO_2 capture and storage, green hydrogen, and electrification, that will have a large impact on the design of industrial processes. These decarbonization options can increase or decrease final energy use in industrial sectors. It is beyond the scope of this report to quantify all the energy efficiency effects of all the decarbonization measures. But in some places in the report we will address the importance of the measures and qualitatively discuss their impacts.

Reading guide

Chapter 1 includes the definition of energy efficiency and some examples of energy efficiency measures. Chapter 2 describes the history and current situation of energy efficiency policy in the manufacturing industry in the Netherlands. In Chapter 3 an inventory of energy efficiency potentials in the MIDDEN database/sector reports is augmented with information from literature and interviews. In Chapter 4 the results from Chapter 3 are compared to the P6-25 validation study. The report concludes with a discussion in Chapter 5.

1 Definitions and measures

1.1 Definition of Energy Efficiency

Energy efficiency can be defined in multiple ways, and the most appropriate definition depends on the context and the problem where the terminology is used. Most generally, energy efficiency is defined as the ratio of useful outputs to physical energy inputs (Saunders et al., 2021).
The Saunders definition of energy efficiency is used in this report.

1.2 Types of Measures

Industry is extremely diverse in its ways of operation, scale and processes. The idea of ''one size fits all'' does not apply for energy efficiency in industry. A measure that creates a certain energy savings in one industry cannot be said to save just as much in another. Even in the same type of industry, different plants and different sites would have different effects for the same measure. Industry sites will have a number of specific measures that are applicable to them, but there are general cross-cutting technology categories that several industries can implement. Some examples of energy efficiency measures are outlined below. It is not an exhaustive list of energy efficiency measures and only serves here as an introduction to some of the more common measures that will also be mentioned in the following chapters of the report.

Waste Heat Use: 15-50% of energy input in industry is lost in the form of waste heat through exhaust gases, cooling water, and other mediums (Xu, Mao, Liu, & Wang, 2018). Waste heat recovery and use means capturing the lost heat and reusing it in industrial processes for heating or generating mechanical or electrical work. Notable examples of reusing the waste heat are preheating combustion air and/or furnace loads, and space heating. This is a popular measure for industries where a lot of burning and drying processes take place like in boilers, furnaces, ovens, kilns, dryers, incinerators. The potential to save energy for this technology is directly dependent on the temperature range of operation. Heat from flue gases is recovered and used as heat in a process (e.g. in preheating). This replaces heat that is needed for the process and thus counts as savings on required heat. The savings potential is dependent on the temperature and amount of the waste heat.

Heat Pumps: A heat pump is a technological device that can increase the temperature of heat to a temperature where the heat can be used. A heat pump is a technology that extracts heat from a source like ambient air, geothermal heat, waste heat from factories, etc. to amplify and transfer the heat somewhere else (IEA, 2022). For industrial applications, heat pumps are usually used as a heat-recovery equipment increasing the temperature of waste heat to a more useful and higher temperature (U.S. Department of Energy, 2003). The delivered waste heat evaporates the heat-pump working fluid, which is then compressed to a higher pressure increasing the condensation temperature. Next, the working fluid condenses while delivering high-temperature heat to a process stream thus replacing purchased energy. In principle, using the heat outweighs the cost of driving the heat pump, both economically and energetically. They operate on the thermodynamic principle of the Carnot Cycle. Low temperature electrically-driven heat pumps (<90°C) have a TRL of about 9 while heat pumps up to 150°C have a TRL of 6-8 and heat pumps over 150°C have a TRL of about 3 (Maruf, Morales-España, Sijm, Helistö, & Kiviluoma, 2022). For the purpose of this study, we consider high temperature heat pumps that use waste heat as source. The efficiency of a heat pump (and its savings) is measured by a parameter called the coefficient of Performance (COP). COP is defined as the ratio between the heat delivered by the heat pump and the compression energy supplied to it. A key parameter influencing COP is the temperature lift of the heat pump, that is the difference between the temperature of receiving heat and the temperature of delivered heat (U.S. Department of Energy, 2003).

Mechanical vapour recompression (MVR): Mechanical vapour recompression is an open heat pump system. The working fluid is the process stream itself. In this technology the pressure and temperature of the vapour under consideration is increased by compressing it mechanically. This ultimately leads to an increased saturation temperature of the vapour. This is applicable to low-pressure steam exhausts from industrial processes. Low-pressure waste steam can be mechanically compressed in order to increase the temperature of the latent heat in the steam which makes it usable for other processes. The compression energy required is small compared to the amount of latent heat present in the steam after compression which makes this technology an energy-efficiency measure. Coefficient of performance is also used as a measure of efficiency for such open-cycle mechanical vapour compression heat pumps.

Insulation: Thermal insulation is the measure by which heat transfer is controlled for a given spatial environment. In industry, fuel is burned or electricity is used to generate heat for furnaces, boilers, dryers, etc. and used in the production processes. Heat lost during the process reduces the efficiency of the process. Insulating materials can be used on process equipment, pipelines, and storage devices to minimize the loss of heat which ultimately reduces energy input required per unit of output. Insulation has other non-energy benefits in personal protection for workers, process control, noise control, fire protection, and lower thermal stresses thus improving the longevity of equipment.

Electric Motors and Driven Systems: Electric motors convert electrical power into mechanical power and consumes the majority of the electricity in a motor-driven system, while a small amount is used for other ancillary circuits. In industry they are used to drive fans, pumps, compressors, conveyors, etc. The efficiency of motors depends both on their size and their efficiency class. Firstly, optimization of electromotor systems implies the use of a variable speed drive (for variable load requirements) or optimization/replacement of the application (fan, compressor, pump). The scope also includes matching the application with a better suited electromotor in terms of size and power delivered. Secondly, replacing a current electromotor by a more efficient electromotor provides the same output at a lower energy input.

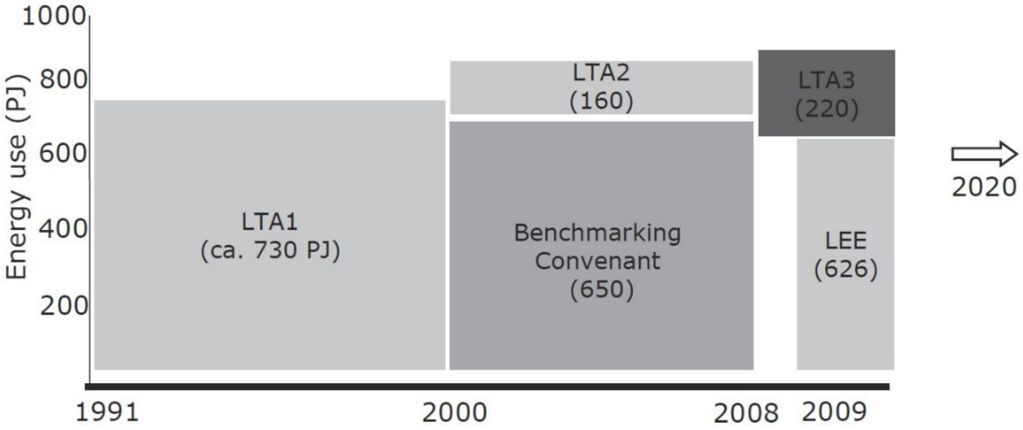
Improved Technology: This category involves other measures that involve an alternative technology or process for the same desired output. Examples include changing from natural gas-fired furnaces to oxyfuel furnaces, preheating with a pulsed electric field instead of steam, microwave drying instead of traditional drying, membrane separation instead of traditional separation processes, etc. The output stays the same, but a different technology creates a different energy and mass balance for the process. Certain technology changes can lead to a lesser energy input requirement for the same output, thus making it an energy efficiency measure.

Process Optimization: This includes the optimization of the process that is in place by using better engineering practices and digitalization. Digitalization of processes include advanced control of processes, better energy management, and better asset management. Often it so happens in industries that a valve does not close on time, furnace pressure is not optimal, combustion air is not mixed well – all of which leads to a higher amount of energy being consumed than actually needed. Fixing these issues for any process would be accounted as Process Optimization. Digitalization helps in monitoring these key parameters for processes and in some cases, advanced artificial intelligence algorithms can even keep the process equipment and parameters optimized for consuming the least amount of energy that it can for a given output of product.

2 Energy efficiency policies in The Netherlands

The Netherlands have consistently tried to improve energy efficiency in their manufacturing industry, firstly, by the implementation of voluntary agreements (VAs) in 1990. These were called Long Term Agreements (LTA; Meerjarenafspraken or MJA in Dutch), later being numbered. The main purpose of these agreements was to speed up the implementation of techniques that would save energy in industry (Abeelen, 2019). Other sectors such as ICT and the financial services sector were also part of the agreements.

Figure 1
An overview of the voluntary agreements in Dutch industry and the approximate total primary energy use (excluding non-energy use) of the participating companies (Abeelen, 2019).



The VAs were also backed up with other, mainly financial, policy instruments such as corporate tax reductions with the Energy Investment Allowance (EIA). In 2000, the larger energy-intensive industry broke off and joined the Benchmarking covenant while about 900 smaller companies joined the second generation VA called LTA2 (Abeelen, 2019). The target for LTA2 and LTA1 were the same: an annual 2% improvement in energy efficiency. For the Benchmarking covenant, the target was to reach the top 10% of most efficient installations in the world (Abeelen, 2019). Yet energy efficiency increased by only 0.5% per year from 2000 to 2007. Following the suspension of the Benchmarking covenant in 2008, the LTA3 was signed as an amendment of LTA2 (Abeelen, 2019). Most companies that were part of the Benchmarking Covenant signed a separate agreement in 2009 called the Long-term Agreement Energy Efficiency for ETS-companies called LEE, which acts as an amendment to the Benchmarking covenant but with different targets and regulations (Abeelen, 2019).

Participating companies of the VAs were obligated to plan and implement all profitable measures on energy efficiency that has a net positive cash flow at an internal discount rate of 15%, while also allowing for an alternate method to use a payback period of 5 years (Abeelen, 2019). The long-term agreements are aligned with the national Energy Agreement for Sustainable Growth which was signed in September 2013 (Netherlands Enterprise Agency, 2015). The agreements resulted in large-scale voluntary collaboration of businesses, institutions, and governments while getting international recognition.

Figure 2 summarises the cumulative results from process efficiency improvements of the LEE covenant from 2009 to 2020. The covenant results also cover chain efficiency improvements, but these are not included here. The largest relative savings were achieved in the paper and board and the beer brewing sectors. The largest absolute savings were achieved in the larger sectors: chemical industry with 36.2 PJ and refineries with 16.7 PJ. Yearly energy use reductions range from 1.0% in refineries to 1.7% in the paper and board sector, with an overall average of 1.1% per year.

Figure 2
Results energy savings through process efficiency in the LEE covenant 2009-2020 (RVO, 2021).

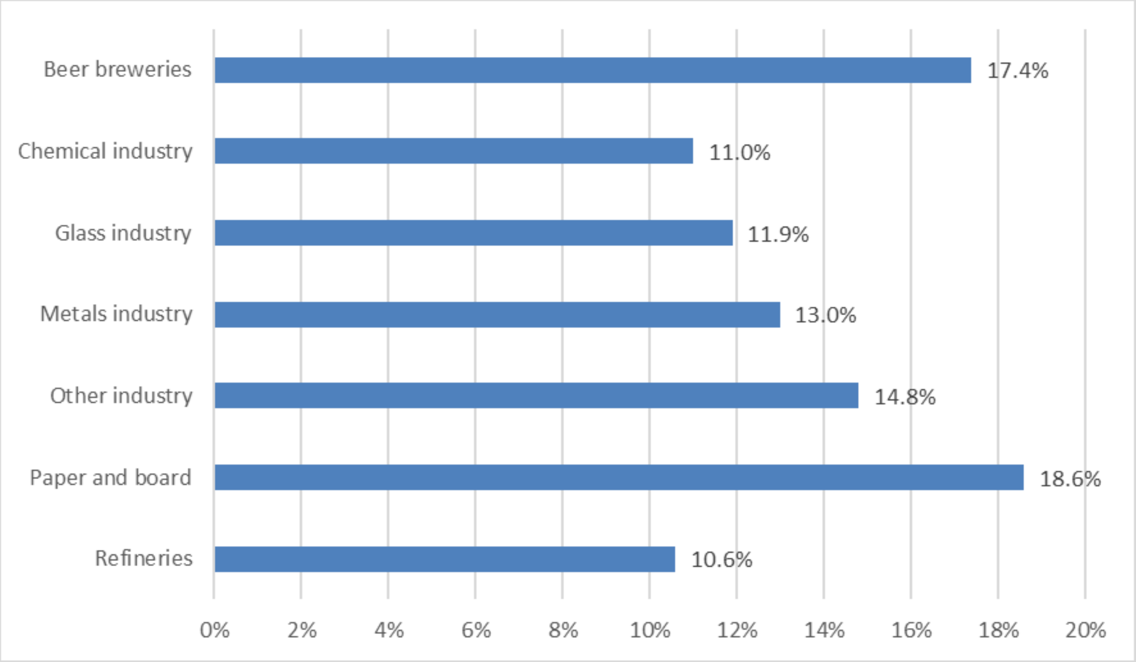
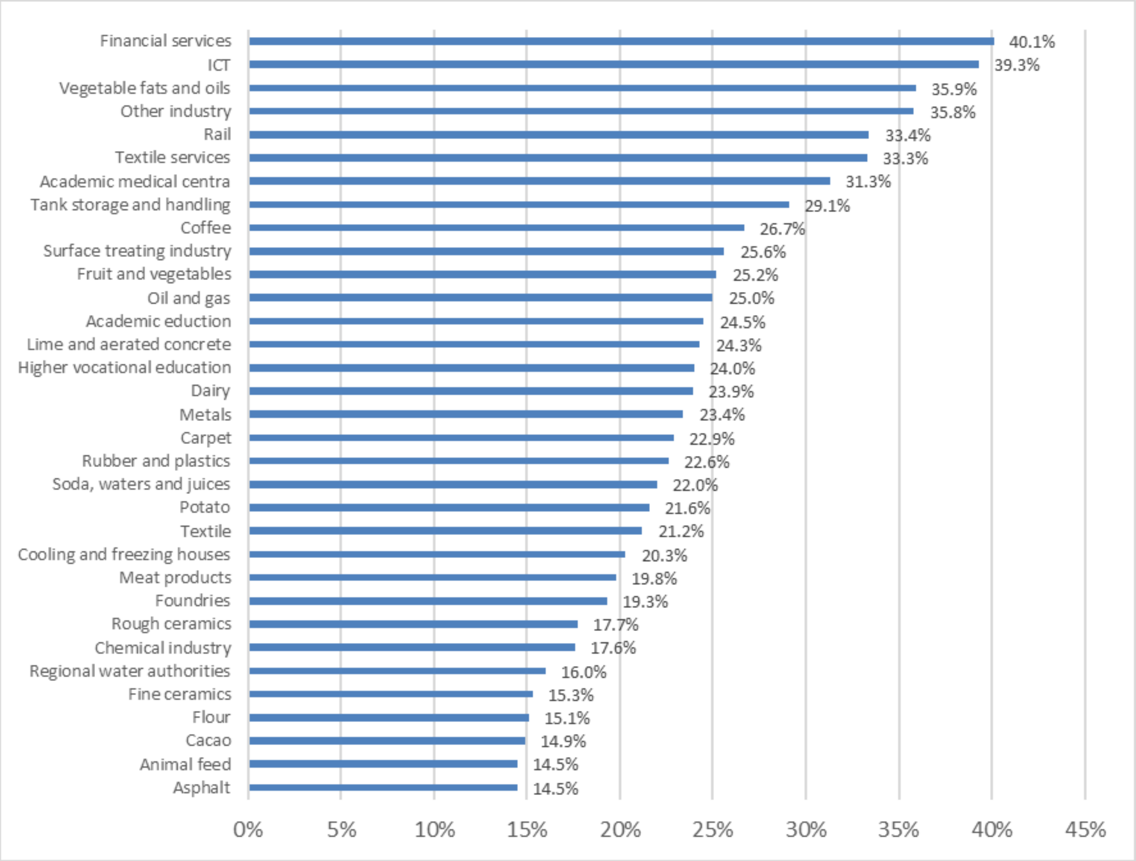


Figure 3 summarises the cumulative results from process efficiency improvements of the LTA covenants from 2005 to 2020. The savings range from an average of 1.0% per year for the asphalt and animal feed producing industries to 2.7% per year for the financial services sector, with an average of 1.8% per year for all sectors covered in the covenant.

Figure 3
Results energy savings through process efficiency in the LTA covenant 2005-2020 (RVO, 2021).



The LEE and LTA covenants came to an end in 2020, along with a shift of attention in national climate agendas from energy efficiency to decarbonization of the economy.

From 2019, The Environmental Management Activities Decree (Activiteitenbesluit Milieubeheer) has stated that organizations in the Netherlands that use 50,000 kWh of electricity or 25,000 m^3 of natural gas (or equivalent) or more per year are obligated to take energy efficiency measures with a payback period of five year or less.

These obligations can be met in three following ways:

1. To take all the energy efficiency measures at the organization with a payback period of five years or less and a competent authority will decide if the obligation is fulfilled.
2. By undertaking all relevant measures for the organization on the Recognized Energy Efficiency Measures List (Erkende Maatregelenlijst energiebesparing, or EML).
3. By applying part of the applicable EML measures. For the measures not taken, an alternative one equal or better to it is to be taken.

Even though the energy-saving obligation forces companies to take all energy-saving measures that pay back for themselves within five-years, according to Minister Rob Jetten (Climate and Energy, D66), out of approximately 90,000 companies only 61,425 companies have reported. Amongst the companies that reported, approximately 15% fully complied with the energy-saving obligation, 40% of companies that implemented at least three quarters of the mandatory measures and 3% have implemented one quarter or less (Energeia, 2022).

The Dutch Emissions Authority (NEa) conducts yearly CO_2-efficiency benchmarking for individual companies (Dutch Emissions Authority (NEa), 2023). While the benchmarking focuses on CO_2-efficiency, there is a clear link to energy efficiency. An analysis of the benchmarking by the NEa was beyond the scope of this report.

Europe has had a fossil energy dependence on Russia, whose war with Ukraine has disrupted supply of natural gas and oil to Europe at the start of 2022. This, along with high fossil fuel prices, has put energy savings and efficiency improvements back up on the agenda for European nations, including the Netherlands. Increasing the energy efficiency of the EU by 1% reduces Russian gas import by 4% and oil import by 5.5% (Paulus, 2022). The proposals for a recast European Energy Efficiency Directive (EED) as part of the European Commission's Fit-for-55 package and the REPowerEU proposal as a reaction to the disrupted natural gas and oil supplies to Europe have also put more attention on energy savings and efficiency improvements in Europe.

The following chapters focus on the technical energy savings potential. The effects of recent market and policy developments are discussed further in Chapter 5.

3 Energy efficiency in MIDDEN

This chapter contains an overview of the energy efficiency measures and potentials based on MIDDEN reports and the MIDDEN database. Gaps in the MIDDEN database have been filled with information from literature and have been supplemented by interviews. The interviews were conducted to verify the MIDDEN measures and potential estimations, to check the general industry sentiment about the measures and their savings estimates, and how much of it can be achieved.

The chapter starts with a section per industrial sector as defined in the MIDDEN nomenclature. At the end of the chapter an overview of the identified measures and potentials is presented.

The following parts of the report expand upon each industrial sector in the MIDDEN database. A commentary on the history of energy efficiency, current situation, and future plans and savings potential is presented about each sector. Interviews with the larger energy-intensive industries have been used to supplement already available information, verification of information, and have a general take from industrial experts on individual measures, policy instruments, barriers to implementation, and the savings potentials. A savings potential is estimated for each industrial sector for the year 2030 as compared to the year 2020, based on MIDDEN data and the interviews with industry. For simplicity we do not account for changes in production in 2030 compared to 2020. Reductions in energy use through energy efficiency measures therefore also result in a reduction of the energy consumption per ton of product produced. Final energy use for the year 2020 are outlined in Table 2 in order for readers to be able to compare energy savings values with current energy use.

Table 2
Final energy use in industry in 2020 (CBS, 2022). The chemical sector (20), building materials sector (23) and basic metals industry (24) are presented disaggregated to reflect the sector division used in MIDDEN.

SBI code	Industry	Final energy consumption [PJ]
08	Mining and quarrying (no oil and gas)	4.1
10-12	Manufacture of food and beverages	80.8
13-15	Man. of textile, leather products	4.1
16	Manufacture of wood products	2.4
17	Manufacture of paper	20.6
18	Printing and reproduction	1.8
2011	Manufacture of industrial gases	17.1
2012	Manufacture of dyes and pigments	2.0
2013	Manuf. Other inorganic basic chemicals	26.0
2014	Manufacture organic basic chemicals	176.7
2015	Manufacture of fertilisers	30.9
2016	Plastics and synthetic rubber industry	27.9
202-206	Other chemical industry	13.2
21	Manufacture of pharmaceuticals	3.9
22	Manufacture rubber, plastic products	9.6
231	Manufacture of glass	8.2

SBI code	Industry	Final energy consumption [PJ]
232	Refractory, other ceramic industry	0.1
233	Manufacture clay building materials	7.8
234	Manufacture of cement, lime, plaster	n/a
236	Manufacture concrete etc. products	3.4
241	Iron and steel industry	29.6
244	Non-ferrous metal industry	11.8
25-28	Metal products and machine industry	20.6
29-30	Transport equipment	4.1
31	Manufacture of furniture	1.6
32	Manufacture of other products	0.9
All	**Total industry (no energy sector)**	**543.7**

3.1 Fertilizer Industry

The ammonia and fertilizer production in the Netherlands is highly integrated and much has already been done on energy efficiency. Energy efficiency improvements in recent years have been small, mostly on the value chain after the ammonia plant (i.e. the production of fertilizers and melamine). Europe-wide the specific energy use for the production of ammonia has decreased by an average of 0.11% per year from 2007/2008 to 2016/2017 (EU ETS benchmark). The EU ETS benchmark rate for 2021-2025 is set to 0.2% per year. If the benchmark rate is met a 0.1%/year incremental improvement would amount to a 0.31 PJ decrease in energy use in 2030 compared to 2020 for the Dutch fertilizer industry. At 0.2% per year this would be 0.61 PJ.

The MIDDEN report on the fertilizers industry discusses the two largest fertilizer manufacturers Yara and OCI and mentions several options for improving energy efficiency (Batool & Wetzels, 2019). These include improvements in the reformer section, improvements in existing carbon dioxide removal, installing a gas turbine before the furnace, low pressure ammonia synthesis, improved process control and improved process integration. Several options for the urea plants are also mentioned, including the use of advanced stripping technology and novel process concepts.

Table 3
Energy efficiency measures for the fertilizer industry identified by MIDDEN.

Part of process	Measure	Savings Value 2030 compared to 2020	Comment
Ammonia	Improvements to the reformer section	n/a	Already (partially) implemented, remaining potential unclear
Ammonia	Improvements in carbon dioxide removal	n/a	Already (partially) implemented, remaining potential unclear
Ammonia	Gas turbine before the furnace	10%	Unknown if already implemented

Part of process	Measure	Savings Value 2030 compared to 2020	Comment
Ammonia	Low pressure ammonia synthesis	n/a	Savings of 0.3 GJe/ton ammonia according to CE Delft (2014). At a production capacity of around 3 Mt ammonia per year this amounts to 0.9 PJ per year. Only applicable to new ammonia synthesis plants
Ammonia	Solid state ammonia synthesis	3%	30% electricity savings. Low TRL (3-5) unlikely to be deployed on short term
Ammonia	Improved process control	n/a	Already (partially) implemented, remaining potential unclear
Ammonia	Improved process integration	n/a	Already (partially) implemented, remaining potential unclear
Urea	Advanced stripping technology	n/a	Potentially already implemented
Urea	Novel process concepts	n/a	Potentially already implemented

Low pressure ammonia synthesis only applies to new plants (Batool & Wetzels, 2019). The TRL level of solid state ammonia synthesis is still low (3-5) and the process is still in laboratory scale (OCI interview). We do not expect new natural gas based ammonia synthesis plants to be constructed in The Netherlands in the near future. It is possible that new ammonia synthesis plants will be constructed for the use of green hydrogen for ammonia production. Energy reduction potential for existing ammonia synthesis plants is estimated by CE Delft at 0.3 GJ_e/ton ammonia (de Bruyn, Koopman, van Lieshout, Croezen, & Smit, 2014). This is equal to the total electricity use estimated in MIDDEN (Batool & Wetzels, 2019). This implies that either the energy saving potential is overestimated or that the measure has already been (partially) implemented. Combined with uncertainty about new green ammonia synthesis plants we therefore do not consider an energy efficiency potential for low pressure ammonia synthesis here.

According to the interview with OCI the other energy efficiency options mentioned in the MIDDEN report, such as improvements to the ammonia plant, improvement process control and improved process integration are part of the current energy efficiency improvement strategy and contribute to the 0.11% per year energy efficiency improvement seen in the EU ETS benchmark. Energy efficiency gains at OCI have also been made at other plants (urea, nitric acid, calcium ammonium nitrate, melamine) under the LEE policy programs. While energy efficiency efforts continue, OCI says most low hanging fruit is gone and larger energy efficiency gains require large changes to the production plants.

The ammonia and fertilizer industry is currently developing plans for decarbonization. The options include carbon capture and storage (CCS), the use of renewable hydrogen or the import of green ammonia. All these decarbonization options would require large interventions at the production site. When large changes are implemented at the production sites it creates an opportunity to reevaluate the entire energy balance of the site and explore what opportunities there are to improve overall energy efficiency. On the other hand, CCS requires additional energy for the capture and transport of CO_2, the production of renewable hydrogen from electrolysis requires additional electricity use, and the import of ammonia means additional energy use for transport.

The decarbonization plans can therefore also lead to a net increase in energy use. Because the decarbonization plans are still being developed, it is not yet clear what the effect will be on the overall energy use and energy efficiency.

Concluding, we estimate that with continued incremental energy efficiency improvements the ammonia and fertilizer industry has a technical energy reduction potential of at least 0.3-0.6 PJ by 2030 compared to 2020. Incremental improvements can be achieved through various measures such as Best Available Technologies (BATs), improved process control, improved process integration and improvements to the ammonia, urea, nitric acid, and other plants. The technical potential is likely to be higher when taking into account larger energy efficiency gains from larger changes to the plants, but there is no quantification of these potentials.

3.3 Iron and steel

Steel manufacturing in the Netherlands is dominated by primary steel production by Tata Steel IJmuiden (TSIJ). They are one of the most efficient steel plants in the world (Keys, van Hout, & Daniëls, 2019). TSIJ have an energy efficiency program called Trias Energetica consisting of three main goals:

1. To reduce unnecessary energy consumption with measures like heat insulation, start-up/shut-down procedures, and design innovation.
2. Use sustainable energy sources for necessary consumption such as wind, solar, biomass, etc.
3. In the absence of sustainable energy sources, more efficient and less polluting fossil fuels are to be used, like natural gas instead of coal.

These principles have helped TSIJ improve their energy efficiency by 35% in 2021 relative to 1989. That is an average energy savings value of 1% per year. Large improvements are now possible only through large technological changes and investments.

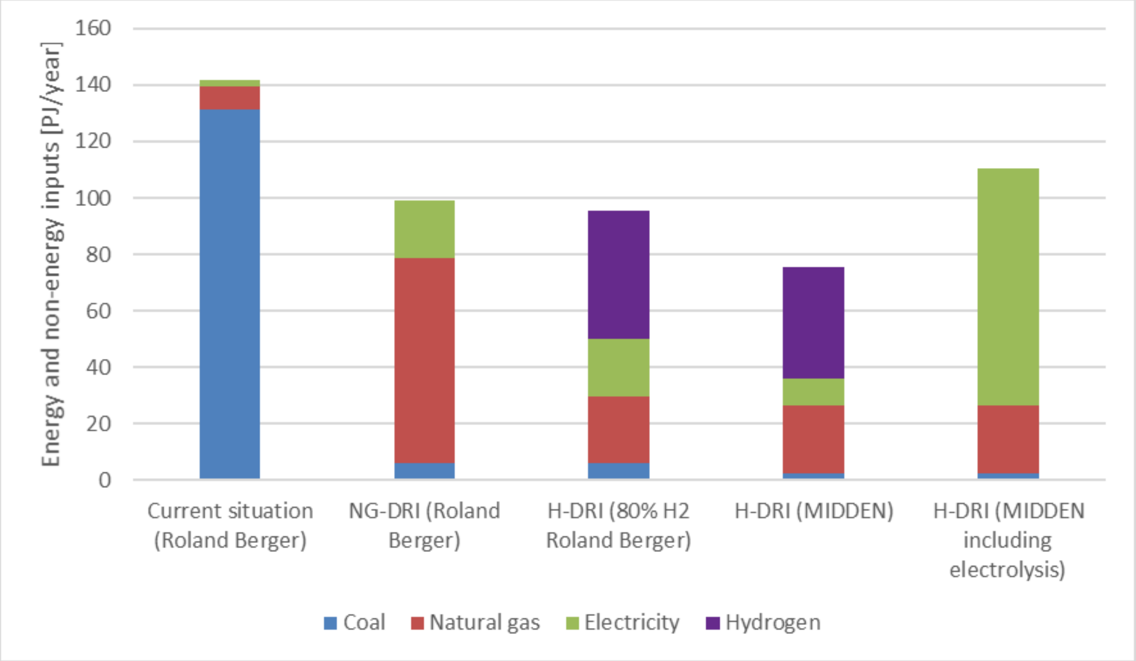
The 2019 MIDDEN report on the Dutch steel sector does not specify any energy efficiency measures (Keys, van Hout, & Daniëls, 2019).

In terms of incremental improvements, TSIJ always looks at the most efficient option when changing a particular piece of equipment. Current projects include a new furnace for the hot rolling mill which can save about 0.6 PJ a year (interview Tata Steel Netherlands). The new rolling mill is expected to become operational in 2023. A different cooling system for the mill is also explored which would allow TSIJ to shut off high pressure pumps thus saving energy. There have been discussions ongoing for having a small waste heat network on the site of about 80°C while integrating it with air-preheating, office heating, and other users. Process gas is internally used wherever possible, replacing natural gas and a part of it is sent to Vattenfall for electricity generation. The rotating parts for the large motors are continuously improved.

TSIJ has committed to changing their steelmaking process from the Blast Furnace/Blast Oxygen Furnace route to the Hydrogen Direct Reduced Iron (DRI) route. While transitioning the site to accommodate the new process, initially natural gas will be used instead of hydrogen. This is due to green hydrogen production still being uncertain to supply in adequate capacity and the operation of DRI completely on hydrogen is unproven. Figure 4 shows that the expected energy and non-energy inputs decrease significantly when switching to DRI steelmaking compared to the current blast furnace route, even when including the electrolysis for hydrogen production. Hydrogen is used as a reducing agent in the DRI process. Based on the expected efficiency improvement of the hydrogen production total energy consumption should decrease even further in the future.

It should be noted that in the current situation some of the gases arising from coke production and the blast furnace are exported to a power plant for electricity production. These are not accounted for in Figure 4. For hydrogen DRI it is relevant whether the hydrogen is purchased or produced on site. The Roland Berger report mentions the hydrogen required while MIDDEN (Keys, van Hout, & Daniëls, 2019) mention both the hydrogen required and the electricity required for electrolysis to produce the hydrogen. Currently TSIJ is looking at 1-1.5 GW electrolyzer capacity on-site (interview Tata Steel Netherlands). It is not expected that hydrogen will be produced on-site before 2030. TSIJ expects hydrogen that is used by 2030 to be imported from the Dutch hydrogen backbone or by ship at the harbor.

Figure 4
Energy and non-energy inputs for production of ca. 7 Mton crude steel per year with various setups. Based on (Roland Berger, 2021; Keys, van Hout, & Daniëls, 2019)



After the transition to H-DRI, the on-site installations after the pig iron production remain the same. So currently for investments in energy efficiency improvements TSIJ focuses on the mills and other installations that are going to remain the same after transition. Such as the replacement of the furnace in the hot rolling mill mentioned above. Current investments in energy efficiency also need to fit long-term plans.

TSIJ believes the 1% per year energy improvement rate can be kept up in the coming years (interview Tata Steel Netherlands). Starting with a 52.2 PJ energy use in 2020[3] and applying 1% improvement per year till 2030 brings us to a total savings potential of 5 PJ in 2030.

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[3] This includes production arising gasses used in the steel production processes and excludes gasses used for electricity and heat production. More information about the energy inputs can be found in the MIDDEN report for the steel industry (Keys et al., 2019).

3.4 Inorganic basic chemicals

There are six MIDDEN reports that fall within the inorganic basic chemicals sector: industrial gases production, silicon carbide, carbon black, activated carbon, salt and chlor-alkali production.

3.4.1 Industrial gases

There are two main industrial gas production processes in the Netherlands. The first is the production of hydrogen (H_2) and carbon monoxide (CO) and syngas (a mix of H_2 and CO) with steam methane reforming (SMR) or autothermal reforming (ATR). Energy efficiency improvements can mostly be achieved through improvements to the reformer section, waste heat utilization, process optimalization and the upgrading of equipment (e.g. motors and pumps). As with the reformers for the fertilizer industry it is expected that the remaining potential for improvement of the reformer section are limited, as many improvements have already been implemented. The re-use of waste heat is an important feature in the design of an SMR (Cioli, Schure, & van Dam, 2021) and the remaining potential is therefore also likely to be limited. Any remaining recovery of waste heat will need to be linked to external demand such as heat networks (correspondence Air Liquide, 2023). The MIDDEN database does not include an estimate for the energy efficiency potential for process optimization or upgrading equipment.

The second industrial gas production process is the production of oxygen, nitrogen and argon. These gases are mainly produced through the cryogenic separation of air, which is considered the most effective technology for air separation. Smaller amounts of the gases are produced at ambient temperature through a process called pressure swing adsorption (PSA). The MIDDEN project has focused on cryogenic air separation. The most energy-intensive part of cryogenic air separation is the compression step to increase the air pressure. The heat from compression is used to bring up the temperature of the cold oxygen, nitrogen and argon produced through the cryogenic distillation. Improvements to the compression and heat exchangers are main opportunities to improve the energy efficiency of the process. New air separation installations have (about 10%) lower energy use due to improvements in air compressors, heat exchangers and turbines (Industry & Energy, 2022). Similar savings are technically possible at existing ASU plants, but whether the energy savings measures are applied depends on costs and benefits (correspondence Air Liquide, 2023).

3.4.2 Chlor-Alkali

The MIDDEN report on chlor-alkali (Scherpbier & Eerens, Decarbonisation options for the Dutch chlor-alkali industry, 2021) identifies three specific measures. Multiple Effect Vaporisation (MEV) of caustic soda increases efficiency by 10% for each extra effect that the vaporization process passes through. According to the report it is not cost-effective to have more than five vacuum pans for the vaporization of caustic soda. That would make a reduction of about 40% of the steam required for the caustic soda preparation possible. This comes out to about 0.3 TJ per kt of chlorine produced. On a total of production of 850 kilotons of chlorine per year this comes out to a reduction of about 0.2 PJ, or about 6% of the natural gas use in the production of chlorine (2% of the total energy use including electricity).

It is possible that mechanical vapour compression can improve the efficiency of the process even further by supplying the required heat for evaporation but this is only expected to be available after 2030.

The second measure mentioned in the MIDDEN report is the use of ‘zero-gap technology’ which has become widely adopted since 2010. It has been partially implemented at Nouryon’s chlor-alkali plant in Botlek since 2017, providing energy savings of at least 10%. It is unclear how much potential remains in the Netherlands.

The third measure mentioned is the oxygen depolarized cathode (ODC) which avoids the production of hydrogen at the cathode by introducing oxygen. The required electrical potential is 30-40% lower, but the economic benefit is less due to the reduced income from hydrogen sales. There is no reported use of the ODC measure in the Dutch chlor-alkali industry.

It is unclear how much of the theoretical 30-40% energy savings (ODC and MEV of caustic soda) can technically be achieved in the Dutch chlor-alkali industry.

3.4.3 Salt

In the salt industry water is vaporized from brine in order to produce salt. Also here Multiple Effect Vaporisation (MEV) is a technology used to increase the efficiency of the water vaporization process with 3-5 connected vacuum pans (Scherpbier & Eerens, 2021). A general rule of thumb observed is that for each extra effect added in a multiple effect vaporisation system, a 10% efficiency gain is made. A trade-off is that the investment costs are higher for each extra effect. In Europe, the maximum amount of effects deployed in the salt manufacturing industry is eight (Westphal et al., 2012).

Mechanical vapour recompression is seen by salt industry experts as a cost-effective technology for the reduction of CO_2 emissions in the salt industry (Scherpbier & Eerens, 2021). The low pressure water vapour that has evaporated from the brine is recompressed to higher temperatures and pressure and used as a heat source to vaporize more brine (Scherpbier & Eerens, 2021) (Den Ouden, Lintmeijer, & Van Aken, 2017). The total electric and heat energy required for vaporization is about half of the required energy for MEV (Westphal et al., 2012).

3.4.4 Carbon black

Cabot B.V. has reported on efforts to improve the energy efficiency of their carbon black plant. In 2015, a project was developed to reduce the use of natural gas during maintenance, which reduced emissions by ca. 1 kilotonne CO_2 (Cabot, 2015). In 2016, the energy consumed by one of the tanks in which feedstocks are stored was reduced using insulating coating. There are seven tanks which are heated by steam. The coating provided a 55% reduction of the energy consumption compared to the non-insulated tanks (Cabot, 2016).

The main energy efficiency measure in the carbon black production industry is tail-gas combustion and energy recovery (Boulamanti & Moya Rivera, 2017). It is common practice in Europe to combust tail gas for drying, boilers or combined heat and power (CHP) installations, or in flares and other thermal combustors (Boulamanti & Moya Rivera, 2017).

3.4.5 Silicon carbide

Microwave heating can be an alternative to traditional heating in the silicon carbide industry that can lower energy use due to lowering the process temperature and increasing the reaction rate

(Xavier & Oliveira, 2021). However, the process is significantly different from the traditional production in ovens and there are some differences in the microstructure of the silicon carbide (Xavier & Oliveira, 2021).

3.5 Organic Basic Chemicals Industry

The Organic Basic Chemicals sector is a large sector producing numerous products. The oil products from the Shell Refinery go to Shell chemicals Moerdijk and Shell chemicals Pernis where they are converted into heavier hydrocarbons. Shell Moerdijk, SABIC Geleen, and Dow Terneuzen have steam crackers which are treated as a part of the organic chemicals sector in MIDDEN. Further organic chemical industry and plastics production sites include LyondellBasell, BioMCN/OCI Delfzijl, SABIC Bergen op Zoom, Indorama Europoort, ExxonMobil and several other sites in Botlek/Pernis, Chemelot and Dordrecht. Steam cracking produces ethylene, propylene, C4 monomers and benzene, as feedstock for the petrochemical plants to convert into other chemicals.

Since chemical and refining industries are vulnerable to high energy costs, energy efficiency is always a priority for them and most of the high energy savings projects has already been exploited. Larger gains can only be realized when larger projects are being implemented but until then only incremental improvement are possible. Autonomous energy efficiency improvements are expected to contribute to an annual yearly increase of 0.5-1% (Ecofys; Berenschot, 2018).

MIDDEN has identified many different measures to improve energy efficiency in both the steam crackers and further downstream chemicals sections (see Table 4). Measures like coalesce filtration systems, heat pumps and heat integration in distillation columns have been reported to reduce the amount of energy required per ton of ethylene produced (Wong & Dril, 2020). DOW Chemicals has conducted a project with steam recompression in Terneuzen which upgraded 3.5 bar steam of the LDPE plant to 12 bar. This has led to an energy savings of 0.244 PJ (Eerens & van Dam, 2022). As shown in Table 4 for many of the measures the potential is unclear, either because estimates of the savings value are missing, the measure is already being applied and the remaining potential is unclear, or industry has indicated in interviews that the measures are not applicable in the current highly integrated sites and major rehauls of the plants are required to implement the measures.

Table 4
Energy efficiency measures for steam cracking and downstream organic chemical plants identified by MIDDEN.

Part of process	Measure	Savings Value 2030 compared to 2020	Comment
Steam cracking	Coalesce filtration	10%	Unclear whether there is potential remaining.
Steam cracking	Heat recovery and use	4%	Already being implemented. Unclear what potential remains at integrated and optimized sites.
Steam cracking	Adsorption heat pumps	3%	Potential at integrated and optimized sites unclear.

Steam cracking	Heat integration in distillation columns	1%	Potential at integrated and optimized sites unclear.
Steam cracking	Steam recompression	6%	Potential at integrated and optimized sites unclear.
Steam cracking	Membranes	8%	Unclear whether there is potential remaining.
Steam cracking	Process control sensors	5%	Unclear whether there is potential remaining.
Steam cracking	Efficient turbines and motors	n/a	Already being implemented. Remaining potential unclear.
Other organic chemical plants	Heat integration	n/a	Already being implemented. Remaining potential unclear.
Other organic chemical plants	Waste gas recovery systems	n/a	Already being implemented. Remaining potential unclear.
Other organic chemical plants	Electrifying steam drives	n/a	Already being implemented. Remaining potential unclear.
Other organic chemical plants	Improved catalysts	n/a	Major revamping of process units necessary. Potential unclear.

For the chemical industry, heat pumps and MVR are very specific applications and not yet available for process temperatures above 150°C that are often required in chemical plants (Marina, Smeding, Zondag, & Wemmers, 2017). VNCI's roadmap for Dutch chemical industry has assumed that technologies like heat pumps and MVR can improve annual energy efficiency by 0.5%-1% for a typical payback time of five years or less (Ecofys; Berenschot, 2018).

Insulation, in theory, has a high technical potential but the implementation is a challenge, because of the scale of the sites. Insulation upgrades are generally part of long-term maintenance and safety strategies and even determining the theoretical potential for insulation in big sites can be a long and difficult project. Therefore an insulation campaign would be very large with many small projects (Shell interview).

Replacement of steam drives in crackers by electric equipment is dependent on a company's long-term vision on electrification. If for example the steam crackers are replaced by electric crackers, the whole heat balance of the plant will change. It therefore makes sense for the companies to wait for large decarbonization projects like this to explore new heat integration opportunities. Yet it means that while there may be energy savings potential by for example replacing older steam drives with newer, more efficient steam drives, the companies might not want to make such investments because the new steam drive may not be the optimal solution in the new plant setup with an electric cracker.

To conclude, there is much unknown about the (remaining) energy efficiency potential in the organic basic chemistry sector. The existing facilities are highly integrated and optimized, energy efficiency measures are already implemented and larger savings require larger changes to the sites. Large changes to sites need to fit in the long term strategy for the plants. Based on the VNCI's estimate of 0.5%-1% improvement per year we assume there is a technical energy savings potential of at least 1% per year for the organic basic chemistry sector. Compared to 176.7 PJ/year energy use in 2020 (see Table 2), this would come out to a reduction of 16.9 PJ/year in 2030.

3.6 Paper and Board Industry

The pulp and paper industry forms the fourth largest industrial user of energy worldwide (Rademaker & Marsidi, 2019). Paper and board is a diverse sector in itself, producing a multitude of products such as graphic paper, graphic paper made from recovered paper, corrugated board, solid board, and others. The energy consumption varies significantly from mill to mill for a variety of reasons, most important of which are type of product, scale of production, quantity of recovered paper, etc. Bulk producing sites are considerably larger (corrugated board and graphic paper) consuming more energy than the more specialized paper mills that produce a larger variety of products in lower quantities. In 2020, total final energy consumption by the industry was 20.6 PJ (see Table 2), of which a significant share is produced by on-site CHP and boilers. The boilers and CHPs are majorly natural-gas-fired, while some companies use biogas or other imported biomass (Rademaker & Marsidi, 2019).

The MIDDEN report identifies several measures in the paper and board industry for improving energy efficiency such as compression refining, microwave drying, air-laid technology, and capture of evaporated water (CapWa). Compression refining has achieved 20% energy savings in pilot projects but has not been implemented beyond the pilot project. Microwave drying is not in the agenda of the companies either, and the sector does not look into it as it has a low TRL. Air laid technology has a niche market where it can be delivered and is not developed yet for general application. Its specificity of application makes it a long-term strategy for a few companies. CapWa has also been piloted in other parts of the world (e.g. South Africa), but has not been much explored in the Netherlands.

VNP estimates that heat pumps can save around 40% of energy use in the paper and board industry (VNP, 2022). The issue with their implementation is that sometimes the temperature lift is too high to be achieved with a single heat pump. To solve the problem, heat pumps need to be stacked together consecutively, combining a closed and an open heat pump. The SDE++ subsidy scheme provides subsidies for singular heat pumps, but not multiple ones. According to VNP, this makes creating a good business case for stacked heat pumps difficult and thus creates a gap between technical and economic potential. MVR and heat pumps differ in application from mill-to-mill. It is difficult to get subsidies as it is hard to standardize the technology for cascading industries like paper. The Minister for Climate and Energy has asked PBL to investigate the possibilities for including a category with combined heat pumps for the SDE++ 2024 (Ministry of Economic Affairs and Climate Policy, 2023), which means the option may be included in the subsidy scheme in the future.

According to VNP, shallow geothermal energy (500-1500m) is being looked at as a heat source for Heat Pump systems. Moreover, when there is a temporary stop in the plant, it is energy efficient to be able to store the heat somewhere for example phase change materials or heat batteries.

To conclude, based on our interview with VNP the technical energy savings potential for the Paper and Board industry comes out to 8.2 PJ/year (40% of 20.6 PJ in 2020). According to the VNP the high potential of heat pumps and MVR can only be achieved when the measures are tailor-made for specific mills and are used in combination with each other.

3.7 Refineries

Refineries are complex systems with many different processes. The basic process is the distillation of crude oil into smaller carbon-chain components. Further processes involve physical and chemical upgrading into valuable components. In 2020, refineries had a total energy use of 168.3 PJ (see Table 2). Most refinery units have gas-fired furnaces and an extensive steam system, using mostly self-produced fuel gas, with additional natural gas. Fuel gas is a methane-rich gas that is a by-product in most refinery processes and can be consumed on-site in boilers and furnaces. BP, Esso, and Shell also have CHP units on site which provide the sites with steam and electricity (Oliveira & Schure, 2020).

According to the LEE results the refinery sector reduced yearly energy use through improvements in process efficiency by 16.7 PJ (10.6%) in 2020 compared to 2009 (RVO, 2021), or approximately 1% per year.

MIDDEN identifies waste heat utilization as energy efficiency measure. Refinery processes generate a lot of heat at different temperature levels which are cascaded, and lowest pressure steam levels can be used for purposes like district heating. Some sites already distribute residual heat to third parties, for example, the Pernis residual heat initiative by Shell. Currently 0.6 PJ of natural gas is offset by district heating using residual heat (Oliveira & Schure, 2020). The total residual waste heat potential is estimated at 57-83 PJ/y, 31-37 PJ at temperatures below 100 °C and 26-46 PJ at temperatures above 100 °C. The waste heat with temperature below 100 °C is more difficult to utilize directly. Therefore, it is expected that adding a heat pump to the system might increase the functionality of the waste heat. Heat pumps have a Coefficient of Performance of above 1, meaning that they can potentially reduce energy use by more than the 31-37 PJ/year estimated residual heat of below 100 °C. In practice the waste heat available will depend on the waste heat integration on site. Shell indicated in an interview that the residual heat available at the Shell refinery is not as high as estimated by Oliveira and Schure (2020), but no own estimate was shared.

3.8 Other industries

The next sectors have been analysed using the MIDDEN reports and literature sources. No interviews have been conducted to supplement the information. The following industries are available in the MIDDEN database and each have a report on their decarbonization options.

3.8.1 Activated carbon industry

Activated carbon is produced by Cabot Norit Nederland B.V. in Zaandam and Klazienaveen.
The corporation has already increased the efficiency of its production process by investing in waste heat recovery and generating 50 MW of cogeneration power. Energy savings can be realized by using peat with a lower moisture content, using more efficient electromotors, and replacing current lighting by LED lighting. The waste gas can be used more efficiently as well if the carbon monoxide and hydrogen in it can be separated from the waste gas. It is unclear how much energy can be saved by these measures.

3.8.2 Aluminium Industry

In the Netherlands, the two main types of activities in aluminium manufacturing are: 1. The production of secondary aluminium using majorly scrap at e.g. E-MAX in Kerkrade and Zalco in Vlissingen. 2. Production of pre-baked carbon anodes for primary production at Century in Vlissingen. Aluchemie in Rotterdam and Aldel in Delfzijl have terminated the production of primary aluminium and are therefore not included here.

In MIDDEN, there are multiple energy-efficiency measures categorized under the two different activities. The specific measures are outlined in Table 5.

Table 5
Energy efficiency measures applicable to the aluminum industry identified by MIDDEN.

Part of Process	Measure	Savings Value	Comment
Melting/Casting of primary and secondary aluminum	Regenerative burners	40% natural gas	To replace cold-air gas-fired burners. They are able to recover 85% of the heat in exhaust gases by using a porous ceramic bed as heat storage which is used to preheat combustion air.
Melting/Casting of primary and secondary aluminum	Oxyfuel burners	40% natural gas	To replace cold-air gas-fired burners. They use pure oxygen instead of conventional combustion air.
Melting/Casting of primary and secondary aluminum	Improving furnace insulation	2%-5%	n/a
Melting/Casting of primary and secondary aluminum	Optimizing air-fuel ratio	15%	n/a
Pre-baked Carbon anodes	Optimizing air-fuel ratio	5%-25%	n/a
Pre-baked Carbon anodes	Improving furnace pressure control	5%-10%	n/a
Pre-baked Carbon anodes	Preheating of green anodes	10%-30%	From the waste heat of flue gases
Pre-baked Carbon anodes	Improved sensor and control systems	5%-10%	n/a

3.8.3 Biofuels industry

The main energy efficiency measure identified by MIDDEN for the biofuels industry is the use of waste heat. The waste heat can be increased in temperature using mechanical vapour recompression or closed industrial heat pumps. The potential for energy savings through these measures has not been estimated.

3.8.4 Building Materials and Asphalt Industries

The industries covered under this sector are container glass, fiber glass, glass wool, ceramics, cement, stone wool and asphalt. Most of the measures identified in MIDDEN are industry-specific.

Most of the energy in the building materials industry is used in high temperature furnaces. MIDDEN identifies waste heat use and preheating as the primary measures for energy savings. There are also decarbonization measures that also lead to energy efficiency gains (e.g. the replacement of gas-fired furnaces with electrical furnaces or oxy-fuel furnaces in the container glass and stone wool industries). Using oxy-fuel furnaces reduces the potential for waste heat utilization as the volume of flue gases in oxy-fuel furnaces is lower than in regenerative or recuperative furnaces, and limited technology exists for waste heat recovery in oxy-fuel furnaces.

The concept of preheating batch materials is not generally applied, since preheating certain materials can cause unwanted chemical reactions, dust formation, and clogging - all of which affect furnace integrity. For example, the fiber glass industry does not benefit from preheating raw materials. Instead, waste heat is used to heat buildings and production areas.

The exact application of general measures also has a degree of specificity for each plant and each industrial sector which needs to be taken into account to achieve the highest amount of improvement possible. The sum of the identified energy savings potentials in the buildings industry comes out to over 5 PJ.

Glass industry

The Dutch glass industry has been at the forefront of using the latest technologies and having world-class quality of production and energy efficiency (Papadogeorgos & Schure, Decarbonisation options for the Dutch container and tableware glass industry, 2019). The Dutch glass industry is quite heterogenous: container, tableware, fiber, glass wool, and other niche applications. MIDDEN identifies several measures for energy efficiency improvements, mainly in the melting and refining section of the manufacturing process. Technology improvements such as oxy-fuel furnaces, batch/cullet preheating and waste heat recovery. (Zier, Stenzel, Kotzur, & Stolten, 2021) states that the most promising techno-economic option for fuel savings is the use of Optimelt TCR Plus (TCR heat recovery + oxygen preheater) and a cullet preheater system. (Papadogeorgos, 2019) states that Optimelt TCR technology can also be combined with an Organic Rankine Cycle system. Assuming glass industry in the Netherlands operates on air-regenerative furnaces, upgrading to an oxy-fuel furnace with Optimelt TCR Plus (30% savings) with Cullet Preheater (4% savings) and Organic Rankine Cycle (5% savings), the container glass industry can save 1.63 GJ natural gas and 0.05 GJ electricity per ton of glass produced. With a production capacity of over 1 million tonnes per year in the Netherlands (Papadogeorgos & Schure, Decarbonisation options for the Dutch container and tableware glass industry, 2019) this amounts to potential savings of around 1.7 PJ (out of 8.2 PJ total energy use in 2020 (see Table 2)). As some of the measures are already implemented in the Dutch container glass industry (Papadogeorgos & Schure, Decarbonisation options for the Dutch container and tableware glass industry, 2019) the potential is expected to be lower than 1.7 PJ/year.

The measures identified for the glass wool industry are similar to those of the glass containers industry, focused on improved furnace design and the use of waste heat (Krijgsman & Marsidi, 2019). The only measure that was quantified is the use of an oxy-fuel furnace. With an estimated 60 kt of product output and 17.3 TJ energy use per kt of product (Krijgsman & Marsidi, 2019), total estimated energy use if 1 PJ per year. 10-15% energy savings through the application of oxy-fuel furnaces would amount to a reduction in energy use of 0.10-0.15 PJ per year.

Only waste heat recovery was identified as a measure for the fibre glass industry. There is no estimate for the savings potential.

Table 6
Energy efficiency measures in the container glass, glass wool and fibre glass sectors identified by MIDDEN.

Sector	Measure	Savings Value 2030 compared to 2020	Comment
Container Glass	Cullet/Batch Preheater	12-20%	Evaporates moisture in the batch and reduces furnace peak temperature
Container Glass	Organic Rankine Cycle	5%	A thermodynamic cycle to recover energy from low temperature waste heat sources
Container Glass	Optimelt TCR	21%	An advanced heat recovery method for oxy/fuel fired glass furnaces
Container Glass	Optimelt Plus	26%	An improved version of Optimelt TCR
Container Glass	Improved furnace design	n/a	A reconstructed crown and basin using improved refractories can reduce heat losses by 50-60%
Glass wool	Improved furnace design	0%	Standard BAT for glass wool is already applied
Glass wool	Oxy-fuel furnace	10-15%	Primarily aimed at reducing emissions, but has energy efficiency benefits as well.
Glass wool	Batch pre-heating with waste heat	n/a	There are challenges associated with pre-heating such as clogging and dust formation.
Glass wool	Waste heat to produce steam	n/a	Already applied
Glass wool	Waste heat for heating curing ovens	n/a	A heat exchanger will be required due to the presence of corrosive elements in the flue gas.
Fibre glass	Waste heat use	n/a	Already partially applied. Further application in drying and curing sections requires further studies.

Ceramics

In the ceramics industry a combination of industrial heat pumps and an extended tunnel kiln can yield maximum savings (Bresier, 2020). The combined savings amount to 42%. Considering a sectoral energy use of 7.8 PJ in 2020 (see clay materials manufacturing in Table 2), this amounts to energy savings of around 3.3 PJ per year.

Table 7
Energy efficiency measures in the ceramics industry, updated based on (Bresier, 2020).

Measure	Savings value 2030 compared to 2020	Comment
Heat recovery	9%	From flue gases using the Heat Matrix technology.
Industrial heat pump	28%	Not yet proven (TRL3-8) for >100 °C temperatures required for the ceramics industry.
Hybrid drying	8%	Uses two different drying phases: 1. Aerothermal drying 2. Semi-steam drying. Exact improvement depends on the water content.
Extended Tunnel Kiln	18%	Reduction in natural gas consumption

Cement

The MIDDEN report on the cement industry outlines the production process of cement in the Netherlands which takes place at two sites, ENCI Rotterdam and ENCI IJmuiden (Xavier & Oliveira, Decarbonisation Options for the Dutch Cement Industry, 2021). However, 2020 onwards the production of clinker inside the borders of the Netherlands was halted and currently the production process consists of only drying, dosing, and grinding. The raw materials are retrieved from other companies (for example, blast furnace slag is bought from Tata Steel IJmuiden). The blast furnace slag received has considerable amount of water in it and needs to be dried, and hence a drying process is involved for both sites. Replacing the existing natural gas dryers with heat pump dryers is an option that will also decrease energy use, but there is no estimate for the reduction in the report. The energy efficiency measures identified by MIDDEN are mostly restricted to the grinding process which takes up 90%-100% of the electricity consumption or the cement sector in the Netherlands (Xavier & Oliveira, Decarbonisation Options for the Dutch Cement Industry, 2021). Upgrading the grinding configuration to the BAT (Roller Press + two Vertical Rolling Mills) can reduce electricity consumption by 26% in IJmuiden and 42% in Rotterdam (Xavier & Oliveira, Decarbonisation Options for the Dutch Cement Industry, 2021). Additionally, high efficiency classifiers that separate fine grains from coarse grains can also be used to save 12% electricity for IJmuiden and 8% electricity for Rotterdam (Xavier & Oliveira, Decarbonisation Options for the Dutch Cement Industry, 2021). Considering a shift from the current practices in IJmuiden and Rotterdam to the Roller Press + High-Pressure Roller Mills configuration along with the use of high-efficiency classifiers, the cement industry in the Netherlands can save up to 0.2 PJ of electricity.

Table 8
Energy efficiency measures in the cement industry identified by MIDDEN.

Measure	Savings value 2030 compared to 2020	Comment
Heat pump dryer	n/a	Requires new dryer section. Energy efficiency is a co-benefit of the electrification of the dryer.
BAT (roller press + vertical rolling mills)	13-25%	26-42% electricity savings. Higher savings possible in Rotterdam than IJmuiden due to current setup
High efficiency classifiers	5-6%	8-12% electricity savings. Higher savings possible in IJmuiden than Rotterdam due to current setup

Stone wool

Two measures have been identified for the stone wool industry: insulation and heat recovery. Insulation of the furnaces is already applied. It is unclear what the remaining potential of the two measures is.

Table 9
Energy efficiency measures in the stone wool sector identified by MIDDEN.

Measure	Savings Value 2030 compared to 2020	Comment
Insulation of furnaces	n/a	Rockwool B.V. uses its own product to insulate the furnaces. Unknown if any potential remains
Heat recovery	n/a	Direct recovery through a heat exchanger is the most efficient method. Unclear if already applied at Rockwool B.V.

Asphalt

For asphalt production only improving the fuel combustion in heating drums has been identified as energy efficiency measure. The potential has not been assessed.

3.8.4 Food and Beverages Industry

The type of industries covered by this sector are: potato products, vegetable oils and fats, starch, sugar, dairy, and maltings and breweries. The sector is versatile in the range of product outputs and production processes. This creates the conditions for numerous sector-specific measures to be prevalent for this sector. There are some cross-cutting measures that apply to multiple sectors, namely heat recovery, mechanical vapour recompression, and the use of membranes.

Potato products industry

Measures in the potato product industry include heat recovery and upgrading to best available technologies and practices for peeling, pre-heating, blanching, and freezing. The savings values have been transformed from energy savings per step in the process (e.g. peeling, blanching, and frying) to savings in total energy use. West et al. (2021) make use of two articles with varying breakdowns of energy use per step in the production process, which leads to ranges for the energy savings potentials for a number of measures; particularly for the blanching, frying and freezing steps.

Table 10
Energy efficiency measures in the potato products industry identified by MIDDEN

Measure	Savings Value 2030 compared to 2020	Comment
Higher efficiency steam peeler	3%	25% energy savings in the steam peeling process. Also reduces peel loss, water usage, and maintenance costs.
Heat recovery from steam peeler	7%	65% reduction in steam required for steam peeling

Measure	Savings Value 2030 compared to 2020	Comment
Pulsed Electric Field for preheating	85% for preheating	Unclear what the share of preheating energy use is in the total energy use
Closed-loop blanching	1-3%	20-25% energy savings for blanching. Effect on total energy use dependent on estimate for share of blanching in total energy use.
Heat recovery from fryer	6-15%	23-30% energy savings for frying. Effect on total energy use dependent on estimate for share of frying in total energy use.
Optimizing air temperature control and refrigerant circulation	7-14%	30% energy savings for cooling and freezing. Effect on total energy use dependent on estimate for share of freezing in total energy use.
Multi-flow injection	n/a	Helps reduce temperature fluctuations and improves heat transfer

Starch industry

In the starch industry two energy efficiency measures have been identified: membranes for potato juice and mechanical heat recompression. Both have already been implemented in at least 1 potato starch production plant, reducing the remaining energy savings potential for the sector. The energy savings potential of mechanical vapour recompression has not been estimated.

Table 11
Energy efficiency measures in the starch industry identified by MIDDEN.

Measure	Savings Value 2030 compared to 2020	Comment
Membranes for concentrating potato juice	8%	Reduces the volume of potato juice that needs to be dewatered. Already applied in at least 1 plant
Mechanical vapour recompression	n/a	Already implemented in at least 1 potato starch plant. Also applicable to other starches

Vegetable oils and fats

A variety of energy efficiency measures have been identified for the vegetable oil and fats sector. Also here the energy savings for the total process have been estimated based on reported energy savings potentials per step of the process. For rapeseed and soybean oil production the steps include crushing, refining and oil modification. For palm oil production, crude palm oil is imported and there is no crushing taking place in the Netherlands. As crushing is an energy intensive process, the energy savings potentials for refining and oil modification translate to a larger total energy savings potential for palm oil production than for rapeseed and soybean oil production. A rough estimate for the technical energy savings potential based on these measures comes out to 3.7 PJ/year (out of an estimated 7.9 PJ/year energy use). The majority of the savings potential is from the use of membranes for solvent extraction for rapeseed and soybean oil (1.8 PJ) and vertical ice condensing for palm oil (about 1 PJ). It is possible that a portion of the energy savings potential has already been realized. There is also some overlap between the two degumming measures (approximately 0.1 PJ/year of the potential).

Table 12
Energy efficiency measures in the vegetable oils and fats industry identified by MIDDEN.

Measure	Savings Value 2030 compared to 2020	Comment
Membranes for solvent extraction	23%	Applicable to rapeseed and soybean oil. 50% savings compared to conventional solvent extraction. TRL 6-8
Membrane degumming	1%	Applicable to rapeseed and soybean oil. 30-50% savings compared to the conventional degumming process. TRL 6
Enzymatic degumming	2%	Applicable to rapeseed and soybean oil. Provides a higher oil yield. Potentially already implemented in the Netherlands
Enzymatic interesterification	8%	Higher share in total energy savings for palm oil (18%) as the oil modification step is a larger portion of the total energy use compared to rapeseed and soybean oil (6%)
Vertical ice condensing technology	13%	80-90% reduction for deodorization compared to traditional method. Higher total energy savings for palm oil (39%) as the oil modification step is a larger portion of the energy use compared to rapeseed and soybean oil (6-7%)
Mechanical vapour recompression	n/a	Can be combined with membrane separation

Maltings

Heat recovery is the main energy savings measure identified for the maltings industry, particularly from the kilning process which is the most energy intensive step in the maltings production process. Significant improvements have been made to the specific energy consumption for malting in previous decades, making it uncertain what exactly the remaining energy savings potentials are.

Beer brewing

A large number of energy saving measures have been identified for the beer brewing industry. For many measures the savings potentials have not been quantified. The largest measure identified is switching from batch processing to continuous processing, which can save up to 50% of the required utilities according to a Belgian brewhouse where the technology has been implemented (Meura, n.d.). The switch would require a major changes to the production facilities and its applicability to the Dutch breweries is therefore uncertain. Like the malting industry, significant improvements to the specific energy consumption for beer production have been made in the past decades, making it unclear what the remaining energy savings potentials are.

Table 13
Energy efficiency measures in the maltings and brewing industries identified by MIDDEN.

Process	Measure	Savings Value 2030 compared to 2020	Comment
Maltings	Glass tube heat exchanger	n/a	Recovers up to 20% of the energy from the ''air off'' from the malting kiln to preheat air going into the kiln. Unclear how much energy this saves in the total process
Maltings	Heat recovery with heat pumps	9%	Unclear whether this refers to mechanical vapour recompression or closed heat pumps. 9% reduction in energy consumption in the kiln which is responsible for 58% of electrical energy and 99.8% of thermal energy used in malting
Maltings	Improved process control with empirical AI models	n/a	Still in infancy but potential for the future
Beer brewing	Dynamic low pressure wort boiling	n/a	Lowers boiling time and thus thermal energy required
Beer brewing	Internal boiler	n/a	As compared to an external boiler
Beer brewing	Steam injection	6-11%	Direct steam injection in the wort kettle can reduce thermal energy required for wort boiling by 40%. Wort boiling uses approximately 20-40% of all thermal energy in breweries. Thermal energy is about 70% of total energy use in brewing.
Beer brewing	Raising the gravity (concentration) of the wort	n/a	Gives a higher yield of beer
Beer brewing	Flash/UV pasteurization	n/a	Lower heat demand than conventional pasteurization
Beer brewing	Continuous processing over batch production	50%	Halves heat and electricity demand, and prevents peak demands. Requires large changes to plants so applicability uncertain
Beer brewing	Heat recovery with vapour recompression or heat pumps	n/a	Various applications. No estimates for energy savings potential

Sugar industry

The sugar industry has also achieved large decreases in energy use since 1990, with a reduction of 50% compared to 1990 already achieved in 2016 (RVO, 2018). Considering this, there may only be a limited potential for additional energy efficiency measures. One measure identified is mechanical vapour recompression. MVR has been successfully piloted at the Cosun Beet facility in Dinteloord with energy savings of around 55 TJ/year (BlueTerra Energy Experts, 2020). While the pilot project reduced energy use by less than 2%, the remaining potential for MVR is larger.

Dairy products industry

In the dairy industry measures have been identified that can reduce the energy required for some of the most energy-intensive parts of the production process: evaporation and drying. For evaporation a part of the required thermal processes can be substituted by mechanical processes using membranes and reverse osmosis, and mechanical vapour recompression. A zeolite adsorbent can be used to make the drying process, to produce milk and whey (protein) powders, more efficient. The application of a zeolite adsorbent for spray drying has been demonstrated in the dairy industry (Topsector Energie, n.d.). Lastly, heat pumps can be used to lift the temperature of waste heat, making it suitable for pasteurization, evaporation or other processes.

Rough estimations of energy use based on the MIDDEN data show that milk powder is responsible for over half of the energy consumption in the dairy processing industry in the Netherlands. The energy savings potential for the entire sector is therefore largely dominated by the savings potentials for the milk powder production. The technical energy savings potential based on the identified measures comes out to about 3 PJ/year (out of an estimated 10 PJ/year energy use). Out of the savings potential 2 PJ/year is from the milk powder production. The application of zeolite for spray drying is the largest measure, as it has the highest energy savings potential for milk powder production. Other products with significant energy savings potentials based on these estimates are whey powder, whey protein powder and lactose.

Table 14
Energy efficiency measures in the dairy products industry identified by MIDDEN.

Measure	Savings Value 2030 compared to 2020	Comment
Closed-loop spray drying with zeolite	17%	Applied to the spray drying, so only applicable to the powder products. 40-50% savings on energy use for spray drying. Overall energy savings higher for powders (21-25%) than for protein powders (12-16%) as spray drying energy is a smaller part of total energy use for protein powders
Pre-concentrating milk or whey with membranes (reverse osmosis)	7%	Applied to the evaporation process. Larger effect for lactose (42-49%) as the initial dry matter content of lactose before water removal is relatively low, meaning that relatively more water can be removed by the application of membranes. Relative savings are 7-9% for mil and whey protein powder and 14-15% for (sweetened) condensed milk.

Measure	Savings Value 2030 compared to 2020	Comment
Mechanical vapour recompression	7%	Applied to the evaporation process. Larger effect for lactose (37%) as evaporation is a larger share of total energy use. Effect for milk and whey (protein) powders is 5-8% and 8-18% for (sweetened) condensed milk.
Heat pumps	n/a	Using waste heat and a closed heat pump system as opposed to an open MVR

3.8.5 Natural gas production

The main energy efficiency option for the Dutch natural gas production sector is the improvement of compressor efficiency. Centrifugal compressors can be restaged to improve the energy efficiency when the operational conditions of natural gas wells change over time (Serna Tamez & Dellaert, 2020). Natural gas or diesel compressors with a typical overall thermal efficiency of around 30% can be replaced by electric compressors with efficiencies of 95-99% (Serna Tamez & Dellaert, 2020) (Joshi & Bolech, 2022).

3.8.6 Plastics industry

The plastics industry is quite diverse and wide in its range of products and production processes. MIDDEN includes the following industries: PVC at Shin Etsu Botlek, polyolefins at Dow and SABIC (Chemelot), polycarbonate at SABIC Bergen op Zoom, PET at Indorama Europoort, and several other industries at the Botlek/Pernis, Chemelot and Dordrecht industrial sites.

In general the plastics industry has numerous exothermic processes which creates a prime situation for waste heat recovery and heat pumps or mechanical vapour recompression. To be able to use the recovered heat suitable heat sinks should also be available. Alternatively electricity can be produced using an Organic Rankine Cycle. Other measures identified include separation technologies like membranes and catalysts, especially in the polycarbonates industry. Short term improvements can be achieved with the optimization of equipment and processes.

3.8.7 Tyre industry

The MIDDEN report on the tyre industry looks into Apollo Vredestein as the manufacturer. No energy efficiency measures have been reported by MIDDEN.

3.9 Overview

Many energy efficiency measures have been identified by MIDDEN, both generic and sector specific. At the larger energy-intensive industries such as chemicals manufacturing, refining, and iron and steel production process optimization and energy efficiency improvements, like upgrading rotating equipment and the use of residual heat, are common practice. Further incremental improvements in energy efficiency are expected, yet estimates for remaining technical potentials are limited. Larger gains in energy efficiency require larger changes to the plants, such as the replacement of older furnaces with more energy efficient new furnaces. At integrated production sites, large adaptations for the reduction of CO_2 emissions (e.g. electric cracking) can create opportunities to reevaluate the plant energy balance and improve overall energy efficiency.

Most frequently mentioned general energy efficiency measures are waste heat use and the use of mechanical vapour recompression or industrial heat pumps. For many sectors in MIDDEN the technical potentials for the application of heat pumps and mechanical vapour recompression have not been estimated.

An overview of the identified technical energy efficiency potentials is presented in Table 15.

Table 15
Overview of the technical energy savings potentials in MIDDEN. For 2030 compared to 2020, assuming constant production level as in 2020.

Sector	Technical Potential Estimate (PJ)	Clarification
Fertilizer	0.3-0.6	Based on 0.1-0.2% annual incremental improvements 2020-2030
Iron and Steel	5	Based on 1% annual improvement 2020-2030
Inorganic Basic Chemicals	n/a	No estimate
Large Volume Organic Chemicals	16.9	Based on 1% annual improvement 2020-2030
Paper and Board	8.2	Based on the potential for MVR and heat pumps
Refineries	n/a	Waste heat potential has been estimated at 57-83 PJ/year. It is expected that a large portion of this potential is already implemented. Remaining potential is unclear.
Activated carbon	n/a	No estimate
Aluminium	n/a	No estimate
Biofuels	n/a	No estimate
Building Materials	5.3	Based on a variety of energy efficiency measures in a variety of subsectors. The highest portion in ceramics (3.3 PJ) and glass (1.7 PJ).
Food and Beverages	At least 6.7 PJ	Based on potentials in the vegetable oil and fats (3.7 PJ) and dairy industries (3 PJ). No estimates for other industries, which means the potential is higher.
Natural gas production	n/a	No estimate
Plastics	n/a	No estimate
Tyre	n/a	No estimate

4 Comparison to the P6-25 study

4.1 Overview from Project P6-25

Extensive research on energy efficiency in the Netherlands has been done previously and there is a good amount of literature on the topic. In this section we focus on a recent project that looked into innovative energy efficiency measures and their role to reduce CO_2 emissions before the end of 2025 in a cost-effective way (Siemons, et al., 2020). The study covers the majority of the manufacturing sectors in a structural way, providing a good overview for the entire industrial sector. A follow-up study was conducted to explore which portion of the identified reduction potential can be enforced with the energy saving obligation (van Lieshout & Keuken, 2021). A recent study by Berenschot used the P6-25 study as a starting point to study energy efficiency potentials with increased energy prices (van Polen, Aartsma, & Straatsma, 2022). This section describes the findings from the P6-25 study and adds discussions based on our interviews with industry. In the next section we compare the P6-25 findings with the overview from the MIDDEN database from the previous chapter.

The CO_2 emission reduction potential was validated in a study for the P6-25 project by independent parties such as Royal HaskoningDHV and PDC. The project has identified 15 innovative but mature technologies and the emission reduction potential that they could have on Dutch industry. Certain important boundary conditions have been assumed to limit the complexity of the project:

1. Only limited to Dutch industries.
2. Capital for technologies is readily available.
3. Skilled labor, including third parties, are available.
4. All projects can be realized before the end of 2025.
5. The payback period of implementing the technologies is 5 years or less including subsidies and weighted average cost of capital of 8%.
6. The 15 technologies assessed are limited to a selected number of suppliers in terms of technological configurations, parameters, etc.

The ultimate result of the P6-25 validation study was an overview of the CO_2 reduction potentials of the 15 preselected technologies (Siemons, et al., 2020). Multiple overviews had been made, considering planning limitations and economic feasibility. For the purpose of this report we focus on the technical reduction potential, as economic circumstances such as technology costs and energy prices are subject to changes throughout the years. We have also disregarded the boundary condition that projects have to be realizable before the end of 2025. For this report we have converted the P6-25 validation study technical CO_2 reduction potentials into energy reduction potentials (see Table 16). For the full calculations see Appendix 1.

In the P6-25 study, the chemicals sector (SBI 20) is broken down into industrial gases (SBI 20.11), steam crackers (SBI 20.14), nitrogen fertilizer (SBI 20.15), and the wider chemical industry (SBI 20 – (20.11+20.14+20.15).

There are many similarities between the technologies included in the P6-25 project and measures identified in the MIDDEN project. The measures include improved efficiency for electromotors, either by optimizing the existing motors or by replacing the existing motors with more efficient models.

Two types of heat recovery and use are included: flue gas heat recuperation for flue gas at temperatures of up to 200 °C and the use of high temperature heat pumps, mechanical vapour recompression and heat transformers using lower temperature waste heat (<100 °C) and increasing the temperature to a more useful level. The heat transformer is an absorption heat pump that uses a fully reversable chemical reaction to capture waste heat energy to transform it into process heat (Siemons, et al., 2020).

Five ICT measures for process optimalization were included in the P6-25 validation study: advanced process control, energy management analytics, asset management analytics, data infrastructure and digital twinning. For data infrastructure it was concluded that it will not provide energy savings by itself. Digital twinning was formally not in the scope of the project and also not studied in detail.

Three technologies were included in the separation technology category: membrane separation of hydrogen from hydrocarbons, membrane separation of nitrogen and oxygen from air and pervaporation-based ethanol drying. Only for the membrane separation of hydrogen from hydrocarbons did the validation study conclude that there is a potential for energy savings.

The power flex category included flywheels and hybrid electric boilers. The flywheels were not analysed in detail because there is no direct reduction of CO_2-emissions and application in industry is expected to be limited. Electric boilers to replace fossil-based boilers or CHPs were included in the P6-25 report. We have excluded electric boilers from the scope of this report as we consider it primarily a decarbonization measure, with a secondary benefit of improved overall energy efficiency. We have included the P6-25 energy savings potential for the use of electric boilers in Table 16 and Appendix A to provide a complete overview of the savings potentials as identified by the P6-25 validation study.

While not included in the 15 innovative technologies in the P6-25 validation study, an estimation of the potential for insulation measures was included in the appendix of the report. The assessment was done based on a literature review.

The overview in Table 16 shows that the most significant potential identified in the P6-25 validation study is waste heat recovery with heat pumps (here including mechanical vapour recompression and heat transformer). There is significant overlap between the potential of the three technologies as they partially make use of the same waste heat sources. The corrections are largest in the sectors where the largest potentials were identified (wider chemical sector and food). The potential identified for efficient electromotors, ICT measures, hybrid boilers and insulation are all also relatively large. The potentials for direct heat recuperation from flue gases and membrane separation of hydrogen from hydrocarbons are relatively modest in comparison. A correction was also made for the overlap between the measures of flue gas heat recuperation and power flex (for more refer to Appendix A or Chapter 8 in Siemons, et al. (2020)).

Table 16
Overview of technical energy reduction potentials in 2030 in the P6-25 validation study (PJ/yr) (own calculations based on Siemons, et al., 2020).

Technology groups	Motors and drives[a]	Flue gas recuperation	Heat pumps[b]	ICT[c]	Separation[d]	Power flex[e]	Insulation	Overlap	Totals
Industrial gases	0.8	0.2	0.0	0.7	0.0	4.2	0.2	-0.1	5.9
Steam crackers	1.7	1.9	4.8	2.0	0.0	0.0	5.8	-3.2	13.0
Ammonia & N- fertilizer	0.3	0.4	0.7	1.2	0.1	0.7	1.0	-0.8	3.5
Wider chemical industry	1.4	1.3	28.5	2.4	0.0	5.2	2.2	-18.3	22.7
Refineries	1.2	3.0	6.9	1.6	2.6	0.0	4.3	-3.6	16.1
Iron and steel	1.7	0.9	0.8	1.1	0.0	0.0	1.1	-0.3	5.3
Food	3.0	1.2	17.9	6.0	0.0	6.3	2.8	-10.6	26.5
Paper & board	1.1	0.4	7.4	1.3	0.0	2.2	0.7	-2.8	10.4
Other industries	-	-	-	-	-	-	-	-	16.6
Overlap correction	-	-2.5	-36.8			-0.3		-39.6	-
Totals	11.2	6.7	30.1	16.4	2.7	18.2	18.1	-	120.0

a) This includes both the optimization of electromotors and replacing electromotors with more efficient models.
b) This is a combination of three categories: high temperature heat pumps, mechanical vapour recompression and heat transformer. All three use residual heat and a form of heat pump to increase the temperature.
c) This includes three subcategories: advanced process control, energy management analytics, and asset management analytics.
d) The potentials refers to membrane separation of hydrogen from hydrocarbons. Other separation technologies were explored in the project but no theoretical potentials were identified within the project scope.
e) This refers to the application of hybrid electric boilers.

For the industrial gases sector estimates based on the P6-25 validation study come out to 1.7 PJ per year, excluding hybrid boilers. Main measures are similar to those identified in MIDDEN: improving the efficiency of electromotors, process optimization with ICT measures. Heat integration and insulation account for 0.2 PJ each. Air Liquide believes the potential for electromotors has been overestimated because many optimalisations have already been made to the electromotors (correspondence Air Liquide, 2023).

For the chemical industry, heat pumps and MVRs are very specific applications and not yet available for process temperatures above 150°C that are often required in chemical plants (Marina, Smeding, Zondag, & Wemmers, 2017). The P6-25 estimate on heat pumps and MVRs are thus an overestimation, according to Shell (interview Shell). Both Shell and DOW indicate that digitalization and ICT measures are already implemented as best as possible and that they therefore believe the remaining potential to be smaller than estimated here based on the P6-25 validation study. Insulation has a high technical potential in theory but the implementation is a challenge, because of the scale of the sites. Insulation upgrades are generally part of long-term maintenance and safety strategies and even determining the theoretical potential for insulation in big sites can be a long and difficult project. Therefore an insulation campaign would be very large with many small projects (interview Shell). For refineries the same reservations were shared by Shell about the potentials estimated for heat integration, ICT measures and insulation (interview Shell).

For the fertilizer industry the P6-25 validation study considers a savings potential for all technologies covered in the study, except for heat transformers. Excluding the potential for electric boilers, our estimate based on the P6-25 study amounts to a technical energy efficiency potential of 3.6 PJ. Based on our interview with OCI we believe the sector sees savings potential in some of the measures looked at by the P6-25 study but see the 3.5 PJ as an overestimate of the total potential for these measures. However, how much lower the potential is was also not specified during the interview.

The P6-25 study 'Wider Chemical Industry' sector is a group representing other chemical industries than industrial gases production, steam crackers and ammonia and fertilizer production. The heat Integrations categories hold the majority of the estimated technical savings potential in the wider chemical industry sector.
Tata Steel indicates that they have already been replacing motors as part of the maintenance and energy efficiency activities (interview Tata Steel Netherlands). So part of the estimated 1.7 PJ savings potential will not be available anymore. Tata Steel also says there is more potential in waste heat use and less in insulation, but there are no total potential estimates. Savings are estimated and achieved on a project basis and also depend on factors such as payback time and technical feasibility.

The P6-25 study includes the food sector, but not the beverages sector. The main potentials for the food sector are in heat pumps and mechanical vapour recompression, and ICT measures. There is significant overlap between the heat integration measures and therefore the total potential is lower. Accounting for overlap and excluding hybrid boilers the total potential estimate comes out to 26.5 PJ/year. The final energy consumption of the food industry and beverages was 80.8 PJ in 2020, which indicates that the savings potential estimate is over 30% of the total final energy use.

Also for the paper and board sector the main measures identified are heat pumps and mechanical vapour recompression. Also here there is significant overlap between the two measures (2.8 PJ/year). This aligns with the views of the sector (interview VNP). The VNP also agrees with there being potential for ICT measures, efficient electromotors and electric boilers, although the remaining potential could be lower as these measures are already being implemented in the sector (interview VNP).

The other industries potential was estimated in the P6-25 study by extrapolation based on the energy use in the eight main sectors and the remaining energy use in the industrial sector as a whole. We estimated the potential in energy terms based on the CO_2 reduction potential estimate from the P6-25 study and a standard split in natural gas and electricity use in industry (about 80% natural gas and 20% electricity).

In total, the estimated technical savings potential based on the P6-25 validation study comes out to 120 PJ/year, including electric boilers, and just over 100 PJ/year, excluding electric boilers.

4.2 Comparison to MIDDEN

The P6-25 validation study contains a number of measures that have also frequently been identified in the MIDDEN project, such as improved electromotors, heat recuperation, mechanical vapour recompression and heat pumps. Insulation was not mentioned often in the MIDDEN reports, but a significant energy savings potential was identified by P6-25. The application of membranes was limited to a specific use-case in the P6-25 study, yet we see the application of membranes also for other sectors in MIDDEN, particularly in the food and beverages sector. The P6-25 study identified a significant potential for electric boilers. Electric boilers were excluded from the scope of our study and we therefore do not have a savings potential to compare to the estimate based on the P6-25 study. Electric boilers are mentioned frequently in MIDDEN, so we do see potential for their application.

The major difference with MIDDEN is that the P6-25 study focuses on innovative technologies and therefore excludes most of the equipment upgrade potentials (except for electromotors). Yet based on the MIDDEN data and interviews with large industrial parties, we observe that there is a large potential for energy savings through improvements to existing assets (such as furnaces and rolling mills). This is also in line with earlier findings from the covenants.

A comparison between the findings from MIDDEN and the analysis based on the P6-25 study is given in Table 17. For the paper and board sector the estimates are most comparable as they are both largely based on the potential from heat pumps and mechanical vapour recompression. The measures for the refinery industry are also similar, but there is no estimate based on the MIDDEN data and interviews. The MIDDEN estimates for the fertilizer, iron and steel and organic chemistry are all based on continued yearly incremental improvements to energy efficiency and cover a wide variety of possible measures, including the replacement of existing assets with more efficient ones. These incremental improvements are not included in the P6-25 scope. The P6-25 estimates include some measures that according to the sectors are already being implemented.

Table 17
Comparison between total technical potentials 2030 (PJ/y) MIDDEN and P6-25 (excluding e-boilers).

Sector	Final energy consumption in 2020 (CBS)	Technical Potential Estimate MIDDEN	Technical Potential Estimate P6-25	Comments
Organic chemicals/ Steam crackers	176.7	16.9	13.0	MIDDEN estimate based on 1% annual improvement 2020-2030. P6-25 estimate includes measures that have already (partially) been implemented according to the sector.
Paper and Board	20.6	8.2	10.4	Both estimates mostly based on the potential for heat pumps and MVR.
Food and Beverages	80.8	At least 6.7 PJ	20.3	MIDDEN estimate only for vegetable oil and fats (3.7 PJ) and dairy industries (3 PJ). P6-25 covers all food industry, but excludes beverages.

Sector	Final energy consumption in 2020 (CBS)	Technical Potential Estimate MIDDEN	Technical Potential Estimate P6-25	Comments
Other industries	118.9	At least 5.3 PJ	n/a	MIDDEN estimate only for building materials. No estimate based on P6-25 excluding e-boilers. Including e-boilers the estimated savings potential is 16.6 PJ/y.
Iron and Steel	29.6[4]	5	5.3	MIDDEN estimate based on 1% annual improvement 2020-2030 (including on the use of production arising gases in the steel production process). The reduction of final energy consumption will be smaller. P6-25 estimate includes measures such as insulation for which TSIJ sees less potential, but excludes measures such as upgrades to furnaces.
Fertilizer	30.9	0.3-0.6	2.9	MIDDEN estimate based on 0.1-0.2% annual incremental improvements 2020-2030 covering many EE measures. P6-25 estimate includes measures that have already (partially) been implemented according to the sector.
Wider chemical industry	69.1	n/a	17.5	No estimate for MIDDEN. Largest potential from P6-25 estimate from heat pumps, MVR and heat transformers.
Refineries	128.3[5]	n/a	16.1	Largest potentials from P6-25 estimate from heat integration and insulation. The estimate for heat recovery in MIDDEN is much higher (57-83 PJ) but it is expected that much of this has already been implemented.
Industrial gases	17.1	n/a	1.7	P6-25 estimate for motors, flue gas recuperation and ICT process optimization. These measures were also identified by MIDDEN, but no potential estimated.

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[4] Excludes use of production arising gases during the steel production process. Total energy use including these gases is estimated by MIDDEN at 52.2 PJ per year for the production of 7.05 million tonnes of crude steel per year (Keys, van Hout, & Daniëls, 2019).

[5] Refers to own energy use.

5 Discussion

During the course of this study, it has proved challenging to quantify energy efficiency potentials. While companies shared insights with us in the interviews, these insights were more often of a qualitative than a quantitative nature (e.g. that an estimate is overestimated, but not by how much). The complexity of industries in terms of scale and variety makes it difficult to establish from general data how much energy can be saved. An accurate estimation requires data on the energy and mass balances of plants, sources of waste heat and suitable sinks, quality of insulation on equipment, etc. all of which requires significant site-specific study to quantify. The MIDDEN data provides a start, but is not sufficient by itself to conduct such detailed analyses. Often even the companies do not have a complete overview of savings potentials as they apply a more project-based approach for energy efficiency measures.

On the other hand there are technology based bottom-up studies such as the P6-25 validation study. These types of studies have limitations due to scoping and the necessary generalisations that have to be made across industrial sectors. While the P6-25 study corrected for many of the generalisations and performed checks with industry, the general sentiment from industry is that the potentials for the innovative technologies have been overestimated. The measures identified by MIDDEN have also been mostly derived from general literature which were brought up to the attention of the industries that have been interviewed. The qualitative nature of the answers received during the interviews could not inform on the actual technical savings potential that could be achieved by any one measure. Often the answers focused on the fact that the potential differs from plant to plant on a wide range of factors. Such factors make it a near impossible task to quantify technical potentials for a whole sector.

In summary a significant amount of uncertainty remains about energy savings potentials. This study provides additional insights, but does not remove this uncertainty. Only a handful of interviews could be conducted and they were focused on the largest industries which may or may not paint an accurate picture for the rest of the smaller industries. Every sector, industrial site, and plant is unique in operation, construction and business plans. For many sectors the measures identified by MIDDEN have not been checked with industry and have been merely summarized in a single report. Additionally, estimating technical potential savings is not prioritized by the companies mostly due to the reason that they are focused on the practical and achievable savings.

This study does not look into practical savings potential, but only technical. Companies have to go through an elaborate procedure to implement energy efficiency measures along the course of which they face several barriers. So even though technically the potential may be there, only a part of that can practically be achieved. Main barriers identified in the interviews are: financial constraints, lack of knowledgeable labour who know which plants would benefit from which measure, energy efficiency not being a priority for the managers, validation of technology, and timing issues regarding turnaround.

Energy efficiency measures can be costly depending on the scale of the measure and other factors. Low capital availability in the industries along with high investment costs surrounding energy efficiency measures poses the main financial barrier. DOW Chemical mention in their interview how the complexity of projects can increase the implementation cost by as much as a factor of 5 compared to what is assumed by general energy efficiency studies like the P6-25 validation study.

Considering current national climate targets and polices, decarbonization is above energy efficiency on the agenda of the industries. The bulk of the financial investments available to industries are likely to go to decarbonization projects thus worsening the business case for energy efficiency measures. Existing subsidy schemes do not always fit with the specific solutions developed by companies,

The most prevalent sentiment in the interviews conducted was the unavailability of labour and people in industry who have the knowledge and skills to identify inefficiencies and opportunities and to implement the measures. Hiring external consultants can be expensive and time-consuming. Moreover, extreme energy prices have forced some industries to reduce production or even (partially) shut down production, which makes it an inopportune time for industry managers to focus on new investments – even if these investments (in energy efficiency) could reduce costs. Decarbonization still being at the peak of priorities means that there is more focus on electrification. There is also a technical and economic knowledge gap between industries and technology providers and proof of concept of a technology does not guarantee their applicability in a particular site. This can create a barrier between technical and achievable savings. Pilot projects have been recommended by industry experts to solve this problem. Overall, a set of financial constraints, organisational underplaying and a lack of in-house knowledge and skills creates the big gap between technical potential and realisable savings.

Decarbonization projects in some cases can actually increase the energy use of the company, for instance by applying CCS or hydrogen combustion. Energy efficiency falls behind in terms of priority which increases the gap between technical and achievable savings. Energy efficiency could counteract the increase in energy use from decarbonization projects. Additionally, turnarounds during decarbonization projects are natural moments for energy efficiency projects to be implemented. The plant’s energy and mass balances are re-assessed and better insights can be gained into the possible improvements. If an efficiency measure did not make a good business case previously, considering that production had to be stopped to implement it, it is more likely to make sense when the plant is altered for decarbonization projects. This avoids turnaround for implementing energy efficiency projects for another time.

Currently the energy savings obligation is in effect which makes it obligatory for companies to implement measures with a payback period of 5 years or less. According to interviews the enforcement of the obligation also suffers from the lack of personnel and expertise at the authorities responsible for the enforcement.

Interviews with the companies indicated that a high energy cost does not automatically make energy efficiency projects accelerate. The issue of investment cycles and implementation time contribute majorly to the practical issues that mostly outweigh the cost reduction that is to be achieved from the energy efficiency measure. The assumption about the implementation of energy efficiency measures being directly facilitated by high energy costs is not particularly true in the current situation.

References

Abeelen, C. (2019). Implementation of energy efficiency projects by manufacturing companies in the Netherlands. PhD Thesis.

Batool, M., & Wetzels, W. (2019). Decarbonisation options for the Dutch fertiliser industry. © PBL Netherlands Environmental Assessment Agency; © ECN part of TNO.

BlueTerra Energy Experts. (2020). Resultaten project Flex-TDR Cosun Beet Company Dinteloord. Royal Cosun.

Boulamanti, A., & Moya Rivera, J. (2017). Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry. JRC.

Bresier, J. (2020). Decarbonisation of the Dutch ceramic industry. A techno-economic analysis of decarbonisation technologies. Delft: TU Delft.

Cabot. (2015). Sustainability report.

Cabot. (2016). Sustainability report.

CBS. (2022, May 12). CBS Statline Energy Balance Sheet; supply and consumption, sector. Retrieved from https://opendata.cbs.nl/statline/#/CBS/en/dataset/83989ENG/table?ts=1683891065999

Cioli, M., Schure, K., & van Dam, D. (2021). Decarbonisation options for the Dutch industrial gases production. PBL Netherlands Environmental Assessment Agency; TNO.

Den Ouden, B., Lintmeijer, N., & Van Aken, J. (2017). Electrification in the Dutch process industry: In-depth study of promising transition pathways and innovation opportunities for electrification in the Dutch process industry. Utrecht: Berenschot Group.

Dhas, S. (2021). Decarbonisation pathways for the cement industry.

Dutch Emissions Authority (NEa). (2023, 24 03). CO2-efficiëntiecijfers 2018-2021. Retrieved from https://www.emissieautoriteit.nl/documenten/publicatie/2023/03/24/co2-efficientiecijfers-2018-2021

Ecofys & Berenschot. (2018). Roadmap for the Dutch Chemical Industry towards 2050. VNCI.

Ecofys; Berenschot. (2018). Roadmap for the Dutch Chemical Industry towards 2050. VNCI.

Eerens, H., & van Dam, D. (2022). Decarbonisation options for large volume organic chemicals production, DOW chemical Terneuzen. The Hague: PBL.

Energeia. (2022, November 14). Retrieved from https://energeia.nl/energeia-artikel/40104139/slechts-kleine-groep-bedrijven-voldoet-aan-besparingsplicht

European Industrial Insulation Foundation. (2021). The insulation contribution. European Industrial Insulation Foundation.

IEA. (2022). The Future of Heat Pumps. IEA.

Industry & Energy. (2022, January 24). Air Liquide builds energy efficient Air Separation Unit at Moerdijk. Retrieved from Industry & Energy: https://www.industryandenergy.eu/energy-efficiency/air-liquide-builds-energy-efficient-air-separation-unit-in-moerdijk/

Joshi, J., & Bolech, M. (2022). Decarbonisation options for the Dutch onshore gas and oil industry. PBL.

Kapeluszna, E., & Kotwica, Ł. (2022). The Effect of Various Grinding Aids on the Properties of Cement and Its Compatibility with Acrylate-Based Superplasticizer. Materials (Basel).

Keys, A., van Hout, M., & Daniëls, B. (2019). Decarbonisation options for the Dutch steel industry. PBL Netherlands Environmental Assessment Agency; ECN part of TNO.

Krijgsman, R., & Marsidi, M. (2019). Decarbonisation options for the Dutch glass wool industry. Den Haag: PBL.

Marina, A., Smeding, S., Zondag, H., & Wemmers, A. (2017). A bottom-up approach for determining the European Industrial Heat Pump Potential. ECN.

Maruf, M., Morales-España, G., Sijm, J., Helistö, N., & Kiviluoma, J. (2022). Classification, potential role, and modeling of power-to-heat and thermal energy storage in energy systems: A review. Sustainable Energy Technologies and Assessments.

Meura. (n.d.). The Meurabrew: the brewhouse of the future! First industrial results. Retrieved from https://www.meura.com/documents/casestudy/nl10themeurabrew.pdf

Ministry of Economic Affairs and Climate. (2023). Kamerbrief openstelling SDE++ 2023, DGKE-DSE / 26117178.

Netherlands Enterprise Agency. (2015). Covenant results brochure: Long-Term Agreements on energy efficiency. Netherlands Enterprise Agency.

Oliveira, C., & Schure, K. (2020). Decarbonisation options for the Dutch refinery sector. PBL Netherlands Environmental Assessment Agency; TNO.

Papadogeorgos, I. (2019). Decarbonisation of the Dutch Container Glass Industry by 2050: A model-based analysis of technology options.

Papadogeorgos, I., & Schure, K. (2019). Decarbonisation options for the Dutch container and tableware glass industry. PBL Netherlands Environmental Assessment Agency; TNO.

Paulus, J. (2022, April 4). Energy efficiency is the best choice for Europe's energy sovreignty. Retrieved from Heinrich Böll Stiftung: https://eu.boell.org/en/2022/04/04/energy-efficiency-best-choice-europes-energy-sovereignty

Project 6-25. (2020). Project 6-25 Technology Validation. RHDHV & PDC.

Rademaker , K., & Marsidi, M. (2019). Decarbonisation options for the Dutch paper and board industry. PBL Netherlands Environmental Assessment Agency; ECN part of TNO.

Roland Berger. (2021). Haalbaarheidsstudie klimaatneutrale paden TSN IJmuiden.

RVO. (2018). Resultatenbrochure covenanten [brochure of results from covenants].

RVO. (2021). Resultatenbrochure covenanten. Meerjarenafspraken energie-efficiëntie.

Saunders, H. D., Roy, J., Azevedo, I. M., Chakravarty, D., Dasgupta, S., Rue du Can, S. d., . . . Wei, T. (2021). Energy Efficiency: What Has Delivered in the Last 40 Years? Annual Review of Environment and Resources.

Scherpbier, E., & Eerens, H. (2021). Decarbonisation options for the Dutch chlor-alkali industry. PBL Netherlands Environmental Assessment Agency; TNO.

Scherpbier, E., & Eerens, H. (2021). Decarbonisation options for the Dutch salt industry. The Hague: PBL.

Schleich, J. (2007). The economics of energy efficiency: Barriers to profitable investments. EIB Papers, ISSN 0257-7755; European Investment Bank (EIB), Luxembourg, Vol. 12, Iss. 2, pp. 82-109.

Serna Tamez, A., & Dellaert, S. (2020). Decarbonisation options for the Dutch offshore natural gas industry. PBL.

Siemons, J., Katakwar, P., Croezen, H., Helmi, A., Pol, E. v., Blahusiak, M., . . . Verkaik, N. (2020). Project 6-25 Technology Validation. RHDHV & PDC.

Topsector Energie. (n.d.). Hergebruik van latente warmte van (sproei)drogers m.b.v. innovatieve zeoliet warmtepomp. Retrieved from Topsector Energie: https://projecten.topsectorenergie.nl/projecten/hergebruik-van-latente-warmte-van-sproeidrogers-mbv-innovatieve-zeoliet-warmtepomp-18966

U.S. Department of Energy. (2003). Industrial Heat Pumps for Steam and Fuel Savings. U.S. Department of Energy.

van Lieshout, M., & Keuken, H. (2021). Handhaafbaar gedeelte kosteneffectief CO2-reductiepotentieel in de Nederlandse industrie. Royal Haskoning DHV & PDC.

van Polen, S., Aartsma, G., & Straatsma, R. (2022). Energiebesparing in de industrie. Utrecht: Berenschot.

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production.

Wong, L., & Dril, T. v. (2020). Decarbonisation options for large volume organic chemicals production, Shell Moerdijk. PBL Netherlands Environmental Assessment Agency; TNO.

Xavier, C., & Oliveira, C. (2021). Decarbonisation Options for the Dutch Cement Industry. The Hague: PBL Netherlands Environmental Assessment Agency; TNO.

Xavier, C., & Oliveira, C. (2021). Decarbonisation options for the Dutch silicon carbide industry. The Hague: PBL.

Xu, Z., Mao, H., Liu, D., & Wang, R. (2018). Waste heat recovery of power plant with large scale serial absorption heat pumps. Energy.

Zier, M., Stenzel, P., Kotzur, L., & Stolten, D. (2021). A review of decarbonization options for the glass industry. Energy Conversion and Management: X.

Appendices

Appendix A - Calculations based on the P6-25 validation study

The P6-25 validation study reported the potential impact of energy savings in terms of CO_2 reduction in 2025. For some measures the report also mentions energy savings potentials in petajoules, but for many measures these energy savings potentials are not mentioned. We have calculated the energy savings potential in PJ based on a number of assumptions. In this Appendix we specify the calculations and our resulting estimates of the energy savings potentials in petajoules based on the P6-25 validation report.

Table 18 shows the general assumptions for emission factors and efficiencies that were used for the calculations. These are based on the P6-25 validation study report and a phone call with Marit van Lieshout, one of the authors of the report.

Table 18
General assumptions for the calculations to convert the P6-25 CO_2-emissions reductions to energy savings potentials.

Assumptions	Value
Emissions intensity electricity 2020	0.582 kg CO_2/kWh
Emissions intensity electricity 2025	0.56 kg CO_2/kWh
Emissions factor natural gas	0.20376 kg CO_2/kWh
COP HT heat pump	4
COP MVR	7.5
Efficiency gas boiler	90%
Efficiency electric boiler	99%

We also made assumptions on which energy carrier is referred to when energy savings are mentioned for the various measures:

- For motors and drives all savings are assumed to be electricity.
- For heat integration all savings are assumed to be natural gas, but for heat pumps and MVR there is an increase in electricity use.
- For ICT measures a split of 80% natural gas and 20% electricity is assumed as this is approximately the energy use split for industry.
- For separation and insulation all savings are assumed to be natural gas.
- For electric boilers savings are assumed to be natural gas but there is an increase in electricity use. A correction was made to account for the electricity production of CHPs.
- For the “other industries” category we also assume a 80% natural gas and 20% electricity split based on the average energy use in industry.

Lastly, we decided to disregard two limitations used in the P6-25 validation study that were relevant for the P6-25 project with the focus on 2025. For us the 2025 limitation does not hold the same weight. By disregarding the two limitations we come to a technical savings potential that is more applicable to the 2030 timeframe (or beyond). The two limitations disregarded are:

1. Limitations due to turnaround planning of more than 5 years. Without a specific year in focus for this report we do not see a need to limit the savings potential to measures that can be planned in turnarounds that will happen within 5 years.
2. Limitations due to the use of heat from CHPs. The P6-25 study assumes that heat pumps and MVR only replace heat produced by CHP up to 250 °C. It assumes that it is not yet cost effective to replace CHPs and provide all of the heat up to 250 °C with heat pumps. They therefore limit the amount of heat from CHPs that can be replaced by heat pumps and MVR. The P6-25 validation report mentions that by 2030 replacing all CHPs with heat pumps could be more interesting as there is expected to be an abundance of renewable electricity. We therefore remove the limitation on the amount of CHP heat that can be replaced with heat pumps and MVR. We maintain the limit of 250 °C and assume heat above this temperature is not provided by heat pumps and MVR.

The potential of some of the technologies is overlapping, which is why corrections were made to two groups of measures in line with corrections that were made in the P6-25 validation study. These are:

1. Overlap between high temperature heat pumps, mechanical vapour recompression and heat transformers. These all assume the use of low temperature waste heat, which is why there is overlap between the combined potential. There is no overlap with the flue gas recuperation measure as it was assumed that high temperature residual heat is used for that. The heat pump potential is reduced by 75% to account for overlap with the MVR potential. For sectors with potential for heat transformers the MVR and heat pumps potential is reduced by 75% to account for overlap with the heat transformer.
2. Overlap between flue gas recuperation and hybrid boilers. It is argued that there is overlap because hybrid boilers are used to balance CHPs but if flue gas recuperation is applied then the CHP may no longer be required. So that there are instances when either flue gas recuperation or hybrid boilers will be applied and not both. As a result the combined potential for these two technologies is halved for the fertilizer industry. For the wider chemical sector, food sector and paper sector the smallest of the two potentials is divided by four.

Table 19 shows the starting point: the technical savings potential identified by the P6-25 validation study in terms of kton CO_2/year.

Table 20 shows our converted table of technical energy savings potential in PJ per year, based on the P6-25 validation study.

Table 19
Feasible technical energy savings potential from the P6-25 validation study (kton CO_2/year)

Technology groups	Motors and drives		Heat integration				ICT			Separation	Power flex	Insulation	Total
Industrial sectors	High efficiency electromotors	Electromotors system optimalization	Flue gas recuperation	HT heat pumps	Mechanical vapour recompression	Heat transformer	Advanced process control	Energy management analytics	Asset management analytics	Membranes	Hybrid boilers	Insulation	Total
Industrial gasses	14	51	5	0	0	0	26	14	16	0	90	13	229
Steam crackers	30	112	55	16	24	29	74	36	39	0	0	326	741
Ammonia & N- fertilizer	6	22	10	3	4	0	49	21	19	3	10	56	203
Wider chemical industry	41	146	59	208	212	130	78	33	76	0	90	126	1199
Refineries	21	80	85	25	38	76	65	31	29	73	0	244	731
Iron and steel	48	221	49	8	13	0	46	23	17	0	0	64	479
Food	160	322	67	287	189	27	213	125	123	0	130	161	1755
Paper & board	27	157	20	58	98	0	45	28	28	0	50	37	536
Other industries	-	-	-	-	-	-	-	-	-	-	-	-	806
Totals	347	1111	350	605	578	262	596	311	347	77	370	1027	6787

Table 20
Technical energy savings potential based on the P6-25 validation study (PJ/year)

Technology groups	Motors and drives		Heat integration				ICT			Separation	Power flex	Insulation	Overlap	Total
Industrial sectors	High efficiency electro-motors	Electro-motor system optimalization	Flue gas recuperation	HT heat pumps	Mechanical vapour recompression	Heat transformer	Advanced process control	Energy management analytics	Asset management analytics	Membranes	Hybrid boilers	Insulation	Overlap	Total
Industrial gasses	0.1	0.6	0.2	0.0	0.0	0.0	0.3	0.2	0.2	0.0	4.2	0.2	-0.1	5.9
Steam crackers	0.3	1.4	1.9	1.8	2.0	1.0	1.0	0.5	0.5	0.0	0.0	5.8	-3.2	13.0
Ammonia & N- fertilizer	0.1	0.3	0.4	0.3	0.3	0.0	0.6	0.3	0.2	0.1	0.7	1.0	-0.8	3.5
Wider chemical industry	0.3	1.1	1.3	14.8	10.8	2.9	1.0	0.4	1.0	0.0	5.2	2.2	-18.3	22.7
Refineries	0.2	1.0	3.0	2.0	2.2	2.7	0.9	0.4	0.4	2.6	0.0	4.3	-3.6	16.1
Iron and steel	0.3	1.4	0.9	0.4	0.4	0.0	0.6	0.3	0.2	0.0	0.0	1.1	-0.3	5.3
Food	1.0	2.0	1.2	11.8	5.6	0.5	2.8	1.6	1.6	0.0	6.3	2.8	-10.6	26.5
Paper & board	0.2	1.0	0.4	3.4	4.1	0.0	0.6	0.4	0.4	0.0	2.2	0.7	-2.8	10.4
Other industries	-	-	-	-	-	-	-	-	-	-	-	-	-	16.6
Overlap correction	-	-	-2.5		-36.8						-0.3		-39.4	-
Totals	2.4	8.7	6.7		30.1		7.7	4.0	4.5	2.7	18.2	18.1	-	120.0