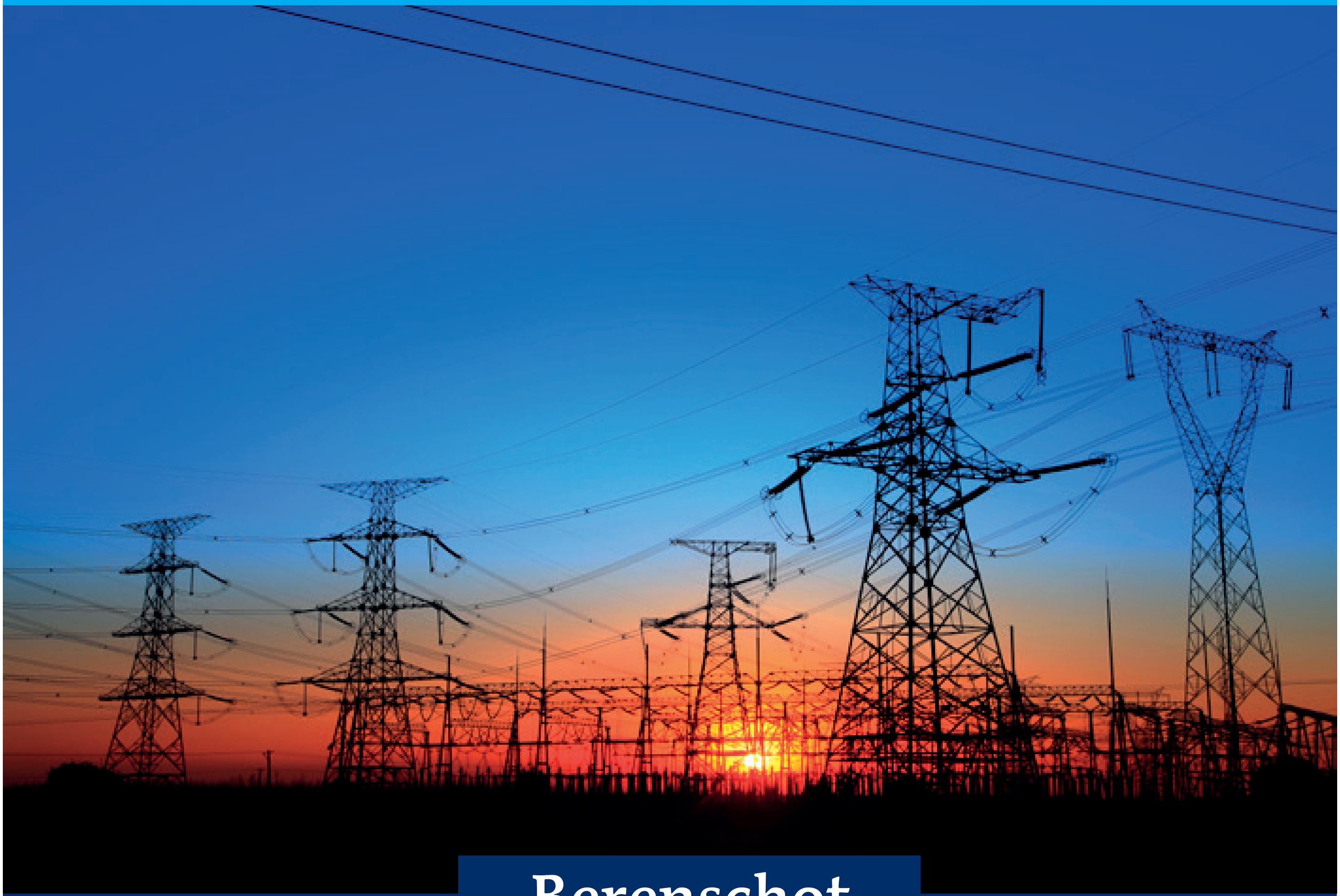

Berenschot

Electrification in the Dutch process industry

In-depth study of promising transition pathways and innovation opportunities for electrification in the Dutch process industry

8 februari 2017

Electrification in the Dutch process industry

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February 8th, 2017

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Berenschot

Content

Management summary

Electrification is one of the possible transition pathways for the Dutch process industry to contribute to an environmentally sustainable economy. As the Dutch process industry accounts for approximately one third of total energy use in the Netherlands, the use of (sustainable) electricity in the industry can have a significant impact on CO_2-reduction in the Netherlands. However, a clear overview of promising technologies and innovation opportunities for electrification in the Dutch process industry is lacking. The purpose of this study is therefore to explore the opportunities and barriers of electrification in the Dutch process industry, and to provide perspectives on how the Netherlands might obtain a distinctive international innovation position in this area.

Trends in industrial energy use and market developments

In general, it is expected that industrial energy demand – for the majority consisting of heat – can be reduced to a certain extent by energy efficiency measures and industrial symbiosis. For the remaining heat demand, four transition pathways are foreseen: geothermal energy, bioenergy (predominantly for niche applications), Carbon Capture Utilization and Storage (CCUS) and electrification.

It is important to note that electrification in itself does not achieve a CO_2-neutral situation, unless the electricity input is in turn CO_2-neutral. In this regard, it is expected that intermittent sources (such as solar and wind) are very unlikely to satisfy the full need of the industrial heat demand. Apart from that, one has to consider that electrification on the basis of renewable power resources is also relevant in other sectors (i.e. transport, built environment).

Despite the growth of renewable sources, most scenarios show that towards 2030 the average electricity price is expected to rise. This means that electricity will not necessarily become cheaper than fossil fuel sources (such as natural gas), which complicates the business case for several electrification strategies. At the same time it is expected that price volatility will increase, implying that electricity may be cheap on certain, generally off-peak moments. This offers perspective for flexible electrification strategies, as described below.

Electrification strategies

Two distinct strategies for electrification have been identified. These are linked to electrification technologies, the energy system, and the way industrial production processes are organised:

- *Flexible electrification*: This type of electrification is aimed at the part-time electrification of processes. The associated technologies are able to undergo starts and stops, ramp up and ramp down, or have the ability to switch between electricity and other modes, in order to accommodate the output fluctuations of renewable electricity supply. Flexible electrification profits from time-dependent price arbitrage between electricity and conventional energy carriers (mostly natural gas), and from additional value in the electricity system such as the balancing market and ancillary services. The number of operating hours of the electrification technology typically depends on the ample supply of (intermittent) renewable electricity combined with the (variable) hours of low electricity demand in general.

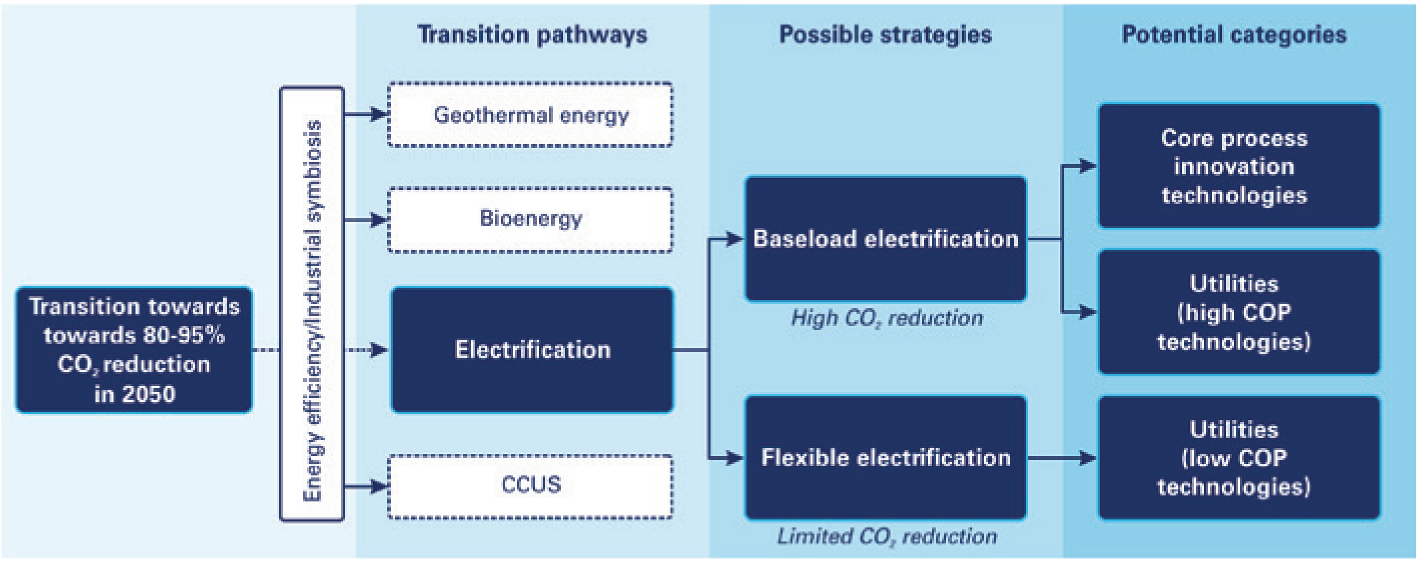
- *Baseload electrification*: Electrification in a baseload fashion. This type of electrification is less attuned to the power system of the future; it can use renewable electricity when available, but other electricity generation technologies need to be present for other moments.

In addition, two application areas have been identified:

- *Electrification in utilities*: Electrification technologies implemented in the industrial utilities, meaning the systems servicing the process but not being core to the process.

- *Electrification in core process or primary process streams:* Electrification technologies that require a change to the process itself.

Some of the identified technologies are suitable for flexible electrification, whereas other technologies are more suited to baseload electrification. For flexible electrification, the extent of fluctuations in the electricity price, the volatility, is relevant. For baseload electrification, the Coefficient of Performance (COP) of technologies is important in utility processes, since the average wholesale price of electricity is not expected to drop (and thus not providing incentives for electrification on itself). An overview of electrification as a promising transition pathway is shown in the figure below.



Promising electrification technologies

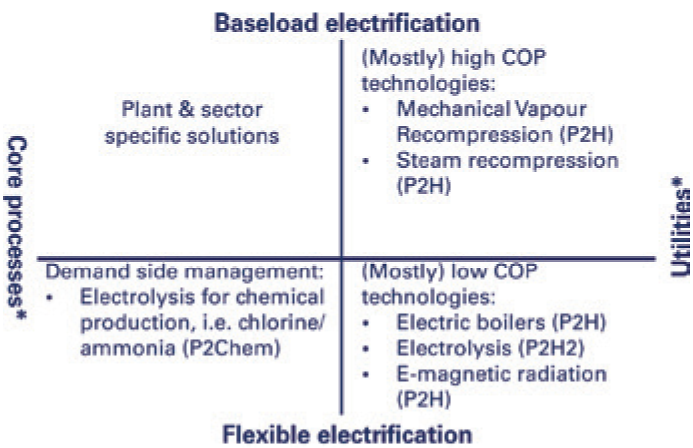
Against this background, an analysis of 1) foreign best practices, 2) current electrification initiatives in the Netherlands, 3) expert interviews and 4) workshops with stakeholders, led to the following overview of electrification categories and promising electrification technologies on the short, medium and long-term.

	Short term 0-5 years	Medium term 5-10 years	Long term 10-30 years
Breakthrough of electrification categories & promising technologies	High potential: Power to Heat • Steam recompression / Mechanical Vapour Recompression (baseload) • Electric boilers (flex) • Electromagnetic radiation (baseload / flex) • HT heat pumps (baseload / flex) →		
	Limited potential: Power for Mechanical Drive • Replacement of steam drive by electric drive (baseload)		
	High potential: Power to Chemicals • Electrolysis for chemical production, i.e. chlorine / ammonia (DSM)* (flex)		
		Limited potential: Power for Separation • Ultra filtration/Nano filtration/Reversed osmosis (baseload)	
			High potential: Power to Hydrogen • Electrolysis (flex)
			Limited potential: Power to Gas • Electro synthesis (baseload/flex)

* For Power to Chemicals, flexible production of chlorine seems most promising. This does not lead to an increase of electrification, but rather to a more flexible power consumption (demand side management)

Power to Heat shows a high potential and a wide range of technologies, applications (sectors, processes, utilities) and parties involved, both in the Netherlands and abroad. Power to Hydrogen has high potential, but is not economically feasible for large-scale application in the current situation, due to the high CAPEX. This category is both relevant in core processes (for instance in producing ammonia), as it is in utility processes. Power to Gas options have a more limited potential than Power to Hydrogen, although both categories might become interesting in the long term. Power to Chemicals is regarded as high potential, showing a wide variety of initiatives; some of them commercial (DSM in chlorine production), but to a large extent in the starting phase (ammonia, formic acid). Electrification for Mechanical drive shows a limited potential, but the unit power levels can be very high. Power for Separation will have a limited potential and is mainly focused on the food industry.

The implementation of flexible electrification (e.g. power to heat boilers) seems to become economically feasible with the increase of price volatility. It is expected that the implementation of this type of electrification mainly applies to utility-related processes. Compared to the electrification of most primary processes, the implementation threshold of utility electrification is perceived as relatively low, as it does not require a complete redesign of primary processes. Yet, certain barriers need to be overcome to meet the full potential of these options. For electrification options that do require a redesign of primary processes, the implementation threshold is very high in most cases due to the sensitivity of process modifications.



**Some technologies may be applied in core processes rather than in utilities (sector specific)*

New roles and business models: ESCOs

The flexible operation of utility processes shows high potential, and creates opportunities for third parties to become involved. As most industries are not interested in coordinating the flexible operation of their assets, outsourcing these activities towards new market players might become essential. Therefore, Energy Service Companies (ESCOs) that coordinate the operation of flexible electrification, need to be put in place. Again, this opportunity is mainly applicable for technologies that operate in utility processes. A possible role for energy companies is foreseen here.

For the involvement of ESCOs, four options (or a combination of the four) may be conceivable: commodity based, services based, financially based and in a joint venture structure. These options are described in chapter 6.2.

Development needs

In order to fully adopt the potential for electrification in the Dutch process industry, and to obtain an innovative position in this field, certain barriers need to be overcome. These barriers, or constraints for further development, were translated into development needs, necessary for the successful commercial breakthrough of electrification and are shown in the figure below. An explanation of these barriers and subsequent development needs are given in chapter 6.3 and 6.4.

			Actor						
Barriers	**Development needs**	**Category**	**Government**	**Process industry**	**Manufacturing industry**	**Grid Operators**	**Knowledge institutions**	**Energy producers**	**Time schedule (short, medium, long term)**
Absence of long-term view on electrification	Outlook on electrification as a transition route	Regulatory	x	x		x	x		Short term
Lack of cooperation between stakeholders	Close cooperation between stakeholders in triple helix structure	Organizational	x	x	x	x	x	x	Short term
Limited temperature application of heat pumps	Focus on research & development of high temperature heat pumps	Technological	x	x	x		x		Short term
Absence of financial incentives	Stimulation of promising technology development	Economic Technological	x	x			x		Short term
Over-emphasis of utility electrification	Focus on redesign of primary processes	Technological		x	x		x		Medium term/ long term
Lack of guaranteed renewable electricity supply	Expansion of renewable electricity production capacity	Technological Regulatory	x	x		x		x	Short term/ long term
Lack of knowledge/ available information	Development of demonstration projects	Technological Organizational		x	x		x		Short term
Absence of financial or fiscal incentives	Funding for demonstration projects	Economic Regulatory	x						Short term
Lack of knowledge/ available information	Communication on best practices	Organizational	x				x		Short/medium term
High CAPEX for required payback times	Establishment of new business models (ESCOs)	Organizational			x		x	x	Medium term
High costs for increased grid tariffs	Adaptation of electricity tariff structures	Economic Regulatory	x			x			Short term
High costs for increased grid capacity	Reassessment of grid connection costs	Economic Regulatory	x			x			Short term
Energy taxes currently in favour of gas	Reassessment of energy taxes	Economic Regulatory	x						Short term/ Medium term
High CAPEX for required payback times	Maintenance of energy efficiency policies	Regulatory	x						Medium term/ long term
Absence of financial or fiscal incentives	Guarantee schemes & revolving funds	Regulatory	x						Medium term/ long term

Focal areas for innovation and implementation

One of the objectives of this study has been to provide perspectives on how the Netherlands can occupy a distinctive international innovation position with regard to electrification. The current innovation landscape in the Netherlands can be seen as an important opportunity here. It has been found that the triple helix structure of government, knowledge institutions and industry, together with a distinct ‘industry and energy landscape’ (i.e. a large concentration of industry in a geographically small area in the context of an energy transition), provides a fruitful ground for research and development of electrification.

The development needs as described in paragraph 6.3 give an indication of the necessary steps in order to facilitate a breakthrough of electrification in the Netherlands. Potentially, some of these development needs enable the movement towards a more innovative international position with regard to innovation. In this respect, four focal areas emerge:

- *Development for application-ready concepts of high temperature heat pumps.* To be able to realise the technical and commercial potential of Power to Heat, higher temperature levels of heat pumps need to be achieved. This is an important development priority for the Dutch industry, but can also lead to large international exposure. A focus on the establishment of triple helix partnerships for research and development of high temperature heat pumps is recommended.

- *Establishment of new business models and market roles (ESCOs).* In the Netherlands and abroad, there is a growing opportunity for aggregators or energy service companies (ESCOs) to become a counterpart of industries. These business models or financial structures are not mainstream yet, but could become interesting best practices for the implementation of energy efficiency measures in an international context. Possible ESCO structures are mentioned in paragraph 6.1.

- *Concepts for intermittent electrification.* In an international context, electrification measures are mainly applied in a baseload fashion. For the Netherlands, the application of flexible electrification (responding to the intermittent character of renewable electricity sources) provides opportunities. This model would also be applicable in other countries that are increasingly depending on renewable sources, such as Germany. The development of strong concepts for flexible electrification (e.g. power to heat, chemicals, hydrogen and peak shaving) could therefore become a desirable innovation abroad. The development of this opportunity would require technical, operational, financial and organisational measures, such as the adaptation of electricity grid tariff structures and possibly the development of ESCOs, as described in paragraph 6.2.

- *Focus on the implementation of high COP technologies.* As analysed in this study, high Coefficient of Performance (COP) technologies such as Mechanical Vapour Recompression (MVR) and steam recompression show high potential for electrification, even in a baseload fashion. Thus, these technologies become interesting for reducing CO_2-emissions regardless of the increasing power prices as depicted in this report. We identify these technologies as a main focus area for the implementation of electrification in the Netherlands.

Introduction

Chapter 1

Our energy system is in the middle of a rapid transition towards more sustainable solutions. Recently, 192 countries agreed on limiting global warming to well below two degrees Celsius during the COP21 in Paris. This means that measures need to be put in place to reduce carbon emissions with 80-95% in 2050 as compared to 1990. Although this transition still comes with many uncertainties, some promising transition pathways towards a more sustainable energy supply are slowly taking shape. One of these pathways is the electrification of industrial processes, which involves opportunities and challenges for both suppliers and end consumers.

1.1 Background

The Dutch process industry accounts for approximately 46%[1] of total energy use in the Netherlands and is therefore an important player in the energy transition. With 250.000 employees and yearly revenues of around 124 billion euros, it also represents an important sector in the Dutch economy. Reducing CO_2-emissions in the process industry entails a number of challenges for the Netherlands:

- In the total industrial energy demand, heat demand is substantial. For the Netherlands as a whole, the heat energy demand is three times bigger than the electricity demand. Within energy-intensive industry, the demand for heat versus electricity is even bigger. In general, reducing CO_2-emissions in heat demand is more difficult than for other purposes.

- Compared to other countries, the Netherlands has an energy intensive process industry, fuelled by a long tradition of abundant availability of comparatively low cost fossil energy sources. A transition to a sustainable non-fossil energy supply is therefore a big challenge in comparison with other countries with less industrial presence.

- Dutch industry is often physically concentrated in production clusters. The processes are networked together as in an industrial ecosystem, where there are many linkages between energy and material flows. These organically grown clusters are optimised. This means that changes in the configuration of energy supply can have huge impacts.

- The energy transition that is envisioned for the Dutch energy system will, to a great extent, depend on a switchover to fluctuating and intermittent energy sources: offshore wind, wind on land and solar energy. This poses challenges in maintaining the balance between supply and demand for energy, especially in the electricity system. On the long term, new flexibility mechanisms are needed.

In decreasing carbon emissions in the process industry, several transition routes are foreseen. Electrification of industrial processes is seen as one of them, where the conversion of electricity from renewable sources could offer a promising solution to replace conventional energy sources, enable new processes, and contribute to energy and resource efficiency.

1 Including feedstock use (see chapter 3.1)

1.2 Problem definition and approach

The Dutch government has different instruments available to implement sustainability in the energy-intensive industry. The Top Consortia for Knowledge and Innovation (TKI) Energy and Industry coordinates an energy-centred innovation program, decides on research strategies and works on the dissemination of knowledge, promising technologies and implementation methods. To ensure effective policy, there is a need for a better understanding of technological electrification options and the most promising transition pathways herein for the energy intensive process industries in the Netherlands. In addition, a better insight into business and market models is required as well as the necessary services to facilitate a broad breakthrough of electrification in the process industry. The underlying objective is to provide perspectives on how the Netherlands might occupy a distinctive international innovation position with regard to electrification.

This study was conducted in three phases. In the first phase, foreign and Dutch initiatives in the area of industrial electrification have been explored. This is predominantly based on desk study and expert interviews (a list of experts consulted can be found in Annex D). In addition, characteristics of the Dutch process industry were described as well as the expected energy use on the short, medium and long term.

The second phase focused on interaction with stakeholders. Because the implementation of electrification requires a cross-sectoral approach, a broad stakeholder analysis was conducted. Different (representatives of) stakeholder groups were interviewed about their vision, drivers and expectations towards electrification. In addition, two workshops with industrial parties were organised in which technology needs were identified. In the last phase, a roadmap was drawn up, providing insight into the most promising transition pathways for electrification (on the short, medium and long-term) and the necessary steps allowing electrification to break through.

Figure 1. Schematic overview of project approach

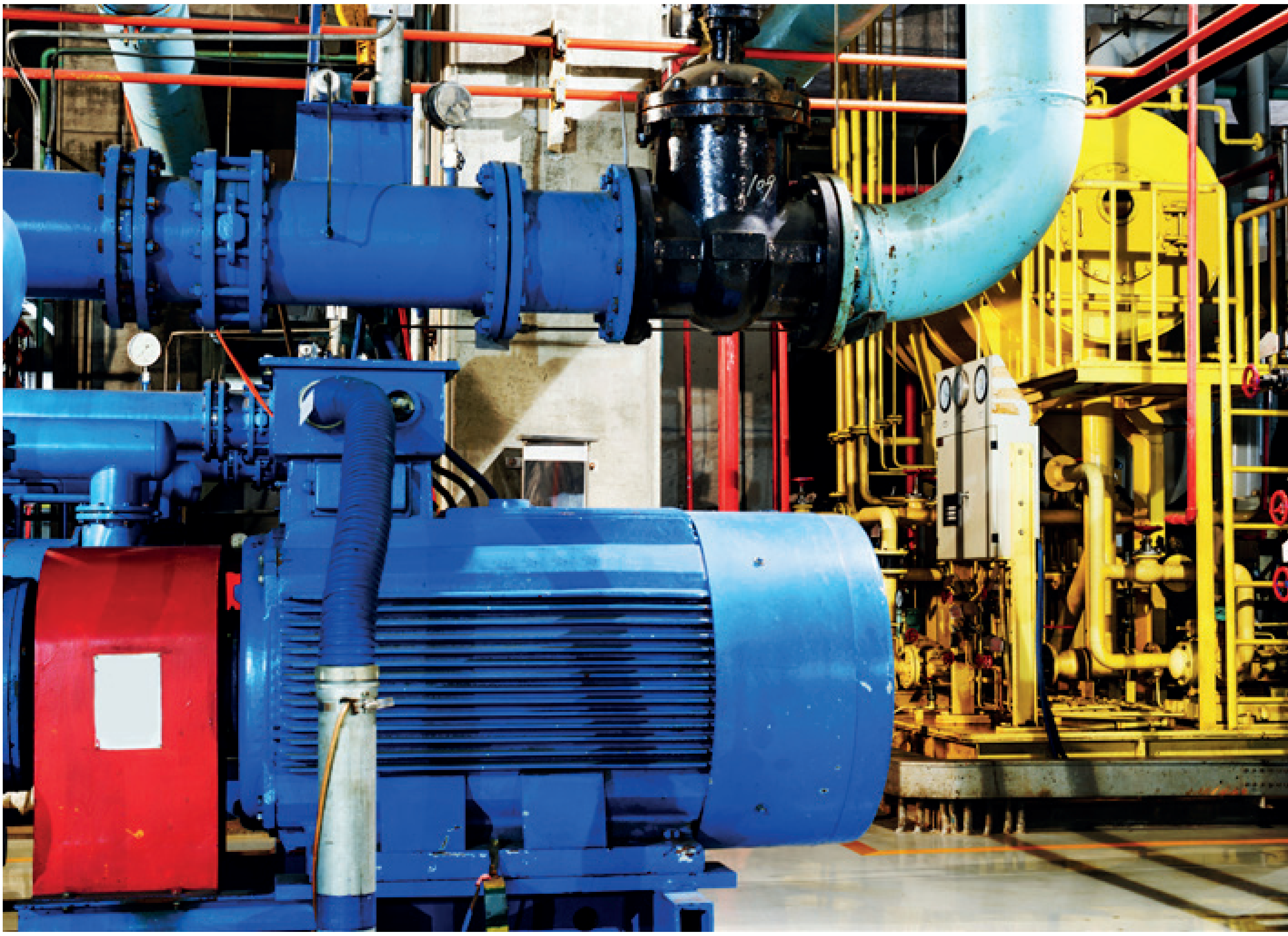
1.3 Report structure

This study is structured as follows. Chapter 2 gives an overview of possible transition pathways and necessary steps for the Dutch industry to reduce CO_2-emissions. Chapter 3 provides a description of the development of industrial energy use and the potential for electrification. This chapter also gives an overview of expected market developments. In chapter 4, an analysis of electrification strategies and promising technologies is shown, derived from Dutch and foreign best practices. Drivers for electrification by different stakeholders in the Dutch playing field are described in chapter 5. The final chapter presents the roadmap, where the transition pathway of electrification and its development needs are further elaborated upon. This chapter is concluded by recommendations on possible ways for the Netherlands to obtain an international innovation position in the field of industrial electrification.

Required transitions towards 2050

Chapter 2

If the Dutch industry is to be committed to the goals agreed on during the COP21 Climate Conference in Paris, it means that CO_2 emissions have to be reduced by 40-50% in 2030 and by 90-95% in 2050 compared to 1990 emission levels. This is higher than the current trajectory as described by the Energy Agenda, as well as in most well-known scenario studies.



If we were to derive possible consequences of these climate goals for the Dutch industry, the following elements need to be considered:

- *More attention for industrial symbiosis and energy efficiency*
  In order to remain competitive and to avoid costly tax or CO_2-measures, industries need to pay attention to identifying saving potentials. Studies by Fraunhofer and Ecofys show that in simple optimisation measures such as insulation, optimisation of pumps and ventilation, saving potentials of 10-15% can be realised. In addition, the need for energy efficiency might favour industrial clusters, to optimise the use of heat and residual products.

- *Decreasing the use of fossil feedstock*
  To realize an 80-95% in CO_2-reduction towards 2050, the use of fossil fuels must be reduced to a large extent. This does not only apply for energy purposes, but also for the use of feedstock materials across industries. In replacing fossil feedstocks, several options can be considered:
  - Electrification, for example switching to electrolysis to produce hydrogen. The hydrogen building block can facilitate carbon capture and utilisation (CCU).
  - Recycling, for example switching from naphtha cracking for ethylene and propylene production to gasification of collected plastic wastes. Another example is chemically recycling of PET streams that are of insufficient quality for physical recycling.
  - Biobased feedstock, for example producing bio-aromates on the basis of biomass instead of naphtha.

- *Focus on investments in clean technology*
  Currently, investments in clean technologies are lagging because they are capital-intensive and there are insufficient incentives. For both government and private investors, it becomes easier to invest in clean technology when there are clear long term commitments to reducing greenhouse gas emissions.

In general, efficiency measures and industrial symbiosis to reduce energy demand are the foremost transition needs to reduce CO_2-emissions, as well as the reduction of fossil feedstock use. For (the remaining) heat demand, different transition pathways are foreseen.

First of all, industrial heat demand can be supplied by deep geothermal energy and, to a lesser extent, bioenergy. ***Geothermal energy*** is seen as a high potential alternative, although more demonstration projects are required to enhance the development of the (relatively new) source. In the current policy framework (specifically with regard to subsidies), ***bioenergy*** (biomass, biogas) offers interesting opportunities, especially in biomass combustion. However, the use of bioenergy remains limited due to issues related to the future sustainable availability of biomass. In that respect, it might have a future for niche applications or might be used as raw material in specific industries, but probably not as a large-scale energy source. ***Carbon Capture Utilization and Storage (CCUS)*** of emissions originating from high temperature heat production or process emissions is considered as another possible pathway. The development of a process to produce CO from CO_2 (e.g. by Differ) to give CO_2 more value is promising. However, CO_2 storage is also still subject to public scrutiny, which complicates the development of the technology. Finally, ***electrification*** of industrial processes is seen as a promising transition pathway, which is the focus of this study. Combinations between the four transition pathways are possible and probably necessary to cover the total industrial heat demand in a sustainable manner.

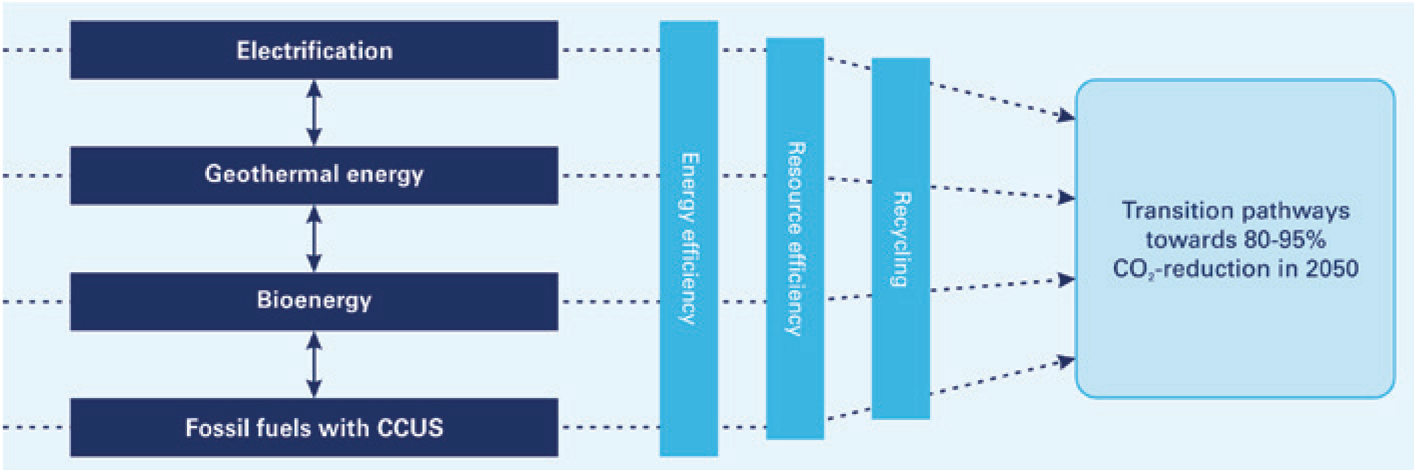


Figure 2. Possible transition pathways towards a sustainable heat supply

Although a strategic consideration of the possible transition pathways was not part of this study, we do highly recommend investigating the optimal combination of pathways in further research.

It is important to note that electrification in itself does not achieve a CO_2-neutral situation, unless the electricity input is in turn CO_2-neutral. In this regard, it is expected that intermittent sources (such as solar and wind) are very unlikely to satisfy the full need of the industrial heat demand.

What is industrial electrification?

With industrial electrification a conventional energy carrier is shifted to electricity, which leads to a reduction of CO_2-emissions on the plant level in the majority of cases. In a narrow definition of electrification, efficiency and process improvement options that are pursued for the reasons of efficiency are not electrification options. *Process intensification techniques* are considered to be efficiency-driven techniques and are outside of the scope of this research. Although they can have higher specific electricity consumption, the reason to pursue them is not electrification per se. We make an exception *for membrane techniques*. These replace a thermal separation processes for a physical one; the driving force is then not heat but electric pump energy. In the narrow definition of electrification these would be excluded. However, we do mention them in this study as membrane technologies are highly relevant for electrically driven efficiency improvement in existing industries.

Trends in industrial energy use and market developments

Chapter 3

To be able to assess the potential for electrification in the Dutch process industry, it is essential to research the current and expected development of energy consumption in the future (towards 2023/2030 and possibly 2050). Looking at these time frames, there are trends in energy consumption, energy supply and market conditions that are considered relevant for this study.

3.1 Energy use of the Dutch industry

For the elucidation of the nature of current energy consumption of the Dutch process industry, we look at the 2015 (provisional) data from the Statistics Office of the Netherlands (CBS, 2016).

Figure 3 depicts the final energy use in the Netherlands[2], for energy and for feedstock purposes, differentiated by sector of the economy. The energy consumption of the refining sector is included in that of the industry. The key insight from this figure is that the combined energy and feedstock use of industry totals to around 1160 PJ in 2015: 46% of the total energy and feedstock use in the Netherlands.

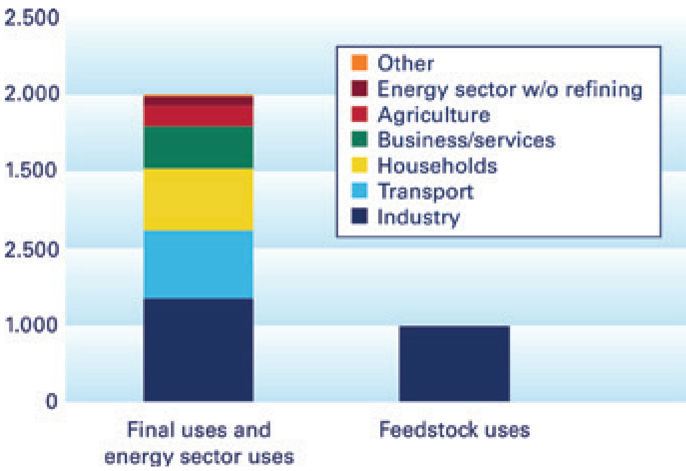


Figure 3. Depiction of final energy use in the Netherlands.
Source: CE Delft calculation, based on (CBS, 2016).

2 In these figures, the illustration of final energy use is chosen since electrification is executed on this level. This depiction is in line with the current trend in literature to look at final energy demand.

A graphical breakdown of the final energy consumption is illustrated in Figure 4. This figure shows that the Dutch industry accounts for a third of total final energy used in the Netherlands.

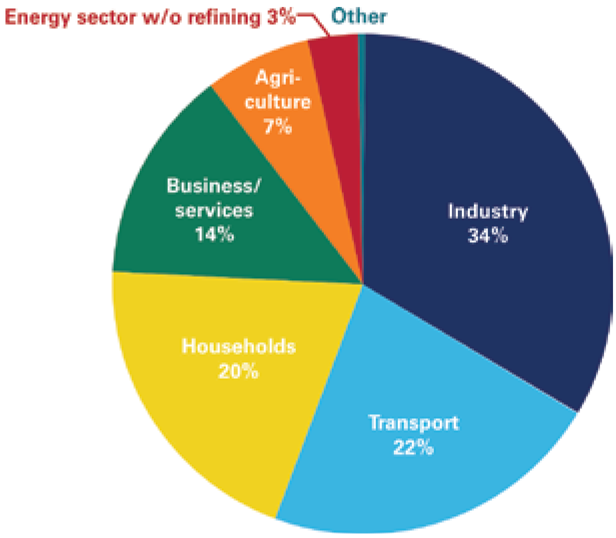


Figure 4. Breakdown of total final energy use (2000 PJ in 2015) to sectors

Figure 5 shows the breakdown of the energy and feedstock use of Dutch industry by the main energy carrier. Crude oil and oil products are the largest energy carrier, accounting for over 600 PJ for energy and feedstock use, followed by gas (accounting for almost 300 PJ). The third most important carrier is electricity with 133 PJ and coal and coal products with 121 PJ.

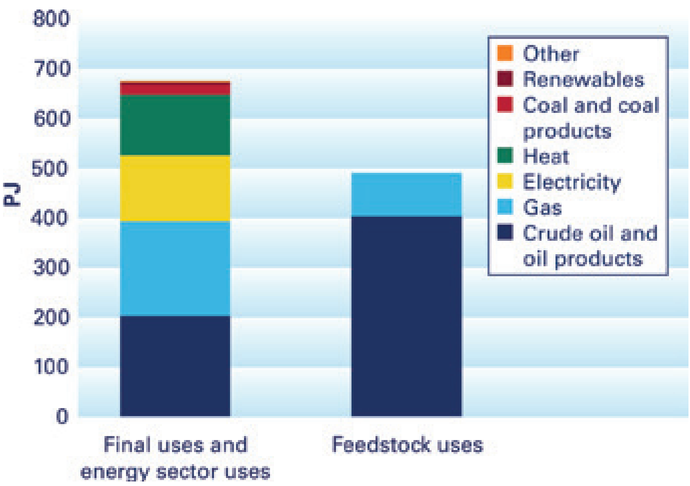


Figure 5. Breakdown of types of energy carrier (2015)
Source: calculations CE Delft on the basis of CBS (2016)

A breakdown of the energy consumption per type of industry is depicted in Figure 6. From the magnitude of the energy consumption, the main industries are chemical and pharma, refining, food and beverage, and iron and steel. Together, these four groups of industries represent close to 90% of the total industrial energy consumption in the Netherlands, as of 2015.

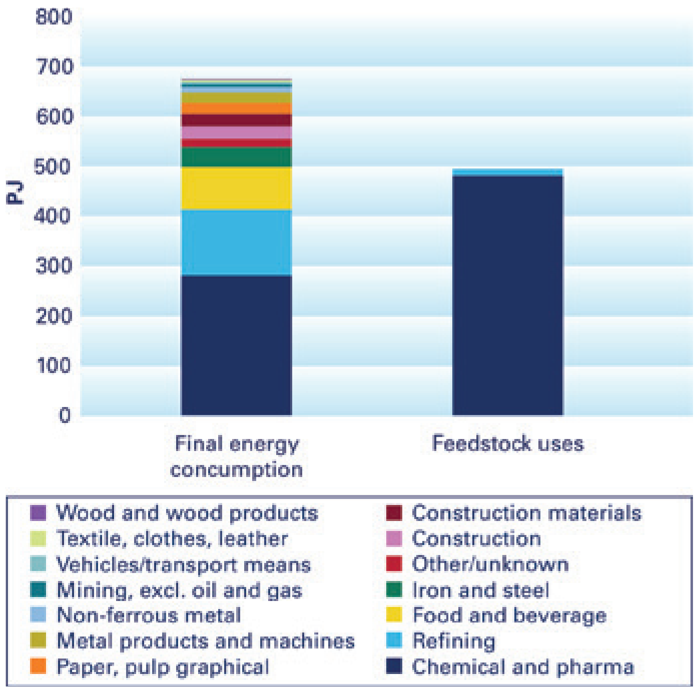


Figure 6. Breakdown by energy use including refining

3.2 Expected future development of industrial energy consumption

To research the expected development of industrial energy consumption, the medium term future exploration in the 'National Energy Outlook' (ECN; PBL; CBS; RVO.nl, 2016) was used, as well as Scenarios for 2030 and 2050 in the CPB/PBL publication series 'Prosperity and Living Environment (PBL en CPB, 2015).[3] It was observed that the NEO scenario found little dynamics in energy consumption, whereas the WLO scenarios show larger changes in the industrial energy consumption.

According to the NEO report, under current policies, it is expected that energy use and greenhouse gas emissions will remain constant when it comes to final energy use. This implicates that energy efficiency measures are in place and working, as production based on fossil fuels is expected to increase towards 2030. The WLO scenarios predict that overall electricity demand in 2050 will increase due to volume growth in industry, electrification and efficiency gains. In both the 'low scenario' (low economic and demographic growth; continuation of current policy) and the 'high scenario' (high economic and demographic growth; substantial climate efforts), heat demand declines with respectively 20% and 10%.

3 See Annex A for an elaborate description on future industrial energy use.

3.3 Potential for electrification

The previous paragraphs provide background on current and future industrial energy consumption. This information is used to identify what part of the current and future energy consumption of Dutch industry can possibly be electrified, given the nature of the energy demand, and the availabilities of techniques that could be cost effectively implemented.

An overview of energy and heat demand split per unit process is included in table 1.

Table 1. Energy and heat demand in the different Dutch industries, demarcated by use type

		Heat energy demand					
Industry	**Total energy demand***	**Total heat demand****	**Chemical conversion, melting, casting, baking**	**Distilling, separation**	**Drying**	**Hot water***	**Other**
Chemical	279	~240	>110	~85	>15		
Refining	132	~111	n.a.	65		n.a.	n.a.
Base metal ferrous	40	~30	~30				
Base metal non-ferrous	11.3	3	3				
Metal products	21	12	12				
Feed and beverage	85	55	7	2.5	26	16	n.a.
Pulp and paper, board	23	18	2		14	1	6
Textile	3,7	3			3		0,7
Construction materials	24	19	19				
Other	53	12	n.a.	n.a.	n.a.	n.a.	n.a.
Total	672		>185	~150	~60	>17	n.a.

Sources: team analysis, *(CBS, 2016), ** (CE Delft, 2015a).

The overview shows that there are several hundreds of PJ of heat demand, for which, in principle, electric techniques are available: approximately 60 PJ of heat demand in drying processes, about 20 PJ heat demand for hot water, more than 100 PJ for low temperature heat demand for distilling and separation, and ~185 PJ of heat for (chemical) conversion melting, casting and baking, of which ~42 PJ for melting, casting and baking.

The total heat demand that is possibly electrifiable will require an analysis on plant level, because heat systems are most often integrated and optimised. Many companies use cascading of heat, making e.g. the potential for heat pumps for hot water production less than the amount that is specified in the table. Also with distillation processes, columns can be linked, which also leads to cascading of heat.

3.4 Market drivers for electrification

3.4.1 Development of renewable electricity

Driven by the push towards renewables and the longer term ambition of decarbonisation, the electricity system in North-western Europe is currently undergoing profound changes. Renewable energy is expected to increase with 10-11% in the period 2013-2023, as a result of the SER energy agreement. If the SDE+ budget is extended to 2030, the percentage of renewable energy will increase further to around 19% in 2030. Wind and solar energy will then contribute to 250 PJ. To illustrate: this is equivalent to the output of around 7.700 offshore wind turbines (or 12.900 onshore wind turbines).[4]

4 Based on 3 MW wind turbines, with 3000 full load hours offshore and 1800 full load hours onshore.

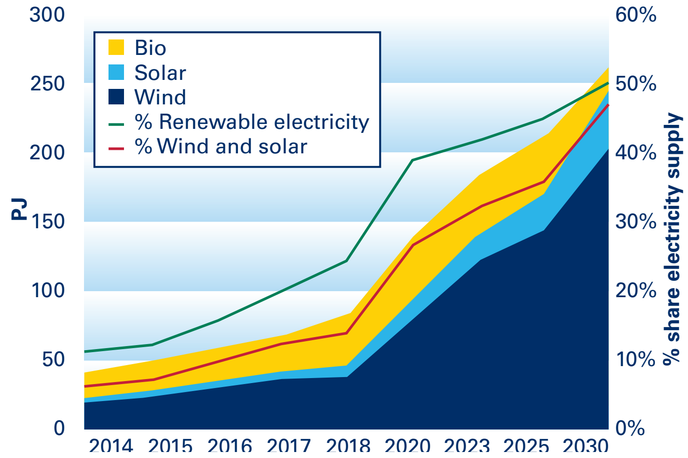


Figure 7. Development of the supply of renewable electricity in the Netherlands

Compared to the potential for electrification as depicted in paragraph 3.2, the growth in renewable electricity will not meet the industrial heat demand for which electrification is technically possible towards 2030. Apart from that, one has to consider that electrification on the basis of renewable power resources is also relevant in other sectors (i.e. transport, built environment).

3.5 Expected market developments

Electricity is an energy carrier of a special nature. Because it cannot be stored without any form of conversion, maintaining the momentary balance between consumption and supply of electricity is a challenge that is reflected in a rather complex market design. Due to the large volumes of electricity that are required for electrifying the significant energy demand of the industry, the wholesale markets (day ahead spot, and long term bilateral markets) are the most important. Looking at power prices, the price level at the day ahead spot markets is most relevant. Moreover, it is interesting to look at volatility of prices, since this may offer opportunities for certain electrification strategies.

Many forecasts on expected market developments are published for the power sector. The results of recent studies, including assessments of future power prices in the Netherlands, are treated in this study:

- The national energy outlook 2016 (ECN; PBL; CBS; RVO.nl, 2016).
- Scenarios for the Dutch Electricity System (Frontier Economics, 2015).
- Scenarios from the Dutch Power2Products study (Berenschot, CE Delft, ISPT, 2015).

Table 2. Comparison of energy market developments

	National Energy Outlook (NEO)		Scenarios for the Dutch Electricity System		Power2Products	
Wholesale price	2020	30 €/MWh (25-50 €/MWh)	2020	46 €/MWh	2023	43€/MWh (40-47 €/MWh)
	2025	50 €/MWh (35-75 €/MWh)	2023	53 €/MWh		
	2030	65 €/MWh (38-90 €MWh)	2035	57 €/MWh		
	In the NEO report, the wholesale price remains at a low level of about 30 €/MWh (25-50 €/MWh) until 2020 and then rises to a level of 50 €/MWh (35-75 €/MWh) in 2025 and 65 €/MWh (38-90 €MWh) in 2030.		In the WLO scenarios, the average price is expected to be 46 €/MWh in 2020, 53 €/MWh in 2023, remaining flat to 2030 and rising to 57 €/MWh in 2035. The trend to somewhat higher power prices starts earlier than in the NEO scenario, but is less severe (post 2025 prices are lower than in NEO).		The Power2Products scenario shows that the average price is lower than in the scenario's from Frontier and ECN: 47, 40, and 42 €/MWh for the respective scenarios.	
Volatility	The NEO itself does not state how price volatility is expected to change. Data received from ECN show increased volatility for 2023 and 2030 compared to the 2013 reference		It is expected that over time, the number of hours where the gas price drops below the level of the gas price will increase. In 2015, this accounts for about 2% of the year (170 hours), in 2020 for 5% (450 hours), in 2023 about 9% (900 hours). In 2030 for 11% (1000 hours) and in 2035 for about 18% of the year (1500 hours).This shows that there might be potential for flexible electrification after 2020.		The scenarios show that volatility will markedly increase with the impact of renewable electricity. Looking at the year 2023, in the scenarios 1, 2 and 3 the power price is below the gas price for 250, 1050 and 850 hours, respectively.	

Looking at the model studies summarised above, it seems plausible to conclude that volatility will markedly rise as a result of increased renewable electricity, but that the development of the average baseload price will probably rise as well. In the simulations by ECN and Frontier, it shows that the large increase in production from wind and solar, expected up to 2023 and afterwards, does not seem to lead to depressed power market prices, or the price effect of renewables is countered by other developments. Berenschot, CE Delft and ISPT show a price decline in their scenarios.

Electrification strategies and promising technologies

Chapter 4

Wind and solar energy are characterised by outputs that depend on weather systems as well as diurnal and seasonal variations. The feasibility of electrification as a (partial) pathway for the Dutch industry to become carbon neutral, depends on the available technologies that offer modes of operations that are attuned to the electricity system of the future.

This chapter gives an overview of different electrification strategies, possible electrification technologies (from foreign and Dutch examples) and an analysis of high-potential technologies.

4.1 Electrification strategies

We identify essentially two distinct strategies for electrification, that are coupled to the electrification technology, the energy system, and the way the industrial production process is organised:

- *Flexible electrification*: the technology is able to undergo starts and stops, ramp up and ramp down, or has the ability to switch between electricity and another mode, to accommodate the output fluctuations of renewable electricity supply. The flexible electrification profits from price arbitrage between conventional energy carriers and electricity. The number of operating hours of the electric technique typically depends on the ample supply of renewable electricity.

- *Baseload electrification*: electrification in a base-load fashion. This is less attuned to the power system of the future; it can use renewable electricity when available but other electricity generation techniques need to be present for other moments.

Furthermore, we would like to pinpoint two distinct application areas:

- *Electrification in utilities*: the technology is implemented in the utilities, meaning the systems servicing the process but not being core to the process. Utilities deal with the steam system (steam generation, distribution, condensation/cooling, heat recovery etc.), compressed gases, (cooling) water et cetera.

  Electrification in core process or primary process streams: electrification techniques that require a change to the process itself. E.g. changing a reactor, a separation technique or a heating technique fundamentally. For companies to undertake this, they face a downtime and require a proven technology that will pay itself back quickly. Investments in this area are always done by the company itself. The technique must be proven and extremely reliable. In this case, electrification may strengthen industrial symbiosis: material streams from certain industries can be input for electrochemical reactions, or products from electro-synthesis can be input to other processes.

An overview of these strategies is given in figure 8.

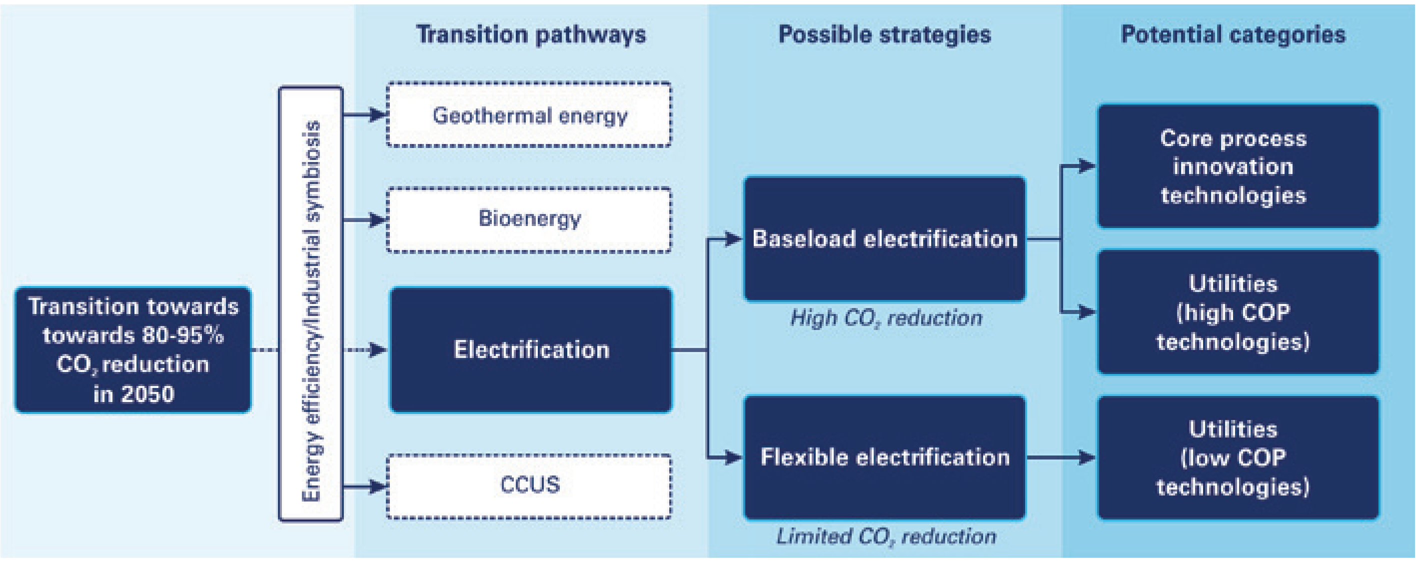


Figure 8. Possible electrification strategies and their application categories

Some technologies are suitable for flexible electrification, whereas other technologies are more suited to baseload electrification. Flexible electrification is promising in industries that use batch processes, especially if the process is relatively OPEX rather than CAPEX-intensive and there is some overcapacity. Flexible electrification techniques also offer possibilities if they can be implemented in a parallel fashion to a conventional energy carrier, so that the conventional technology can be switched over to electric power if it offers cost advantages (e.g. due to the volatility of the power and gas prices, an electric (re-)boiler can be switched on when electricity prices are low due to large wind output, and switched off when electricity prices increase beyond the price of the regular energy carrier). These hybrid solutions have no influence on the process capacity.

Baseload electrification becomes attractive when the electrification technologies offer co-benefits compared to a reference technology, for example a higher efficiency in generating heat (high Coefficient of Performance), higher selectivity or otherwise lower production costs or induced product/process (quality) improvements. Electrification in the baseload also responds to the ambition of firms to transfer to a CO_2-neutral production in case biomass or geothermal energy is not possible.

4.2 Promising technologies (from foreign and Dutch examples)

As part of this study, an extensive research on current Dutch and foreign examples of electrification was conducted. In this research, several categories for electrification were identified:

- Power to Heat
- Power to Hydrogen
- Power to Gas
- Power to Chemicals
- Power for Cechanical drive
- Power for Separation

Moreover, we identified several 'unit operations' (the type of process were the technology is applicable), that were used for the categorization of technologies. This investigation led to the selection of electrification technologies as mentioned in table 3. The full list of examples, including some foreign best practices, is given in Annex B.

Table 3. Overview of electrification technologies by unit operations

Unit operations	Technologies	Category
Process heat – steam and hot water, thermal oil …	Heat pumps Electric boiler / electrode boiler Hybrid CHP-EB concepts Steam recompression / vapour recompression	Power to heat Power to pressure
Process heat – baking, melting and casting	Induction furnace Microwave heating Electric melting Electric arc furnace Plasma heating /plasma recycling Infrared heating	Power to heat
Drying	Infrared drying Impulse drying Impingement drying Microwave drying / combining with convection. Vapour recompression Heat pumps for low temperature drying	Power to heat
Distilling/separation	Mechanical Vapour Recompression Filtration: MF / UF / NF / RO Electrical field / electrostatic techniques Mechanical techniques e.g. centrifugation	Power to heat Power for separation
Sterilisation and pasteurisation	Infrared sterilisation UV Microwave pasteurization and sterilization Microwave blanching of vegetables Heat pumps HP sterilisation	Power to heat Power for sterilisation
Direct process input: electrolysis/ electrochemical conversion	Electro synthesis, e.g. H2, NH3, Fe reduction w/H2 Electro catalysis, eg. CL2, MeOH from H2 and CCU, other bulk. Plasma chemistry	Power to chemicals Power to specialties

For each category, specific conclusions and remarks are given with respect to the Dutch situation.

Power to heat

Power to heat shows a high potential and a wide range of technologies, applications (sectors, processes, utilities) and parties involved, both in the Netherlands and abroad. Although high temperature (HT) heat pumps are seen as a highly promising technology for electrification, technology readiness is currently a limiting factor for industrial (megawatt) application. This is not the case for Mechanical Vapour Recompression (MVR) and steam recompression, as those technologies are already available. However, the CAPEX reduction of both MVR and heat pumps is a condition for successful roll out.

Although electric boilers are commercially available, the economic feasibility in the current Dutch situation is often poor. This can be due to grid connection costs, capacity tariffs and the relatively high power prices for most of the year. Power to Heat projects can be found in several sectors: food, steel, chemical and may also be adopted in the petro chemical sector. Applications are possible as well in processes as in utility generation.

Drying applications is a niche (it is estimated that drying processes account for about 10% of natural gas use in the industry), which can be elaborated in combination with process improvement, process intensification and integrated heat pumps. Branches for application are steel, food, carpet and perhaps also the paper industry. Cold storage is a niche opportunity, which can be developed.

Power to Hydrogen

Power to Hydrogen has high potential, but is currently economically not feasible for large-scale application due to the high CAPEX (currently estimated around 4 times higher than economically viable). The levelised costs of hydrogen by electrolysis is about 5 €/kg (baseload production), which compares unfavourably with the cost of hydrogen from natural gas at 1-1,5 €/kg using the steam reforming process. This category is both relevant in core processes (for instance in producing ammonia), and in utility processes. Branches with high interest in (sustainable) hydrogen production are the chemical, the petrochemical and the fertilizer sector. Technology is not the limiting factor. It is difficult to make predictions when this technology will be competitive, but this can be 10+ years from now.

Power to Gas

The power to Gas electrification option has a more limited potential than power to hydrogen. In the current situation, the CAPEX is higher and the turnaround efficiency is low. A strong argument for Power to Gas is that the product is a universal raw material, which can be fed in or stored in the existing natural gas grid. This also applies to Power to Hydrogen. The time schedule for the economic feasibility of Power to Gas will be 10+ years, or even longer.

Power to Chemicals

Power to Chemicals shows a high potential. There is a wide variation of initiatives, as shown in Annex B; most of them in the starting phase. International chemical industries are doing research concerning the redesign of their processes, which are currently almost all based on fossil fuels and fossil feedstock. Also, universities and research institutes are developing new production processes for (i.e.) hydro carbons, innovative carbon free fuels for automotive, (base) chemicals, steel, et cetera. A specific high power application like chlorine production by electrolysis is suitable for Demand Side Management (DSM). This is an existing process, which needs some adaptations. Chlorine production can be used more intensively as a DSM tool. The time schedule is expected to be 5+ years, or even lower. The branches for power to chemicals are the chemical industry, as well as the transport sector and the fertilizer industry.

Power for Mechanical drive

Electrification for mechanical drive shows a limited potential, but the unit power levels can be very high. At this moment, there is only a limited number of initiatives, but in case of future low electricity prices, the potential can be developed. No research has been done to investigate the potential power level, however the extent of this technology will be in the size of hundreds of MWe. The technology is available, and can be applied today. Sectors of interest are the chemical and petrochemical industry, in particular the large plants like BP, Shell, DOW, Tata Steel, DSM, Yara, OCI Nitrogen, AkzoNobel et cetera.

Power for Separation

Power for Separation will have a limited potential and is mainly focused on the food industry. Currently there are interesting initiatives in the Netherlands, based on development of existing technologies (ultra filtration, nano filtration, reverse osmoses). These technologies will be scaled up and tailored to the specific applications. Time schedule: 5+ years.

Table 4. Overview of electrification categories and promising technologies

	Short term 0-5 years	Medium term 5-10 years	Long term 10-30 years
Breakthrough of electrification categories & promising technologies	High potential: Power to Heat • Steam recompression / Mechanical Vapour Recompression (baseload) • Electric boilers (flex) • Electromagnetic radiation (baseload / flex) • HT heat pumps (baseload / flex) →		
	Limited potential: Power for Mechanical Drive • Replacement of steam drive by electric drive (baseload)		
	High potential: Power to Chemicals • Electrolysis for chemical production, i.e. chlorine / ammonia (DSM)* (flex)		
		Limited potential: Power for Separation • Ultra filtration/Nano filtration/Reversed osmosis (baseload)	
			High potential: Power to Hydrogen • Electrolysis (flex)
			Limited potential: Power to Gas • Electro synthesis (baseload/flex)

* For Power to Chemicals, flexible production of chlorine seems most promising. This does not lead to an increase of electrification, but rather a more flexible power consumption (demand side management)

Drivers for electrification in the Dutch playing field

Chapter 5

Electrification in the process industry demands a cross-sectoral approach. Therefore, a stakeholder analysis was conducted for different groups to identify drivers for electrification:

- *Process industry*
- *Manufacturing industry*
- *Energy producers*
- *Grid operators*
- *Knowledge institutions*

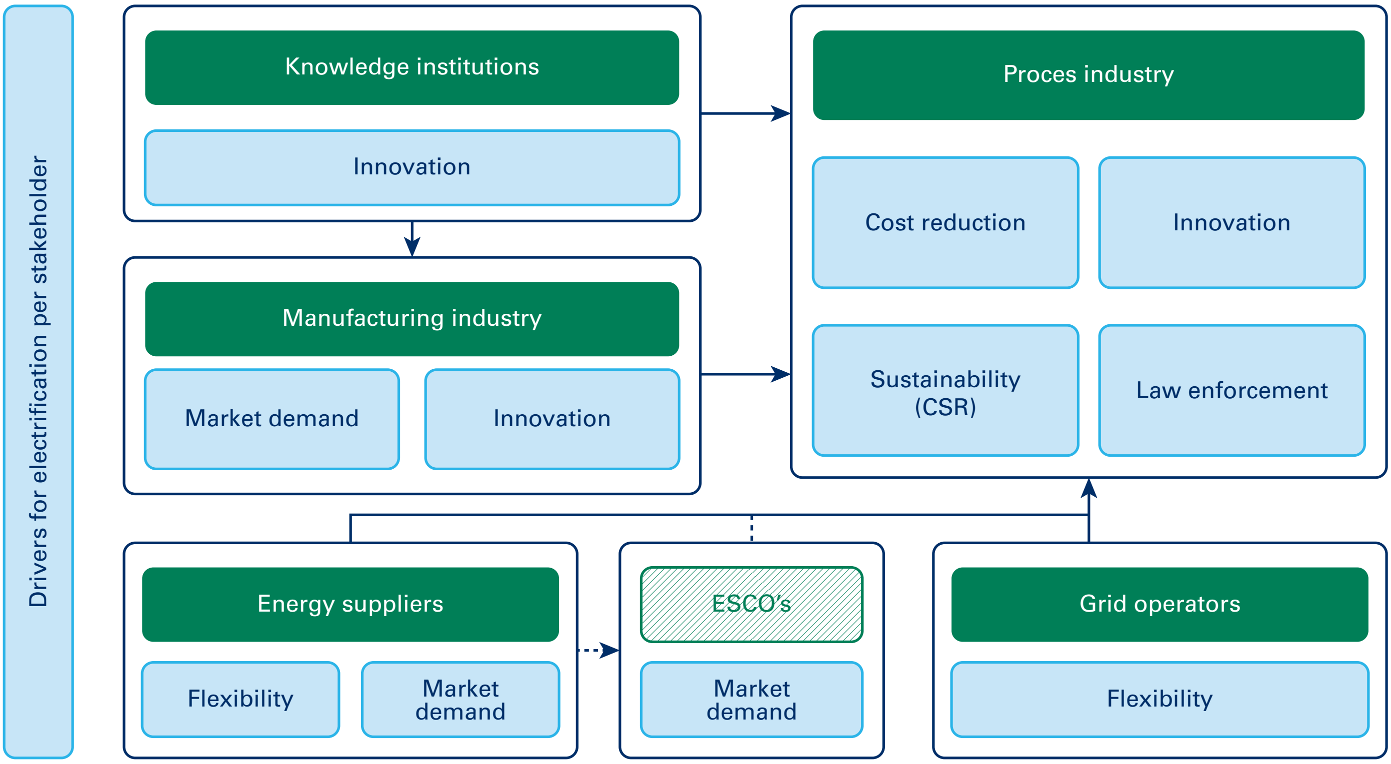


Figure 9. Drivers for electrification per stakeholder

In general, the increasing presence and importance of electricity from renewable energy sources, especially wind and solar, is accepted by all stakeholders. Electricity will play a key role in the future energy system. Taking energy efficiency measures is regarded as the main course of action on the short term. On the long-term, electrification of industrial processes offers interesting opportunities for decarbonisation but has to compete with substitutes, as mentioned in chapter 2.

Figure 9 shows the drivers as mentioned by different stakeholders, when looking at electrification of the Dutch process industry (from their own perspective). The following paragraphs give an explanation of the most important drivers for electrification: flexibility, cost reduction, sustainability and innovation.

Flexibility

The increase in renewable electricity generation capacity leads towards an increasing supply of intermitted renewable electricity. The integration of high shares of renewable electricity from wind and solar energy poses a challenge in terms of matching supply and demand. In this context, there is a growing need for system flexibility. The process industry can provide flexible capacity through electrification of its energy demand. This can either be done by the storage of renewable energy when prices are low (in chemical products, intermediate products such as hydrogen, or as heat or cold) and by using this energy when prices are higher, or by reducing demand when prices are high and catch up processes when prices are low. Different technologies, as shown in chapter 4, can play a role in flexible electrification.

More renewable generation capacity means that windy and/or sunny days, combined with low electricity demand, will result in very low electricity prices; probably lower than gas prices and sometimes close to zero or even negative. The process industry is, to a certain extent, able to respond to this variable infeed of renewable electricity with demand response; either by using more electricity during moments of high infeed of renewable electricity or less on moments when electricity is scarce (and more expensive), or by making flexible use of gas and electricity.

The need for flexibility is especially urgent for grid operators, energy suppliers and authorized Program Responsible Parties (PRPs). On a short term, this driver is mainly urgent for suppliers that have a balancing responsibility in their portfolio

(PRPs). For them, (flexible) electrification of the industry could function as a supply-driven buffer that decreases imbalances. This also accounts for Tennet, the TSO responsible for the balance of the total electricity system. On the long term, the need for flexibility becomes increasingly urgent for grid operators. For them, the choice is to either reinforce the grid (against high social costs) or to 'smarten' the grid. As (large-scale) smart-grid technologies are still in its infancy, the grid operators in the Netherlands, especially those who are confronted with extensive replacement tasks, tend towards grid reinforcements. In this regard, the use of flexible demand side solutions (through electrification and flexible capacity) could contribute to limit the investments needed for grid reinforcements.

Also (renewable) energy producers view the process industry and electrification as important in the context of the energy transition. From a renewable energy market perspective, using extra electricity when there is excess wind and solar electricity has a certain value. If the industry would not use this electricity, the returns for producers would be rather low or even zero on certain moments. By using electricity when prices are low, the industry creates a certain price floor for electricity.

However, it has to be stated that the prospect of flexibility does not directly function as a driver for the process industry itself. For the industry, flexibility only becomes interesting when it comes with cost benefits.

Cost-reduction

Costs and benefits are decisive for almost any investment decision in general, and the process industry is no exception here. In that context, cost-reduction has been mentioned as a (long-term) driver for electrification. In general, technical solutions based on electricity require less maintenance and operation costs when compared to other fossil fuel based technologies. In addition, in many cases electrical solution have a longer life-span when compared to their fossil fuel counterpart. This means that electrification has a positive effect on reducing operational cost (OPEX), which may translate into a competitive advantage.

However, although cost-reduction is seen as a driver for electrification, this is not foreseen as a short term development. Most companies state that electrification is still financially unbeneficial in the coming years. If renewable sources become more mainstream in our energy supply, commodity costs for electricity will probably fall as a consequence of low marginal energy production costs, making electrification a more attractive option.

In addition to cost-reduction, electrification provides the process industry with the opportunity to act on the electricity (wholesale) market, specifically the balancing market. Although balancing itself is not seen as a primary driver, possible additional revenues are regarded as an added benefit. For grid operators, electrification of the process industry can possibly contribute to the stability of the grid.

Sustainability

From a government perspective, decreasing carbon emissions is evidently one of the main drivers for electrification in the process industry. Yet, achieving sustainability objectives, especially reducing CO_2-emissions, also provides opportunities for electrification in the process industry itself. Electricity can be used as a replacement for fossil fuel driven activities, such as heat generation, which is now predominantly based on fossil fuels. At the moment, the energy consumption of the industry accounts for 46% of the total energy use in the Netherlands, as shown in chapter 3.1. More than half of this is used for high temperature heat demand. This demand is mostly covered by the usage of natural gas. By making a fuel switch away from fossil fuels, especially in the context of heat supply, electrification can make a significant contribution to the decarbonisation of the energy-intensive industry. For heat supply, technologies such as electric heat pumps, electric boilers and steam recompression can be used. Next to a fuel switch away from fossil fuels, electrification can contribute to energy-efficiency improvements, for example, by re-using or upgrading residual heat waste.

The motivation for companies in the process industries to pursue sustainable activities differ, and can be activated by intrinsic or extrinsic factors. First of all, there is an imperative to reduce CO_2-emissions and achieve other sustainability objectives because of energy and climate policies. Other companies mention the growing public demand for clean energy and technologies and the importance of a green and sustainable image. Going green acts as a 'licence to operate'. This applies in particular for companies that are close to end-consumers, and (at the moment) to a lesser extent to companies in the process industry. In addition, sustainability is also mentioned in the context of corporate social responsibility.

Innovation

For several stakeholders, achieving an innovative position is regarded as a main driver for electrification. This mainly applies to knowledge institutes and the manufacturing industry.

For knowledge institutes, electrification creates opportunities to develop new products, improve the business case for production processes and therewith obtain a more competitive position for the industry compared to other regions. This is in turn beneficial for the economic position of the Dutch process industry. For the manufacturing industry, innovation is regarded as a driver to be able to respond to (future) market demand and therewith to sustain an economically profitable position as a supplier of the industry.

Roadmap for electrification as a transition pathway

Chapter 6

By 2050, the energy landscape will be significantly different compared to how it looks today. To achieve a 80-95% decrease in CO_2-emissions and meet the energy demand at the same time, a complete redesign of the energy system is required. With this development, equipment lifetimes of 30 years and more in the industry needs to be taken into account.

As described in the previous chapters, electrification is one of the transition pathways towards a CO_2-neutral industry. However, in order to realize the potential for electrification, certain barriers need to be overcome. This chapter gives an analysis of promising (technological) strategies for electrification, the main barriers for further development, and an overview of development needs on the short, medium and long term.

6.1 In conclusion: the potential for electrification towards 2050

The increased supply of solar and wind electricity simultaneously creates opportunities for the electrification of the Dutch process industry as a potential transition route. For this route, two implementation strategies are foreseen: flexible electrification and baseload electrification. The first type of electrification is aimed at part-time electrification of processes, where industries make use of electricity if power prices are relatively cheap. Baseload electrification however concerns the electrification of processes that demand full business continuity.

The suitable technologies that have been identified for flexible electrification are mainly related to Power to Heat. However, the variety in technologies is relatively small. With respect to Power to Heat this mostly concerns direct conversion technologies, such as electric (re-)boilers, and to a lesser concerns extent technologies such as Mechanical Vapour Recompression (MVR), (high temperature) heat pumps and electromagnetic radiation. For heat pumps, research and development on high temperature industrial applications are essential on a short term to unleash the full potential of the technology. On a longer term, electrolysers (Power to Hydrogen) have been identified as an option to increase the flexibility in the production of (sustainable) hydrogen (in addition to hydrogen production based on natural gas). However, this technology is not economically feasible yet. The economically most viable technologies for baseload electrification are Mechanical Vapour Recompression, (high temperature) heat pumps and steam recompression.

Market drivers

The feasibility and applicability of electrification technologies for both flexible and baseload electrification depend on market conditions and drivers. Based on different scenarios, it is expected that yearly average electricity prices will slightly increase towards 2030/2035. This means that one of the preconditions for baseload electrification, low commodity prices, is not met in case of simple substitution in the industrial utilities (e.g. from gas-fired heating to electric resistance heating). This has been the case throughout history, and the onset of renewable energy does not change this fact for the future, for baseload situations. Therefore, baseload electrification (in utility processes) seems only viable for technologies that have a high Coefficient of Performance (COP), such as high temperature heat pumps and Mechanical Vapour Recompression. To a larger extent, these technologies are economically viable today, however the potential is often not realized due to lack of capital for investments and/or very stringent economic criteria for industrial applications. Thus, for now and in the foreseeable future, this large potential can only be developed when these factors are eliminated by using a different investment model.

The implementation of flexible electrification (with e.g. power to heat boilers) seems to become economically feasible with the increase of price volatility. Based on different scenarios, it is expected that price volatility of electricity will increase towards 2023, 2030 and further. A focus on the development of electric boilers, electrolysers, and other potential technologies in the coming decades will show a shift in capital expenditures for these technologies. It is expected that the implementation of this type of electrification mainly applies to utility-related processes. Compared to the electrification of most core processes, the implementation threshold of utility electrification is perceived as relatively low, as it does not require a complete redesign of primary processes. Yet, certain barriers need to be overcome in order to meet the potential of this option, as described in paragraph 6.4.

Electrification of core processes

For electrification options that do require a redesign of primary processes, the implementation threshold for the industry is presumably high in most cases due to the sensitivity of process modifications. In addition, such process innovations are less suitable for the involvement of third parties, as each process is considerably plant specific. This means that the operating expertise for the specific technology needs to be present within the company, which increases the implementation threshold.

Therefore, electrification of core processes is mostly expected for those technologies that are proven, reliable, well-known and relatively easy to operate. In addition, the technologies to which this applies are highly sector-, plant- and process specific. It is possible to overcome implementation thresholds relating to the requirement to use only proven technologies in the core process, but this is difficult. It requires companies willing to invest in demo plants. In that respect, a certain phasing of application can be identified. Meaning that there are (presumably enough) companies willing to invest, but only in demonstration and pilot projects as a first step. After successful experiences these applications might then be scaled up. The government can help by shaping fruitful conditions for this innovation step. Initiatives that foster this risk taking and innovation also help. Naturally, certain innovations are mainly foreseen when market conditions or different external drivers are in place.

An overview of electrification as a promising transition pathway is shown in figure 10. Naturally, this figure solely shows the promising technologies as known today. Towards 2050, innovative solutions will possibly become available and the redesign of core processes might evolve to a more mature stage.

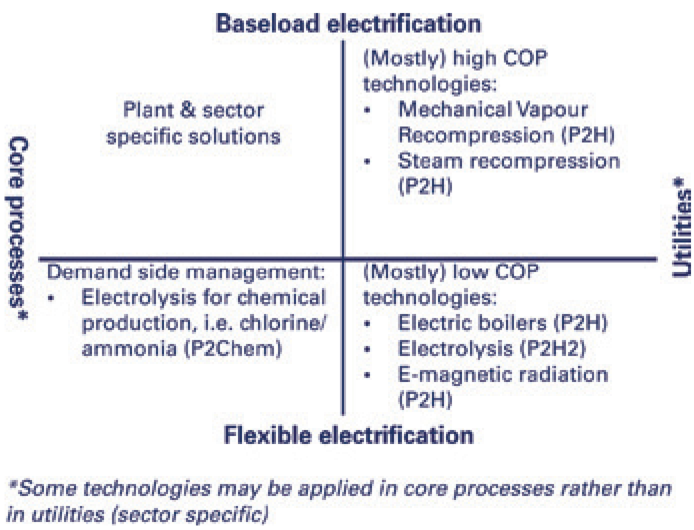


Figure 10. Promising technologies for electrification (as known today)

6.2 New roles and business models: ESCOs

The flexible operation of utility processes shows high potential, and creates opportunities for third parties to become involved. As most industries are not interested in coordinating the flexible operation of their assets, outsourcing these activities towards new market players might become essential. Therefore, Energy Service Companies (ESCOs) that coordinate the operation of flexible electrification need to be put in place. Again, this opportunity is mainly applicable for technologies that operate in utility processes. A possible role for energy companies is foreseen here.

The term Energy Service Company is rather generic, but usually involves the development of energy efficiency measures by an external company with external investment opportunities. ESCOs often provide performance guarantees through Energy Perfomance Contracts. Currently, ESCOs have mainly been used in the public sector, rather than in an industrial context.[5] However, some innovative solutions are being developed in the European and U.S. markets.

For the involvement of ESCOs, four options (or a combination of the four) may be conceivable:

- Commodity based: in this type of ESCO, an external energy company delivers a commodity, such as steam or hot water, to an industrial party. This is much like the original delivery of an energy commodity such as electricity and gas; however the commodity of steam or hot water is much closer to the actual service needed by the end consumer. In this situation, the ESCO invests in the electrification technology (e.g. electric boiler or heat pump) in order to convert the electricity commodity into steam or hot water and sells the output to a contracted industry.

- Services based: in a services based ESCO, an external party does not deliver an energy commodity; instead an energy service is delivered, e.g. a temperature in a room or in a certain process. The ESCO party takes care of the entire installation process: from the design of the installation to the management and maintenance of the installation delivering the service. The industrial party pays a fee for the service.

- Financially based: in this option, the ESCO arranges a financial agreement with an industrial party for the investment of new equipment, as an off-balance financing. This may work as a leasing construction, in which the industry pays off the equipment in a monthly or yearly contract, for several years. Potentially, the contract also includes the delivery of electricity for a fixed price.

- Joint venture: in this type, a Joint venture is established to invest in a certain piece of electrification (for instance steam recompression). This is much like the earlier arrangements in the Dutch programme for stimulation of CHP (Combined Heat and Power) as arranged in the ‘80s and ‘90s. Typically such a joint venture would exist between an energy utility (delivering the electricity) and the industry. In the contract, the conditions for electricity delivery and sharing of revenue for flexibility services e.g. to the TSO are included.

This is only a first glance at ESCO possibilities. A comparison and selection of the best options is required, going beyond the scope of the current project and recommended for further study.

6.3 Main barriers for further development

In order to fully adopt the potential for electrification in the Dutch process industry, and to obtain an innovative position in this field, certain barriers need to be overcome. These barriers, or constraints for further development, were identified in the research phase through a large number of interviews with different stakeholders and two elaborative workshops with end-users (process industry) and equipment suppliers (manufacturing industry). Most of the identified barriers are in line with the outcome of the Power2Products study by Berenschot, CE Delft and ISPT.

The identified constraints are similar for each unit operation and industrial sector, and therefore categorised into economic, technical, regulatory and organisational barriers.

5 Best practices for Industrial Energy Efficiency (Copenhagen Centre on Energy Efficiency, February 2016)

Economic	• High CAPEX for required payback times (two to three years) • High costs for increased grid capacity / grid tariffs • Uncertainty of future market price development • Absence of financial incentives
Technological	• (Perception of) reliability / lack of proven technology • Lack of technical coordination for the flexible character of future assets • Limited temperature application of heat pumps
Regulatory	• Absence of long-term view on electrification • Absence of financial or fiscal incentives • Energy taxes currently in favour of gas
Organizational	• Lack of knowledge / available information on successful electrification examples • Difficult internal decision-making process • Lack of cooperation between stakeholders • Lack of resources (manpower) and knowledge
Other	• Safety risks of refrigerants (heat pumps)

6.3.1 Economic barriers

The most important barriers as mentioned by the industry are related to economic factors. Foremost, the investment costs of electrically driven equipment are currently too high to match the required payback times of (usually) two to three years maximum. Additionally, a constraint related to the technical domain is the (lack of) available capacity on the power grid. In order to switch from a gas-driven process to an electricity-driven process, the capacity of the power grid often needs to be increased. In many cases, this is a costly operation for the grid operator and for the industry itself. Besides grid expansion and reinforcement measures, another constraint relates to the current structure of the network tariffs and the capacity fee. Even if grid capacity is technically available, the increase of electrical consumption implies a higher capacity fee for the industry. Currently, companies have to pay a higher fee retroactively for the whole year when they use more electricity than contracted. This can be very prohibitive especially for electrification options with a flexible nature. In many of these cases, the electrification is only activated for those hours with lower electricity prices. The economic benefits are thus gained for only a limited number of hours, while the higher capacity fee applies for the whole year. Costs to increase grid capacity and higher grid tariffs make the business case for electrification for most cases inviable. Restructuring of the rules of grid tariffs could mitigate some of the obstacles for some electrification options, especially when flexible electrification is concerned.

High capital investment costs of available equipment are related to the fact that the production of electrification equipment is not mainstream. More mass production of electrification technologies would logically cause a drop in investment costs for end-users.

Another economic barrier that poses a risk to the implementation of electrification is the uncertainty of future market price developments. Although it is widely assumed that the increase in wind and solar energy supply leads to a decrease in electricity prices, it is very uncertain to what extent this will develop. Besides, an even greater uncertainty is found in the future prices of natural gas, as this is dependent on many external factors. This uncertainty in the economic development of both carriers hinders the stability of the business case and therewith the decision making process of end-users.

Moreover, many end-users mention the fact that there is no financial or fiscal incentive from the government as a constraint to implement electrically driven equipment in their industrial processes. For example, there is a lack of available subsidies for industrial electrification and waste heat recovery and it is unclear to what extent these policies will evolve in the coming years. Financial backup in the form of an investment fund would encourage end-users to adopt electrification pilots.

6.3.2 Technical barriers

One of the main constraints for the further development of electrification is the (perception of) reliability of available equipment. Most promising technologies for electrification are not necessarily new, but not mainstream in the process industry and therefore not proven as successful technologies. As reliability is one of the most important drivers for Decision Making Units, the lack of successful electrification examples poses a barrier for further development. Therefore, communicating the successful adaptation of electrification in existing initiatives seems to be necessary.

The coordination of assets is mentioned as another technical barrier for further development. This mainly has to do with the time needed for the start-up or shut-down of electrically driven equipment. To be able to take advantage of fluctuating electricity prices, more flexible technologies are needed in comparison to the current processes that are designed to run continuously. Thus, equipment needs to be developed that matches the flexible character of the fluctuating energy market, including the necessary control strategies to switch from one carrier to another.

Another technical barrier, specifically related to Power to Heat, is the currently limited temperature application of heat pumps. In order to reach the temperatures needed for many industrial processes, electrically driven heat pumps need to upgrade heat to temperatures up to 250 °C. To be able to realise the technical and commercial potential of Power to Heat, higher temperature levels in combination with an economically affordable CAPEX level must be achieved.

6.3.3 Regulatory barriers

In relation to the absence of financial incentives as stated before, various stakeholders mention the need for a long-term (governmental) view on the implementation of electrification in the process industry. Such an outspoken view could offer more stability in the decision making process of end-users. Related to this aspect, stakeholders mention the fact that energy taxes are currently set in favour of gas as a constraint for electrification, which prevents industrial end-users from using more sustainable alternatives. In this respect, the current structure of grid tariffs is also mentioned (see 5.2.1).

However, the most important regulatory barrier seems to be the lack of financial risk coverage. Many end-users are at least interested in the implementation of electrification in their (future) processes, but foresee major financial risks, mainly related to future market price developments. In order to grow the potential for electrification, financial risks have to be reduced.

In addition, the way the EU Emission Trading System (ETS) functions at present, financial incentives from a carbon emission point of view are almost non-existent.

6.3.4 Organizational barriers

Apart from technical, economic and regulatory barriers, the development of electrification brings about quite a few organizational challenges. Most importantly, it is stated that there is a general lack of knowledge and information about the technical possibilities of electrification throughout the whole industry with exceptions. As electrically driven equipment is not mainstream in most cases, and as there is a lack of successful implementation examples, the subject is relatively unknown. This hinders the application of electrification in the process industry on a short-term.

Moreover, interviewees mention that they have to deal with a difficult internal decision making process, in which they often need to convince decision makers of the benefits of electrification. In this process, reliability and economic prospects are the most important factors. More knowledge and information on successful examples would increase the perception of reliability, as financial incentives would help to improve the general payback times.

Finally, the lack of cooperation between stakeholders is mentioned as a barrier for the development of electrification as a whole. The importance of connecting cross-sectoral knowledge, continuing applied research and setting up multi-stakeholder pilots is underlined.

3.3.5 Other barriers

Lastly, a barrier related to the implementation of electrification that was often mentioned is a safety risk. For instance, mechanical heat pumps use ammonia as its refrigerant, or even n-butane. The application of these refrigerants comes with certain hazards, due to which extra safety measures are needed. This aspect forms another constraint in the decision-making process of end-users.

6.4 Development needs

As stated in this report, electrification has already found its first application in the Dutch process industry. However, for the successful commercial breakthrough of electrification, certain development needs have been addressed by different stakeholders. These development needs originate from our view on electrification as a transition route towards 2050, combined with the barriers we have identified and the analysis of the most promising technologies for electrification and their current status.

For the successful breakthrough of electrification, we address the following needs:

- *An outlook on electrification as a transition route.* To be able to increase the stability in the development of electrification initiatives, the industry is in need of a clear view from the Dutch government on electrification as a transition route, including corresponding industrial policy. In addition, to underpin policy choices, there is a need for robust energy scenario analysis aimed at a future with electrification of industrial heat demand. Due to the huge impact, it is imperative to calculate this in a scenario taking into account all system consequences. As many of today's discussions about the future energy system are taking place without much knowledge of this impact, this is deemed to be rather urgent.

- *Close cooperation between stakeholders.* To develop electrification initiatives, close cooperation between stakeholders is necessary. This includes (for instance) cooperation between applied knowledge institutes and industry in demonstration projects, between government and industry (representatives) on development needs, and cross-sectoral cooperation between industries on technology development. Research and knowledge institutes play a key role here.

- *Stimulation of promising technology development.* This research gives an overview of most promising technologies for electrification, both for baseload and flexible application. Some promising technologies still require developments, such as the temperature application of heat pumps, as mentioned above. But other technologies, such as electrolysis and electric boilers, also still require development to match the required CAPEX levels. Attracting development funds and cooperating between equipment providers, knowledge institutes and industry is essential in order to meet the full potential of these techniques.

- *Application of high temperate heat pumps.* A specific barrier often mentioned as a huge development need for the breakthrough of electrification, is the temperature application of heat pumps. To be able to realise the technical and commercial potential of Power to Heat, higher temperature levels must be achieved. This is therefore an important development priority.

- *Focus on redesign of primary processes.* This study shows that electrification is currently most viable for utility processes that do not require a complete redesign of processes. However, it is to be expected that efficiency or electrification measures will have a more significant impact in primary processes on the long term. Therefore, a focus on research and development on the redesign of primary processes, for instance in the chemical industry, is necessary.

- *Expansion of renewable electricity production capacity.* Obviously, electrification in the process industry is only feasible as a transition route towards a low carbon society, if the electricity comes from renewable sources. Thus, expanding renewable electricity production capacity in the coming years remains an important development need.

- ,*Development of demonstration projects.* Most promising technologies still require high capital expenditures or lack proof of concept, which asks for the development of pilots or demonstration projects for these technologies.

- *Funding for demonstration projects.* To familiarize with the concept of electrification, there is a strong need for the deployment of pilots and demonstration projects for certain technologies (e.g. HT heat pumps and electrolysis). As the CAPEX expenses are high, an external fund could offer solutions.

- *Communication on best practices.* A lack of knowledge on successful examples is mentioned as one of the barriers concerning the development of electrification. Therefore, a platform that addresses questions and communicates best practices and current initiatives is desirable.

- *Establishment of new business models/market roles (ESCOs).* As the business case for electrification projects is often not viable for the industry, or as future market price developments are uncertain, there is a growing opportunity for aggregators or energy service companies to become a counterpart. Certain companies could engage in the technical coordination of (flexible) assets as well, which is currently seen as a challenge for industrial companies.

- *Adaptation of electricity tariffs structures.* High capacity connections are currently expensive in use due to the capacity tariff structures. An adaptation of tariff structures to meet the need for flexibility in the energy system would improve the business case for electrification, especially for flex techniques.

- *Reassessment of grid connection costs.* Substantial electrification implies significant grid investments costs. Already, companies struggle with high costs for increased grid capacity in their business case. A reassessment of grid connection costs for end-users is desirable, as electrification contributes to a common objective.

- *Reassessment of energy taxation.* As energy taxes for the Dutch industry are currently in favour of gas, there are few incentives to switch to electricity as a main carrier. Electrification could be incentivized by the Dutch government by reassessing the structure of energy taxes for the energy-intensive industry. In addition, higher energy charges will improve the Return on Investment for energy efficiency investments, including ROI of electrification options. [6]

- *Maintenance of energy efficiency policies.* Many industries use payback times of two to three years, while business cases for electrification often require longer payback times. When the current 'Wet Milieubeheer' is maintained by the Dutch government, all efficiency measures with payback times below five years need to be incorporated. This includes electrification opportunities. However, this would not cover all electrification potential as there are many technologies which require longer payback times.

- *Guarantee schemes & revolving funds.* One of the identified barriers for electrification, especially electrification of baseload processes is related to high financial and economic risks (see 5.2.1). In that respect, new financial provisions, such as guarantee schemes and the development of revolving funds might by necessary in order to achieve large-scale electrification of baseload processes, For instance, green bonds - a relatively new source of finance - are becoming increasingly popular in an international context.[7] These are bonds specifically meant to finance environmental efficiency measures, issued by public bodies, banks or corporations. The investors that buy the bonds are pension funds or insurance companies.

6 Attention should be paid to how revenue of higher taxes could be fed back to industries via e.g. fixed rebates.
7 Best practices for Industrial Energy Efficiency (Copenhagen Centre on Energy Efficiency, February 2016)

Table 4. Development needs for electrification

Barriers	Development needs	Category	Actor						Time schedule (short, medium, long term)
			Government	Process industry	Manufacturing industry	Grid Operators	Knowledge institutions	Energy producers	
Absence of long-term view on electrification	Outlook on electrification as a transition route	Regulatory	x	x		x	x		Short term
Lack of cooperation between stakeholders	Close cooperation between stakeholders in triple helix structure	Organizational	x	x	x	x	x	x	Short term
Limited temperature application of heat pumps	Focus on research & development of high temperature heat pumps	Technological	x	x	x		x		Short term
Absence of financial incentives	Stimulation of promising technology development	Economic Technological	x	x			x		Short term
Over-emphasis of utility electrification	Focus on redesign of primary processes	Technological		x	x		x		Medium term/ long term
Lack of guaranteed renewable electricity supply	Expansion of renewable electricity production capacity	Technological Regulatory	x	x		x		x	Short term/ long term
Lack of knowledge/ available information	Development of demonstration projects	Technological Organizational		x	x		x		Short term
Absence of financial or fiscal incentives	Funding for demonstration projects	Economic Regulatory	x						Short term
Lack of knowledge/ available information	Communication on best practices	Organizational	x				x		Short/medium term
High CAPEX for required payback times	Establishment of new business models (ESCOs)	Organizational			x		x	x	Medium term
High costs for increased grid tariffs	Adaptation of electricity tariff structures	Economic Regulatory	x			x			Short term
High costs for increased grid capacity	Reassessment of grid connection costs	Economic Regulatory	x			x			Short term
Energy taxes currently in favour of gas	Reassessment of energy taxes	Economic Regulatory	x						Short term/ Medium term
High CAPEX for required payback times	Maintenance of energy efficiency policies	Regulatory	x						Medium term/ long term
Absence of financial or fiscal incentives	Guarantee schemes & revolving funds	Regulatory	x						Medium term/ long term

6.5 Innovation opportunities

One of the objectives of this study has been to provide perspectives on how the Netherlands can obtain a distinctive international innovation position with regard to electrification.

Based on insights of the specific Dutch industrial and energy situation, some inspiring foreign examples, current electrification initiatives in the Netherlands, and the given development needs for the large-scale breakthrough of electrification in the Netherlands, some interesting conclusions can be drawn on the opportunities for the Netherlands to become an innovative country in the field of electrification.

First of all, the unique industrial landscape of the Netherlands, comprising of a large (mainly clustered) concentration of industry in a geographically small area, offers interesting research and development possibilities with respect to electrification. The clustered industrial structure facilitates the short-range exchange of several electrification products such as heat, steam and chemicals. Thus, electrification in such industrial clusters could have a more promising future than encountered elsewhere. This needs to be studied in relation to the potential for the Netherlands to innovate unique possibilities for its own industrial clusters, which are possibly applicable elsewhere.

In addition, the energy system in the Netherlands is unique in that sense, that our process industry has traditionally been fuelled by a wide availability of fossil energy sources, predominantly natural gas. With the transition towards renewable energy sources and the subsequent increase of renewable electricity production capacity, electrification on the demand side becomes an increasingly urgent but also immensely challenging transition pathway. Especially given the fact that our future energy sources are characterized by an intermittent availability of electricity, which is in direct contrast to the nature of the process industry (that is mainly designed to run continuously). On the one hand, this provides a challenge, on the other hand this could generate unique innovations. For instance, a hybrid system driven by electrification from intermittent renewable sources (at low-priced market moments) and efficient fuel-based technologies including CHP and/or with input of green gas (at high-priced market moments) could provide a unique opportunity for application in the Netherlands and elsewhere. This would require, inter alia, adaptation of infrastructure tariff structures in order to be feasible.

Finally, there is a feature that is rather non-unique, being the fact that industrial investments are generally considered on very short timescales and pay-back times. This is a fact throughout the world, preventing many investments in industrial energy efficiency and carbon reduction. It is our observation that this problem needs to be solved in any case, for any industrial energy transition towards a carbon-free society (be it by electrification or by any alternative). For the Netherlands, with its uniquely high share of industrial energy demand, it is a “condition sine qua non”. Therefore, development of ESCO facilities are a mere necessity. This may be difficult to achieve, but once established, it can be applied elsewhere as well.

Next to this ‘industry and energy’ landscape, the innovation landscape already in place in the Netherlands, based on the ‘triple helix’ structure of government, knowledge institutions and industry, provides a potential fruitful ground for research and development on electrification. Therefore, it is plausible to note that:

- Innovation is highly necessary in the Netherlands in order to meet the challenges we are faced with in our future energy supply;
- The Netherlands is suited with the right circumstances to be able to obtain an innovative international position in this field.

In order to become an internationally respected player in the field of electrification, different factors are considered relevant. First al all, a continuous focus on the triple helix structure is deemed essential for successful cooperation and innovation. A characteristic of innovation is that development choices will have a certain inherent risk (especially when early TRL stages are concerned), which can be of different nature (technical, organizational, economical). In order to mitigate such risks, and stimulate innovation and investment decisions, continuous interaction and dialogue between all stakeholders about their wishes and needs (and the development into (long-term) R&D programmes) is important. In the Netherlands, this model is already well-known and visible in different partnerships and institutes. To successfully adopt the model for electrification purposes, a clear position on electrification as a transition pathway is needed, as also stated in paragraph 6.2 and 6.3.

Focal areas for innovation and implementation

The development needs as described in paragraph 6.3 give an indication of the necessary steps in order to facilitate a breakthrough of electrification in the Netherlands. Potentially, some of these development needs enable the movement towards a more innovative international position with regard to innovation. In this respect, four focal areas emerge:

- *Development for application-ready concepts of high temperature heat pumps.* To be able to realise the technical and commercial potential of Power to Heat, higher temperature levels of heat pumps need to be achieved. This is an important development priority for the Dutch industry, but can also lead to large international exposure. A focus on the establishment of triple helix partnerships for research and development of high temperature heat pumps is recommended.

- *Establishment of new business models / market roles (ESCOs).* In the Netherlands and abroad, there is a growing opportunity for aggregators or energy service companies (ESCOs) to become a counterpart of industries. These business models or financial structures are not mainstream yet, but could become interesting best practices for the implementation of energy efficiency measures in an international context. Possible ESCO structures are mentioned in paragraph 6.1. When establishing these ESCO roles, we can combine the interests of three types of parties:

    - The industries involved, aiming for lower cost and/or lower carbon emissions/more renewable energy sourcing;
    - Generators of renewable energy (like wind parks), aiming for higher revenue especially at intermittent moments of high production of renewable energy (avoidance of price dips);
    - The energy utilities in general, aiming for a growth of their sales in electricity combined with a more service-oriented approach.

    The main target would be to achieve business models able to invest in electrification on a longer-term basis than currently employed. For the Netherlands, with its uniquely high share of industrial energy demand, this is a necessity and also a unique opportunity.

- *Concepts for intermittent electrification.* In an international context, electrification measures are mainly applied in a baseload fashion. For the Netherlands, the application of flexible electrification (responding to the intermittent character of renewable electricity sources) provides opportunities. This model would also be applicable in other countries that are increasingly depending on renewable sources, such as Germany. The development of strong concepts for flexible electrification (e.g. power to heat, chemicals, hydrogen and peak shaving) could therefore become a desirable innovation abroad. The development of this opportunity would require technical, operational, financial and organisational measures, such as the development of ESCOs and possibly the adaptation of electricity grid tariff structures, as described in paragraph 6.3.

- *Focus on the implementation of high COP technologies.* As analysed in this study, high COP technologies such as MVR and steam recompression show high potential for electrification, even in a baseload fashion. Thus, these technologies become interesting for reducing CO_2-emissions regardless of the increasing power prices as depicted in this report. We identify these technologies as a main focus area for the implementation of electrification in the Netherlands.

Future energy consumption and market developments

Annex A

A.1 Expected future development of industrial energy consumption

To be able to assess the potential for electrification in the Dutch process industry, it is essential to research the expected development of energy consumption in the future (towards 2023/2030 and possibly 2050). Looking at these time frames, there are autonomous trends in energy consumption, but also trends in policy that should be incorporated.

When attempting to answer this question, studies conducted on a system, society or economy wide level are especially relevant. In this respect, the medium term future exploration in the 'National Energy Outlook' (ECN; PBL; CBS; RVO.nl, 2016) was used, as well as Scenarios for 2030 and 2050 in the CPB/PBL publication series 'Prosperity and Living Environment (PBL en CPB, 2015). Both studies show development of energy use in the Netherlands for the near-, middle- and long-term future. In addition, a CE Delft composed overview of likely shifts in heat demand in some sectors was used.[8]

8 This overview was used as input to discussion sessions for the think tank heat market, hosted in 2015.

National Energy Outlook

A first source of forecasts for 2020, 2023 and 2030 can be derived from the National Energy Outlook (NEO), an annually conducted study (ECN; PBL; CBS; RVO.nl, 2016). The NEO outlines the current state of the Dutch energy system (in an international context) and provides two plausible forecasts for the future. These forecasts are based on as up-to-date as possible information relating to prices, markets, technology and policy. The NEO forecasts incorporate established government policies, and optionally also 'intended' policies[9].

9 The 'existing policy' variant refers to specific measures that have already been officially published as well as measures that are as binding as possible, such as the European Emissions Trading System (ETS) and subsidies for renewable energy. The 'intended policy' variant is based on existing policy plus published intended measures that were not yet officially implemented but were specific enough to incorporate in the calculations, such as a large number of measures from the Energy Agreement for Sustainable Growth (SER 2013).

Reference scenarios Prosperity and Living Environment

A second source of forecasts contains reference scenarios for the period to 2030 and 2050 and can be found in the CPB and PBL publication ‘Prosperity and Environment’ 2015, known under the Dutch abbreviation WLO 2015 (Toekomstverkenning Welvaart en Leefomgeving). These scenarios are an update of the 2006 versions. The WLO 2015 aims to be a broadly applicable set of future scenarios that are coherent and applicable to a large set of policy fields of the Dutch government (infrastructure and environment, economic affairs, built environment). The WLO presents two scenarios, ‘high’ and ‘low’, that differ in demographics, economic growth, world trade, climate policy, etc. The scenarios detail demographics, macro-economics, regional development, urbanisation, mobility, agriculture and climate and energy. With regards to the latter:

- In the ‘low’ scenario (low economic and demographic growth), climate policy is comparable to current climate policies, resulting in 45% carbon savings in 2050. The WLO predicts that in this scenario, average global temperatures at the end of this century will be 3.5-4 degrees higher. This would have a very significant effect on living conditions in large parts of the world, including the Netherlands.

- In the ‘high’ scenario (high economic growth, high demographic growth), climate efforts are substantially increased compared to the current situation but still causing a temperature change of 2.5-3 degrees at the end of the century. Carbon emission savings are 65% in 2050 – below the official target.

- For the stated purpose of sensitivity testing the WLO scenarios include ‘2 degrees’ scenarios with substantially higher CO_2 prices as compared to the ‘high scenario’. These scenarios lead to 80% emission reductions in 2050.

The WLO reference scenarios were made without taking into account the ambitions of the COP21 Paris Climate Conference, which are currently widely agreed upon.

A.1.1 Industrial energy use in the scenarios

The development of industrial energy consumption by the two studies is depicted in figure 1.

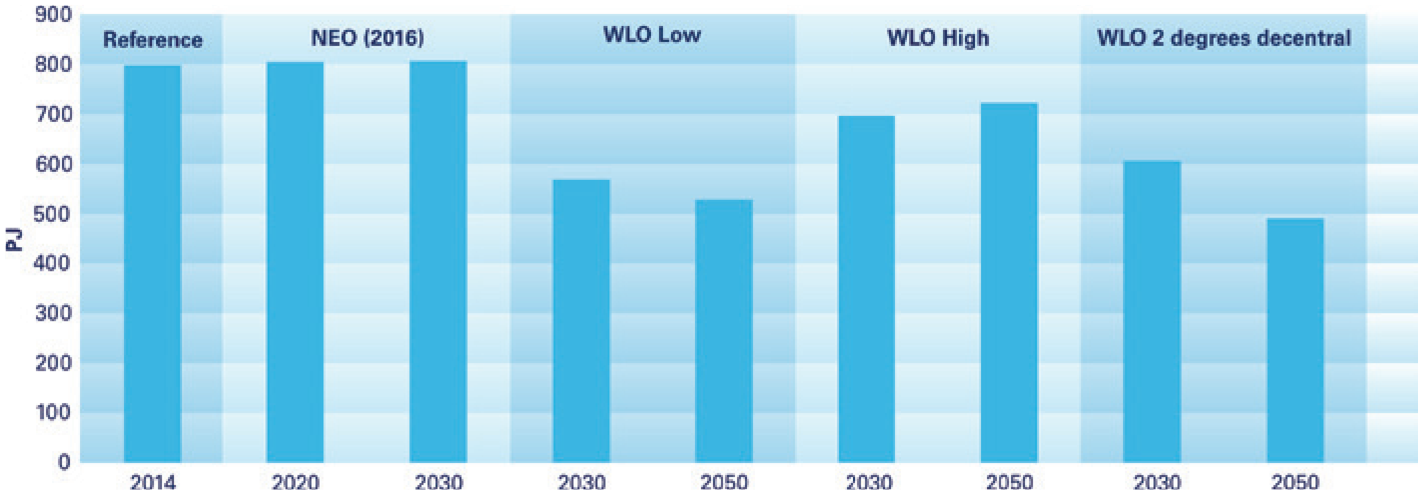


Figure 1. Development of energy use in industry in NEO (2016) and WLO (2015) scenarios

It can be observed that the NEO shows little dynamics, whereas the WLO scenarios show larger changes in the energy consumption, with some interesting observations.

The NEO reports the following general trends for the near future (NEO, 2016):

- Decrease in energy use or greenhouse gas emission is not structural yet. Under the current policies, the energy use and the greenhouse gas emissions in industry are expected to remain constant when it comes to final energy use. The fact that energy use is expected to remain constant shows that the proposed energy efficiency measures of the SER Energy Agreement are supposed to be realised and thus included, since production based on fossil fuels is expected to increase towards 2030.

- Private investments in innovative clean technologies are lagging. On the short term, investments in innovation tend to significantly reduce costs of clean technologies enhancing their competitiveness. Good examples of how investments in the early stages of implementation of a technology can reduce the costs of a technology are solar panels and electric cars. Other technological options with comparable potential significance for the reduction in greenhouse gases are CCUS and gasification of biomass. These technologies still await similar investment levels.

- A mentioned significant barrier for investment in energy efficiency and renewable energy production is a lack of clarity on climate ambitions and subsequent policies to meet these ambitions. The energy agenda (2016) partly solves this by giving indications of policies that will act on the industry to become more energy efficient and emit less CO_2.

The WLO scenarios predicts the following industrial development:

- The overall electricity demand in 2050 increases in both scenarios (low 17%/high 38%) due to volume growth in industry, electrification of processes and partly reduced by realised efficiency gains.

- Heat demand declines in the low scenario with approximately 20% and in the high scenario with 10%. The high scenario contains a volume increase of 50% and 1.5% per year efficiency savings. Heat demand is more satisfied with heat pumps instead of gas fired heaters in both scenarios.

- Steel production is expected to diminish by 3% in the low scenario to 2050, and increase by 3% in the high scenario. Fertilizers (NH3) and feedstock for plastics are expected to remain at current levels in the low scenario, and are growing 18 and 13% respectively in the high scenario.

- In the high scenario, CCUS is used, and biomass feedstocks and electrification are used for plastics and fertilizer production respectively.

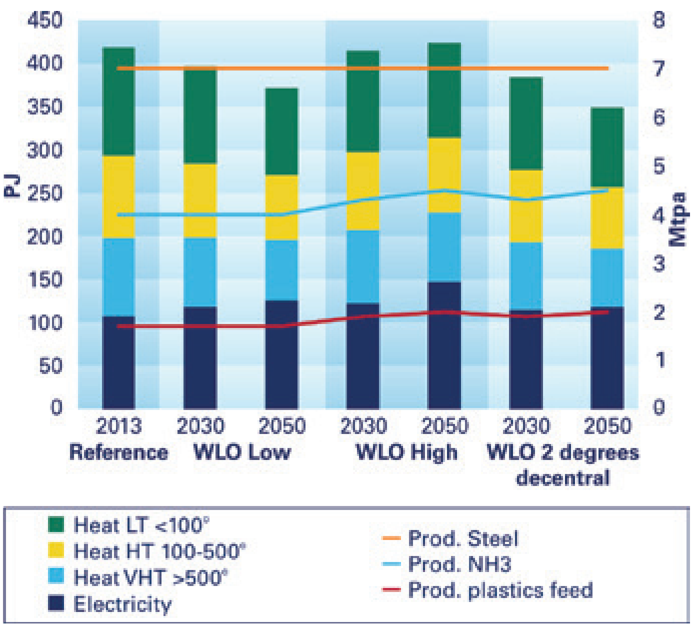


Figure 2. Development of energy use in industry in WLO scenarios

A.1.2 Commodity prices in the NEO and WLO scenarios

It is interesting to have a look at the market circumstances that are assumed in the NEO and WLO. The assumptions differ significantly, as is indicated in the table below.

Table 1. Comparison of commodity prices in NEO and WLO

	NEO (2016)		WLO Low (3,5 - 4°C)		WLO High (2,5-3°C)		WLO 2 degr (<2°C)	
	2020	2030	2030	2050	2030	2050	2030	2050
CO2 (€/tCO2)	11	26	15	40	40	160	100-500	200-1000
Crude oil ($/bbl)	56	94	135	160	65	80	65	80
Gas (€/MWh)	18	29	37	46	18	22	18	22
Coal (€/ton)	42	77	104	117	77	77	77	77

*Assuming the same exchange rate as reported by NEO (1.11 $/€) for 2030-2050

The scenarios clearly show that if CO_2 prices are raised to curb climate change, the demand for fossil fuels decreases and therefore so will the prices. This is the reason that the oil, gas and coal prices are lower in the high and 2 degrees scenarios. Thus, one should realise that if prices of fossil fuels in these scenarios are low, the use of fossil fuels is nevertheless less competitive due to heavy CO_2 pricing with possible supplemental policies.

A.1.3 Other developments affecting energy consumption

Future policies

Both the NEO and WLO scenarios are based on extrapolation of current trends, and do not explicitly contain additional future policies. There is a number of interacting policy movements that would impact future energy use in industry.

- Attempts to open up economies and further liberalise global trade (e.g. TTIP, CETA), and attempts to do the reverse, nascent protectionism
- European and national action to support and protect industries that are considerably more efficient or sustainable than other industries (Resource Efficiency roadmap).
- Specific calls for more policy clarity, policy robustness and long term goals. E.g. from Dutch industry (VEMW position paper), as well as from NGO's and parliament.
- A more ambitious Energy Agenda put forth by the ministry of Economic Affairs.
- Since the Paris COP21 agreement has been ratified by the European Union, we may expect some significant changes in policies in the years and decades to come and therewith a strong urge to reduce CO_2-emissions in the industry.
- Market demand for products with small CO_2 footprint and or good Life Cycle Assessments (LCAs)
- Increased role for CSR (MVO) due to shareholder value pressure
- Specific breakthrough technologies, e.g. in industry, in raw materials or in demand for industrial products (that could be stimulated by directed policy).

More energy-efficient technologies, applying emerging processes

Existing industries will increasingly face competition from new built factories in emerging economies. There is a real threat that without investments in energy efficiency, Dutch and EU industries will be replaced by industry in other parts of the world. This is because when new factories are built; this offers possibilities to employ new and innovative technologies and processes that are inherently more energy efficient than either current or “yesterday’s” technology as currently applied by the Dutch and EU industry. This means that if the European energy intensive industry wants to remain competitive on a global scale, sometime during the years up to 2030, a significant upgrade of the applied process technology will be required to achieve significantly greater operational energy efficiency (for instance: the spinning disc reactor, developed at the TU Eindhoven, is already sold for mass production in India, but it has not seen application in Europe).

Major energy efficiency improvements are possible if the latest insights in catalysis, reactor design (including process intensification) and separation technology (membranes, crystallisation technologies) are applied. Electrification can be part of this. This is critical: without innovation and new processes, the competiveness of the present industries will slowly but steadily deteriorate, leading to a risk that Dutch production locations will in the end cease to be viable. In a ‘managed decline’ scenario, industrial energy consumption and carbon emissions will decrease, but this will be at the expense of a large loss of economic activity and related welfare.

Resource efficiency: raw materials, new feedstock, CCU

A different possible development is the shift to different raw materials as feedstock, making more use of recycled content. These initiatives are promoted under the flag of circular or bio-based economy and this can significantly decrease the CO_2 footprint of production chains, while there will remain a sizeable energy consumption related to the processing of the circular streams.

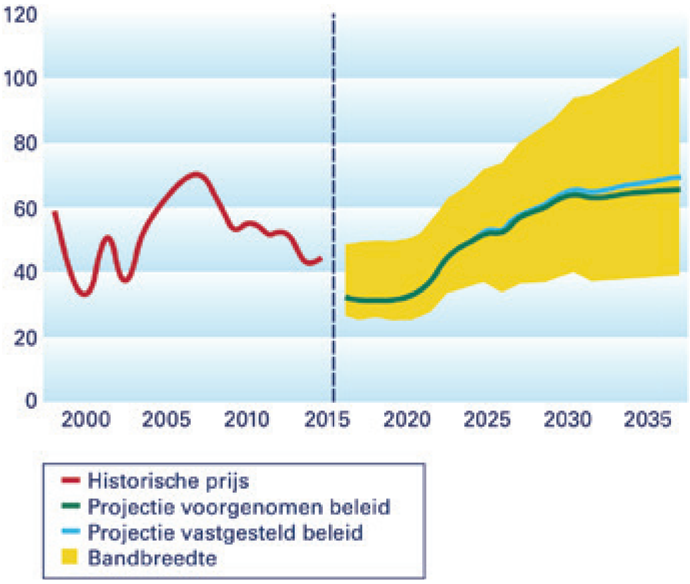
Supporting a switch to more resource efficient production within Europe would increase resource efficiency and decrease overall energy use within the European industry. This would contribute to meeting climate goals by promoting very sustainably produced products with a price advantage, either by direct tax or increased price of CO_2 rights to discourage inefficient energy use.

A.2 Scenarios for electricity prices: 2016-2035

1) ECN - National Energy Outlook (2016)

The NEO’s electricity prices are derived from market simulations of the wholesale market in an international context with a simulation model (COMPETES).

Average wholesale price. The development of the average power price up to 2035 in the NEO 2016 is depicted in 9. The trend of declining power prices is simulated to hold to 2020, but the NEO expects that after 2020, prices will rise towards 2030. The price remains at a low level of about 30 €/MWh (25-50 €/MWh) until 2020 and then rises to a level of 50 €/MWh (35-75 €/MWh) in 2025 and 65 €/MWh (38-90 €MWh) in 2030.



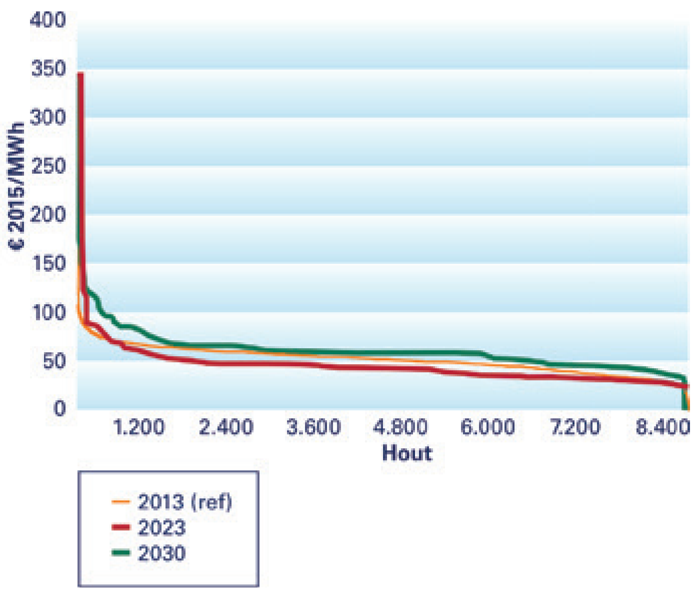
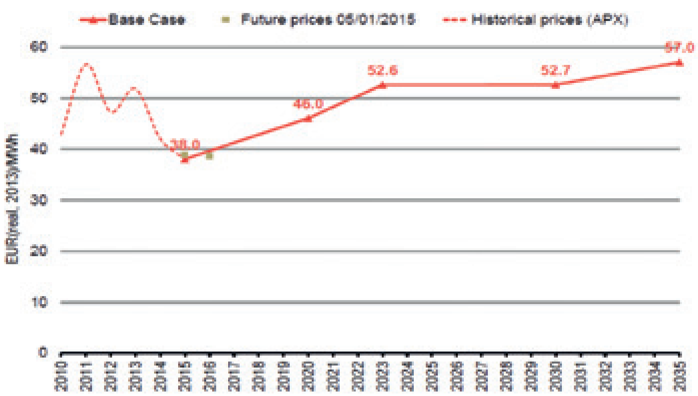


Figure 3. Commodity price ($€_{2015}$ / MWh) from ECN NEO, price duration curve for the fixed policy scenario (courtesy: ECN)

Volatility. The NEO itself does not state how price volatility is expected to change. The curves in figure 3 were obtained from ECN policy studies and show the distribution of the hourly prices, under the *fixed policy* scenario. The ECN model (COMPETES) was used to simulate volatility in the so-called FLEXNET project, in which the flexibility provision in the future power system was investigated. This study showed that interconnection (the international trade option) is the most important source of flexibility and will have a large share in future flexibility provision. International trade tends to depress volatility. The curves show increased volatility compared to the 2013 reference. This mainly has to do with the price spikes and more limitedly with low power prices. In the simulation, clearly the power system is able to absorb the renewable energy that is produced in the scenarios. It must be noted though, that the 2030 curve has rather limited wind production as it is the fixed policy variant (no new policy after 2023).



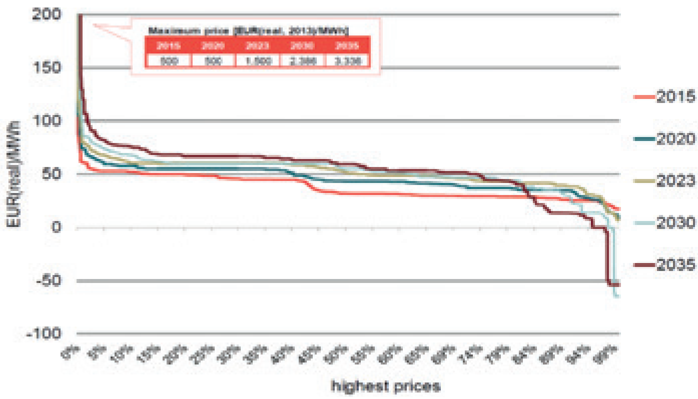


Figure 4. Commodity price (€$_{2015}$/MWh) and price duration curve Frontier (2015)

Volatility. Looking at the end of the price duration curve (right in the graph), the number of hours where the power price drops below the level of the gas price can be estimated[10]. In 2015, this accounts for about 2% of the year (170 hours), in 2020 for 5% (450 hours), in 2023 about 9% (900 hours). In 2030 for 11% (1000 hours) and in 2035 for about 18% of the year (1500 hours).This shows that there might be potential for flexible electrification after the year 2020.

Frontier also shows high price spikes in the future, which shows a potential for demand flexibility the other way round, e.g. limiting energy demand during some hours.

2) Frontier Economics – Scenario's for the Dutch Electricity System (2015)

Frontier Economics uses a somewhat different scenario development and a different power market model.

Average wholesale price. The results of their scenario in terms of the average yearly price and the price duration curve are depicted in Figure 4. Frontier expects the average price to increase to 46 €/MWh in 2020, 53 €/MWh in 2023, remaining flat to 2030 and rising to 57 €/MWh in 2035. The trend to somewhat higher power prices starts earlier than in the NEO scenario, but is less severe (post 2025 prices are lower than in NEO).

10 For the years 2020/2030/2035, Frontier calculates with a (LHV) gas price of 29/ 32/33, ECN with 21/32/34 €/MWh.

3) Berenschot, CE Delft, ISPT - Power 2 Products – study (2015)

ECN and Frontier have modelled the power market assessing the integrated European system. This is accurate, but includes numerous effects modelled (such as interconnection investment and flexible power plants) that tend to dampen volatility. In the Power to Products project of 2015, an elaborate study was made on the power market, in which CE Delft, Berenschot and ISPT designed scenarios for the Dutch electricity system explicitly to investigate how volatility could materialise. The scenarios showed that volatility will markedly increase with the impact of renewable electricity.

Figure 5 show the fluctuations of average price levels over a number of time scales, for the year 2023 for three different future scenarios developed in the Power to Products project. The simulations were performed with a power market simulation model under the assumption that Dutch overcapacity of wind and solar production needs to be used within the Netherlands, because similar weather patterns are observed within surrounding countries. The figure shows that, distributed over the year, there are numerous moments where electricity is cheaper than gas.[11]

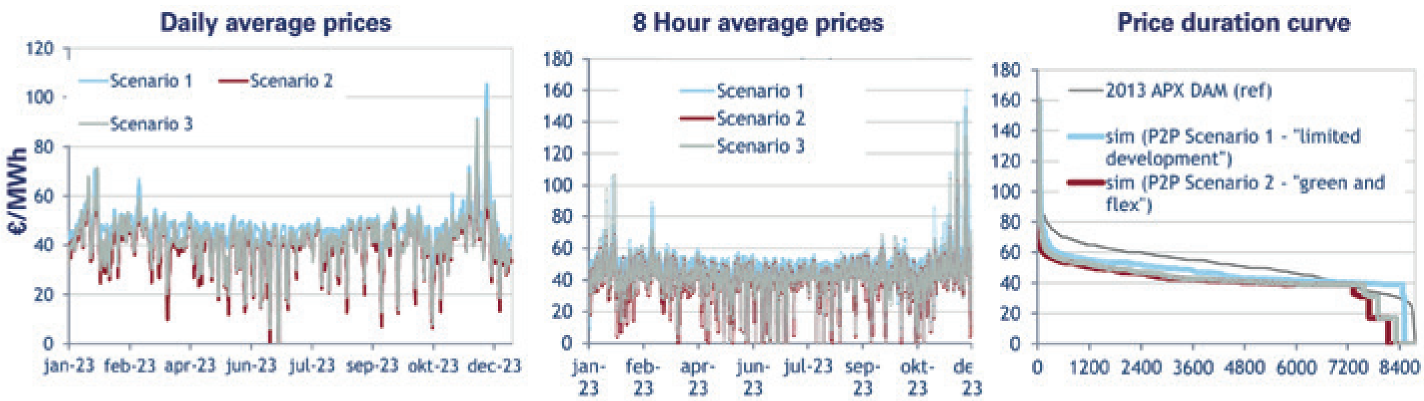


Figure 5. Volatility depicted in price levels on different time scales (2023) (€$_{2015}$/MWh)
Source: (Berenschot, CE Delft, ISPT, 2015)

In the study, it was also investigated how many hours there were in the different scenarios that would allow the application of specific techniques, such as power to heat. Looking at the year 2023, in the scenarios 1, 2 and 3 the power price is below the gas price for 250, 1050 and 850 hours, respectively[12]. The average price is lower than in the scenario's from Frontier and ECN: 47, 40, and 42 €/MWh for the respective scenarios. The price duration curves from the scenarios made in the power2products study show the prices over the year sorted from high to low. The scenarios with more renewable energy show increased volatility with some changes to the curve depending on e.g. increasing the flexibility of CHPs. For a further treatment of the scenarios designed and the consequences for the price formation and volatility please refer to that study.

11 The base gas price in the scenarios is 30 €/MWh
12 Scenario 1 contains only 4 W wind and 2 GW solar and current CHP. Scenario 2 contains 11 GW wind and 7 GW solar, and CHP is maximally flexible. Scenario 3 contains 10 GW wind and 6 GW solar and more CHP is phased out.

Gross list of electrification examples

Annex B

Type	Electrification technologies	Unit operations	Sector / industry	Development status (Demo/commercial)	Energy savings potential (if available)	Specific electricity use (efficiency)	baseload / flex?	remark	Ref. nr.
Power2 Heat	Heat pumps	Low temperature drying, Pasteurization, Hot water for cleaning/ sterilization	All	Commercial for hot water, demo for steam producing		COP = 3,5 for steam producing heat pump (120°C)	Preferably baseload	ECN CAPEX should decline from 900k€ → 200 k€	1
Power 2Heat	Electric boiler, Electrode boiler, Combining EB with CHP	Hot water, thermal oil Steam generation,	All	commercial		99% - 99,9% efficiency	Flex	Not for baseload	2
Power 2Heat	Steam recompression/ vapour recompression	Steam system optimisation (e.g. for distilling drying etc.)	Various	commercial					3
Power 2Heat	Induction furnace	Baking, melting, casting	Metal	commercial					4
Power2 Heat	Microwave heating	Drying	Various	commercial	Also possible to combine electromagnetic drying with convection				5
		Heating. pasteurisation or sterilisation of milk	Dairy industry	demo			baseload		6
		blanching	Vegetable processing	commercial			baseload		7
		Baking	Bakeries	Commercial	25%		batch		8
Power2 Heat	Electric melting	Melting	Metals	Commercial					9
Power2 Heat	Electric arc furnace	Iron production based on scrap	Metals	commercial					10

Type	Electrification technologies	Unit operations	Sector / industry	Development status (Demo/commercial)	Energy savings potential (if available)	Specific electricity use (efficiency)	baseload / flex?	remark	Ref. nr.
Power2 Heat	Plasma heating	Heating	Glass	research	Tests with High Intensity Plasma Melter in fibre production demonstrated 50 – 70% improvement in energy use compared to direct firing (specific energy requirements of 4.33 GJ/t are reported for the technology, compared to 8.88 GJ/t which is industry average in the US) (GMIC, 2004. p. 167).	Tests with High Intensity Plasma Melter in fibre production demonstrated 50 – 70% improvement in energy use compared to direct firing (specific energy requirements of 4.33 GJ/t are reported for the technology, compared to 8.88 GJ/t which is industry average in the US) (GMIC, 2004. p. 167).			11
Power2 Heat	Infrared	Heating	Ferro						12
		Sterilisation, pasteurisation	Food						13
		Drying	Paper, coating						14
Power2 Heat	Impulse drying	Drying	Paper Sludge	demo	By allowing 5 to 10 percent points of increased drying, impulse drying can reduce heat energy consumption by 0.44 to 0.9 GJ/t-paper (assuming 2.5 MJ/kg of steam) (BREF, 2010. p 665)	An estimate has put the possible savings in dry steam utilization at 50 to 75%. Another study reports the energy savings of around 18 to 20% or 2.1 GJ/ton of paper. Electricity requirements increase by 5 to 10% (Kramer *et al.*, 2009. p.112).	baseload		15
Power2 Heat	Impingement drying (steam / air)	Drying	Food and beverage Textile Paper	Commercial	It has been estimated that the impingement drying technique can save up to 10 to 40% steam compared to traditional gas-fired or infrared drying technologies.	However, electricity consumption increases by 5%.	baseload		16

Power2 Heat	UV	Curing of paint/coating/ inks/ adhesives, Control of polymerisation reactions	Various		flex		17
		Air purification			Flex		18
		Sterilisation and desinfection			Flex		19
P2H2	Electrolysis	H_2 production	H2 production	commercial		Higher yield H2 electrolysis under development	20
		Ammonia from H_2	Chemicals	demo	Baseload/ flex	Business case needs external input in case of flex	21
		Reduction of iron ore with H_2 from electrolysis instead of coal	Metals	research	baseload		22
P2Com	Electrolysis	Decentral Cl_2 production	Chemicals	commercial	Baseload/ flex	Business case needs external input in case of flex	23
		Methanol production from H_2 and CO_2		commercial	Baseload/ flex	Business case needs external input in case of flex	24
		Aluminium production	Aluminium	commercial	baseload	Current production technology	25
P2Com	Electro synthesis	Electro synthesis of ammonia from H_2O and N_2 bypassing H_2	Chemicals	Research/demo?	Baseload/ flex	Business case needs external input in case of flex	26
		CO_2 based chemistry for ethylene glycol, isopropanol and acetic acid		demo	Baseload/ flex	Business case needs external input in case of flex	27
P2S	Electro synthesis	Production of various specialties (see reference)	Chemical	Commercial			28
P2S	Plasma polymerisation	Coating	chemical	commercial	baseload		29
P2S	Plasma	Recycling	Non-ferrous metals				30

Foreign and Dutch best practices

Annex C

C.1 Promising technologies from foreign examples

The primary result of the survey is a 'technology matrix' or 'gross list' that lists the techniques we found, as included in Annex B. Here, we elaborate on a few promising technologies for electrification that can find application in the Netherlands[13]:

- Electromagnetic energy/microwave heating, drying
- Heat pumps: compression heat pump
- Mechanical Vapour recompression (with special case steam recompression)
- Electric (re-)boiler + including CHP hybrid concepts
- Replacement of steam drive by electric drive

C.1.1 Electromagnetic radiation (microwave heating, drying, etc.).

Electromagnetic radiation

Country: USA, Sweden, Germany and others
Sector: food industry, metal products industry, petrochemical industry, plastics industry, wood industry, etc.
Unit process: electromagnetic radiation is applied for drying, baking, and heating of vapour containing products.

Description

Because of the very concentrated interaction between material or moisture and radiation processing time is shortened and energy consumption is reduced with tens of percentage points. It can be integrated with existing drying equipment by placing it in front or behind the existing installation. As a pre-dryer, typical energy saving rates amount to 25% - 35%.
The microwave equipment requires no too little heat-up or cool-down time, meaning less waiting and more efficient use of time. The process can hence be applied as a flexible power consuming process. But in view of potential savings in processing time and energy consumption maximum utilization and in view of the involved investment costs maximization of operational time is more logical from an economic point of view.

Hybrid application is also possible. Combining electromagnetic energy (e.g. microwave or radio frequency) and convective hot air can yield accelerated drying processes by selectively targeting moisture with the penetrating EM energy, yielding far greater efficiency and product quality than drying processes based solely on convection, which can be rate limited by the thermal conductivity of the material.

Supply chain aspects and economy

Electromagnetic radiation equipment applied as pre-dryer requires an investment of $7.000 - $10.000 per kW installed[14 15]. In the USA, investments are re-earned within 12 – 24 months. The microwave has to be replaced every 5.000 – 6.000 hours, costing approximately $100/kW for a 915 MHz tube.

Application and potential

Electromagnetic radiation for baking, heating, drying, sterilization, etc. is a mature technology applied commercially in above mentioned sectors. It can potentially also be applied in paper making especially in the drying section. Though this application has been studied since several decades, up to now it has not been implemented in commercial installations.
An application still in its infancy is high temperature baking of ceramics.
Theoretically, electromagnetic radiation may be implemented as a pre-dryer in probably every type of drying process in the Netherlands. Heat demand for drying amounts to approximately 80 PJ/a. In addition, it can be applied in smaller sectors, such as bakeries.
Total potential that might be implemented up to 2030 is estimated to range between 10 – 20 PJ/a.

13 Based on workshops with industrial parties and our own data
14 R.F.Schiffmann, 'Microwave and Dielectric drying', in A.S Mujamdar (ed.) Handbook of Industrial Drying (4th Edition, 2015).
15 http://www.linn-high-therm.de/fileadmin/user_upload/pages/about_us/download/publications/white_papers/Microwave_Rubber_Heating_Technology.pdf

C.1.2 Heat pumps for hot water and LP steam

Heat pumps for hot water and (low temperature) steam

Countries, Norway, Denmark, Germany, Japan, etc.
Sector: food industry,
Unit process: heating, drying

Description

Heat pumps utilizing waste or residual process heat from industrial processes (or other sources) are used for hot water production. The produced hot water is utilized for e.g. cleaning, pulping and deinking of recovered fibres, preheating of drying air, space heating, preheating of fluids, etc. Temperature lift is restricted to approximately 50°C - 70°C.
Primary reason for implementation is reducing production costs for heat generation. As start-up and shut down time is only several minutes, heat pumps can be utilized as flex consumers of surplus power. In this application heat pumps are utilized in Denmark and Germany, supplying heat to hot water district heating systems. However, investment costs are quite substantial, making it more attractive to utilize them in baseload operation.
High temperature heat pumps that are able to produce steam are being demonstrated in Japan by Kobe Steel, Ebara and Fuji at a capacity of several tens to hundreds of kWth, while in Europe Siemens has developed a pilot scale high temperature heat pump. They allow steam generation based on relative low temperature heat sources such as cooling water from stationary engines.
Pictures below show the heat pumps at Drammen district heating and a 30kW steam generating heat pump.

Supply chain aspects and economy

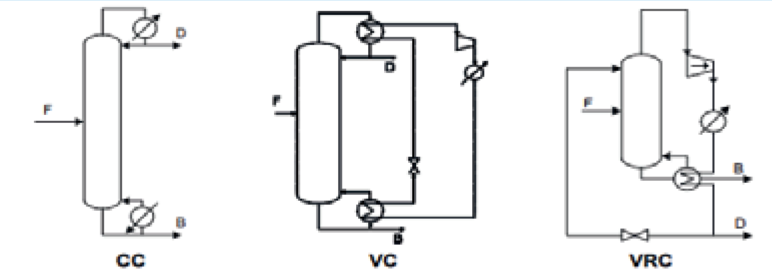
According to DEA, 2016 an electric heat pump with send out capacity of 1 - 10 MWth utilizing a heat source of 35°C and CO_2 as refrigerant (COP 3, 6) requires an investment of 500 euro/kWth - 900 euro/kWth installed. RVO gives specific investments of 250 euro/kWth (COP 4.7, 500 kWe). OPEX (excluding power purchase costs) are given in (DEA, 2012) as amounting to 2.4 - 4.9 euro/MWhe

Application and potential

Hot water heat pumps are commercially available as an off the shelf item. But there are still possibilities for optimization and specific investment costs are expected to decline with 15% - 20% in the period up to 2030.
Low pressure steam producing heat pumps are being demonstrated in Japan and are in pilot scale development phase in the EU.
Theoretically all of the hot water used in Dutch industrial sectors could be covered utilizing heat pumps. In practice the potential will be and should be significantly lower if hot water is generated with onsite waste heat while maximizing heat cascading and energy efficiency on location.

C.1.3 Mechanical Vapour Recompression

Mechanical vapour recompression in other applications than drying
Country: The Netherlands, other EU member states, USA, Japan Sector: chemical industry, Unit process: distillation
Description
In mechanical vapour recompression in combination with distillation the heat of condensing of the separated distillation vapours is utilized as a heat source for the distillation process. For this, the vapours are compressed and then condensed by heat exchange with the mixture that is to be distilled (VRC) or the vapours exchange heat with the working medium in an external evaporation-compression cycle (VC). The technology is applied in baseload. The technology is supplied by conventional suppliers of distillation equipment, e.g. Sulzer.



Conventional column (CC), vapour compression column (VC) and vapour recompression column (VRC)

Supply chain aspects and economy
An older technical review from Sulzer indicates that in distillation the investment fora vapour (re-)compressions system is paid back after just a few years, in many cases within a period of one year. Specific investment costs amount to €1.300/kWe with COP’s ranging from three to ten
Application and potential
The technology is mature and its potential in Dutch chemical industry has been studied. It has seen limited application in the Netherlands (at least 1 site) Based on this analysis the combination of vapour recompression VRC, compression columns (VC) and other heat integrated distillation columns (HIDiC) and novel heat pumps would lead to an estimated 820 MW or 20 – 25 PJ/a savings, which is almost 35% of the reboiler duties of all the pinch columns in the Netherlands.

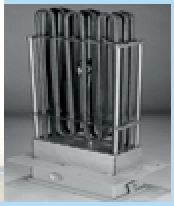
C.1.4 Electric steam boiler + (including CHP hybrid concepts)

Classification

Country: Germany, Denmark, Sweden, Norway, other
Sector: food industry, chemical,
Unit process: heating, drying

Description

Saturated steam with temperatures up to 350°C can be produced with commercially available electrode boilers with capacities of up to 70 MWe. These boilers have an efficiency of up to 99.9% are robust, offer an availability of 100%, have low CAPEX and are able to cycle quickly when hot.
Smaller capacities can be done with electric boilers with resistance elements instead of electrodes. Resistance heating is also possible for heating air or other gases to temperatures of up to 600°C, the efficiency of resistive heaters are up to 99%.
The motive for using these technologies is multiple fold: flexible operating at times of low electricity prices, standby capacity for gas fired boilers, improving the flexibility of CHP.
The operation is typically done in a flexible way. Opportunities mainly occur during periods of low electricity prices resulting from temporarily high contributions from wind during off-peak hours and solar PV (during daytime hours in spring/summer).
Partners technology suppliers: Available from many boiler manufacturers: Bosch, Parat, etc.
Very popular in Denmark, where they are integrated in city heating grids for LT purposes.

Supply chain aspects and economy

Quoted figures for the investment costs of electrode boiler amount to approximately €60/kWe bare equipment or 150-190/kWe all in including electrical connection, with fixed O&M of 1.1 €/kW/y and variable O&M of 0.5 €/MWh (sources (Energinet.dk, 2012; Agora Energiewende, 2014).
For an air heater unit the CAPEX figure is € 60/kWe - € 200/kWe. Investment costs for an air heater installation can vary greatly, depending on structural investments such as foundations required for installation.
In all cases the electricity connection costs to a utility and onsite should be included and are site specific.

Application and potential

Current TRL level is 9, established technology
Theoretically a large share of the Dutch heat demand for hot water and LT steam could be facilitated by the technology. However the practical potential is far more limited, and the numbers of PJ that could be electrified and thus the contribution to CO_2 emissions reduction will depend on the price spread between electricity and conventional energy carriers.
In (CE Delft, 2015b) a possible realisable market potential of 2.5 GWe was sketched. With some 1000 running hours that would save some 11 PJ primary energy.

C.2 Initiatives in the Dutch process industry

C.2.1 Power to heat

Power to heat for heating

Power to heat shows a wide variation of technologies and applications (sectors, processes, utilities). Current available technologies are compression heat pumps, mechanical vapour recompression (MVR), steam recompression, electric boilers, acoustic heat pumps and cold storage.

All of these technologies are commercially available on an industrial scale, except for acoustic heat pumps. High Temperature (HT) heat pumps for industrial application are not available above a 130°C level and systems above about 90°C do not have an acceptable CAPEX. On (HT) heat pumps, a lot of initiatives are launched. MW application of HT heat pumps is not commercially available yet, but it can be expected that this will be achieved within a couple of years. Electric boilers are commercially available up to tens of MW, but have not been economically feasible up to now.

The COP of an E-boiler is approximately 1.0, while the COP for a HT heat pump will be approx. 4, and for MVR and steam recompression will be approximately 10 (depending on pressure difference). For that reason, the economic feasibility for heat pumps, MVR and steam recompression will be better and will be based on baseload. With a COP above 2-3 (for the situation in the Netherlands) these systems reduce the nett CO_2 emissions, because the efficiency of the production of electricity is currently above 43%. Application of E-boilers can be found in the generation of utilities like steam and hot water. E-boilers will be suitable for flex operation and/or back up.

The low number of cold storage projects published is remarkable.

Table 3. Power to Heat for heating

Technology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr.
Production of silicon carbide	Chemical	Heat production (2,700K) by means of resistance heating.	ESD-SiC	<2016	In operation			Flex	1
Steam recompression	Chemical	Steam generation	DOW Benelux + TKI-ISPT	2015-2018	Pilot Commercial available	6 PJ[16]	1 kWe / 10 kWth	Base	2
E-boiler	Food	Steam generation	Avebe, Smurfit Kappa, ISPT	2015	Study; economically not feasible		1 kWe / 1 kWth	Flex	3
E-boiler	Chemical	Steam	AkzoNobel	2016	Study		1 kWe / 1 kWth	Flex	4
E-boiler	Chemical	Steam	Sabic	2016	Study		1 kWe / 1 kWth	Flex + back up	5
E-boiler	All	Steam, hot water	Stork Technical Services	2017	Study		1 kWe / 1 kWth	Flex	6
E-boiler	All	Steam, hot water	Parat (N)	<2013	Commercial available		1 kWe / 1 kWth	Flex + back up	7
Hybrid boiler (gas + E)	All	Steam, hot water	Viessmann (D), Standard Fasel	2016	First of class			Flex + stand by	8
TAP + PCM (Thermal Acoustic HP)	All	Steam or hot water	ECN, TNO (Voltachem)	2015				Base	9
Mechanical Vapour Recompression		Steam or Vapour	Bronswerk Heattransfer	2016	Prototype				10
Mechanical Vapour Recompression	Salt production	Steam or vapour	AkzoNobel	<2016	In operation		1 kWe / 10 kWth	Base	11
Mechanical Vapour Recompression	Food	Steam	Royal Friesland Campina	2016	In operation		1 kWe / 10 kWth	Base	12
HT heat pump	Chemical	Hot water?	Teijin Aramid, Emmen	2016	In operation		1 kWe / 10 KWth	Base	13
HT heat pump	Food	Steam (LP steam 130°C)	Royal Cosun	2016	Study		1 kWe / 4 kWth	Base	14
HT heat pump	Food	Steam (180°C)	Royal Cosun, Aviko	2016	Study		1 kWe / 4 kWth	Base	15
HT heat pump	Chemical	Steam (140°C)	AkzoNobel, ISPT	2016 -2017	Study		1 kWe / 4 kWth	Base	16
HT heat pump	All	Hot water, LP steam	ECN	?			1 kWe / 4 kWth	?	17
Heat pump CAPEX reduction	All	Hot water, LP steam	ISPT, DOW, BHT, IBK, ECN	2016			1 kWe / 4 kWth	Base	18
HT Heat Pump?	Chemical, food	Steam	ECN, Akzo, DOW, Bavaria, Huntsman (STEPS)	2016	?		1 kWe / 4 kWth	Base	19
Hybrid Energy	All	Steam, hot water	TUD		Research				20
HT Heat Pump	Paper	Steam, hot water	IBK, Bronswerk HT, Smurfit Kappa	2015-2016	Pilot		1 kWe / 4 kWth	Base	21
Thermo Acoustical Heat Pump	All	Steam, hot water, air	ECN	< 2005	Pilot, TRL = ?			Base	22
Cold storage	Food	Water	Royal FrieslandCampina	2016	Study				23
Cold storage	All; domestic	Ice	Viessmann	2014	Commercial				24

In conclusion, power to heat has a high potential for electrification. Technologies like the HT heat pump, MVR and steam recompression can only be used in combination with waste heat recovery. These technologies need a reduction in CAPEX and/or OPEX. Direct power to heat applications like the E-boiler require a (longer period of) lower power price and/or a higher fuel (natural gas) price. Because of the high investment, heat pumps and mechanical vapour recompression are only suited for baseload.

16 Basis: 20 projects; 10 - 20 MWt each at 8,760 h/a

Power to Heat for drying

Electrification of drying processes can be done by different technologies; most of them are in a study phase. Infrared drying and Microwave drying are commercially available technologies; application of these technologies is based on process improvement, process intensification, capacity expansion (as add-on) and not on energy (cost) saving arguments. Most applications of electric drying technologies can be found in the food sector.

In a number of cases, the driver for electrification seems to be process intensification and increasing

capacity, instead of electrification for cost reduction. Most of the applications will be baseload.

Table 4. Power to Heat for drying

Technology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr
Electrical air heating	Food	Drying	Royal FrieslandCampina DMV (Veghel), ISPT	2015	Study; economically not feasible			Flex	1
Mechanical Vapour Recompression	Food	Drying	Royal Cosun/ SuikerUnie (Vierverlaten)	2016?	In operation?			Base	2
Microwave (MEAM)	Food, carpets, building materials	Drying	MEAM, Belgium	< 2016	Commercial available?			Base	3
Pre-treatment for drying	Food	Drying	WUR	2016	Research			Base	4
Electric drying: infra-red, micro wave	Food	Drying	WUR	?	Research			Base	5
Micro wave	Steel	Drying	Tata Steel	2017	Study			Base	6
Heat pump integrated dryers	Food, sludge, manure	Drying	Dorset and other Dutch producers of dryers.	2017	Development			Base	7

C.2.2 Power to hydrogen

Power to hydrogen is classified as a separate category, apart from power to gas. Instead of methane, hydrogen can be used as a universal chemical ‘building block’ for the chemical, petrochemical and fertilizer industry. The commonly adopted future technology for Power to hydrogen is electrolysis of water, except in the case of Twente University (membrane technology).

Hydrogen production by electrolysis is nowadays not competitive (the reference technology is steam reforming of natural gas). The main reason is that the CAPEX for electrolysis is too high. Several studies support this conclusion. At this moment, there are no operational ‘power to hydrogen’ projects in The Netherlands for production of hydrogen, except for some local installations for the production of hydrogen. All current initiatives are in the research or study phase; the number of initiatives is limited. Up to now, power to hydrogen is considered as a flex option.

Uniper recently announced to extend its current MW scale pilots in Germany to a unit near Rotterdam for use in petrochemistry and CCU. This is to be connected to the planned off-shore wind power connection.

Table 5. Electro chemistry – power to hydrogen

Technology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr.
Hydrogen production	Chemical	Electrolysis	Nedstack (Arnhem), AkzoNobel	2000+	Commercial				1
Hydrogen production	Chemical	Electrolysis	AkzoNobel	2016	Study			Flex	2
Hydrogen production	Chemical	??	TNO, ECN (Voltachem)	2017	Research			Flex	3
Hydrogen production	Chemical	Electrolysis	TUDelft, Superwind	2008	Study			Flex	4
Production of hydrogen	Chemical Power	Membrane	ISPT, Twente University	n.a.	n.a.			Baseload?	5
Hydrogen production	Chemical	Electrolysis	TNO, Stedin, Smartport, Uniper, BP Refinery Rotterdam and Port of Rotterdam Authority	2017	Study			Flex	6

In conclusion, power to hydrogen by electrolysis technology is commercially available, but economically not feasible yet.

C.2.3 Power to gas

The commonly adopted technology for power to gas is electro synthesis. The first step of this process is the production of hydrogen by means of electrolysis. The second step is to combine the hydrogen with carbon dioxide and convert the two gases to methane (see natural gas) using a methanation reaction such as the Sabatier reaction, or biological methanation.

There are no operational projects in The Netherlands for the production of methane or carbon monoxide. This is contrary to (e.g.) Germany, where a considerable number of power to gas pilot projects are up and running. The number of Dutch initiatives is very limited. Most of the current initiatives seem to be flex options.

Table 6. Electro chemistry – power to gas

Technology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr.
Production of methane	Power Chemical Mobility	Electro synthesis	Energy Valley (Groningen)	2014	Not clear			Flex	1
Production of methane	Power Chemical Mobility	Electro synthesis	MvEZ, TKI Gas	2012				Flex	2
Production of carbon monoxide	Power Chemical	Electro synthesis	Differ, Traxxys	2016	Research			Baseload	3

In conclusion, the technology for power to gas is available on a pilot (MW) scale, but economically not feasible yet.

C.2.4 Power to chemicals

Power to chemicals is a mixed category, with different technologies and different products. Chlorine production by electrolysis of a solution of sodium chloride in water (with hydrogen as a by-product) is the only commercially available technology (AkzoNobel, Sabic). This technology can be used as a flex option by varying the load of the electrolysers. Other options are more or less all in the study or research phase. Some options in the study or research phase are potentially baseload applications, which will make them more promising for electrification. This list is not exhaustive; there might be other initiatives in the Netherlands (e.g. combinations with CCU to methanol and derivatives).

Table 7. Electro chemistry – power to chemicals

zTechnology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr.
Chlorine and hydrogen production	Chemical	Electrolysis	AkzoNobel (Rotterdam-Botlek and Delfzijl), ISPT, Eneco	2015	Study	nil	200 MWe (Botlek) 30 MWe (Delfzijl)	Flex	1
Chlorine and hydrogen production	Chemical	Electrolysis	Sabic (Bergen op Zoom)	2016	Scoping study	nil	20 MWe	Flex	2
Production of ammonia and oxygen	Chemical Power Agriculture (fertilizer)	Electro synthesis	TUDelft, Nuon (Magnum Power plant, Eemshaven, Groningen)	2015	Research			Flex	3
Production of ammonia and hydrogen	Chemical	Electro synthesis	AkzoNobel	2016	Study			Flex	4
Production of formic acid	Chemical mobility	Electro synthesis	TNO, ECN (Voltachem), TU/e (Eindhoven)	2016	Research Pilot (car)			Flex	5
Production of LHC in furnaces	Chemical	Cracking	DOW Benelux (Terneuzen)	2016	Idea			Baseload	6
Production of base chemicals: Methane, methanol , carbon monoxide	Chemical	Electro synthesis	TUDelft					Baseload	7

In conclusion, the only technology which has a high flexibility potential is chlorine production by electrolysis. This will not result in a higher power consumption (increased electrification), but in a more flexible power consumption.

C.2.5 Mechanical drive

A conventional electrification path is ‘power to mechanical drive’. Electrification by means of electrical drives shows limited applications. However, the number of applications may be relatively small; the power levels can be very high in case of compressor and pump drives in the chemical and petrochemical industry. Production plants often use pump and compressor drives by use of less efficient steam turbines. Formerly steam turbines were favourable because of the high reliability. Nowadays there is no difference in reliability between steam turbines and electric motors.

In case of retrofit, electrification is a realistic and economic feasible option. In some cases, the existing steam turbine drive can be kept in place, in order to improve the redundancy and reliability of the plant.

In the cases of vacuum spray drying processes, not electrification is the goal, but the improvement of the product quality and the energy efficiency of the drying process. All options mentioned are baseload applications.

Table 8. Mechanical drive

Technology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr.
Vacuum spray drying	Food	Vacuum Drying	Avebe	2016	Study			Baseload	1
Vacuum spray drying	Food	Vacuum Drying	GMF		commercial available			Baseload	2
E-drives of pumps and compressors (replacement of steam drives)	Chemical Petrochemical	Compression	BP		Commercial available			Baseload	3

In conclusion: power for mechanical drive is a technical and economical feasible option for large mechanical drives.

C.2.6 Separation technologies

Mechanical or electrical separation processes help to reduce the heat needed in drying processes. Only a few (existing) technologies are found to improve the energy efficiency of the separation process, mostly in the first step of dehydration. The main drivers are cost reduction and separation efficiency. All applications found are in the food sector, and all applications are for baseload. The applied technologies (ultra- and Nano filtration, reverse osmosis and electrostatic filtration) are existing technologies, which shall be tailored for the specified products and capacities (upscaling).

Table 9. Separation technologies

Technology	Sector	Unit operations	Parties involved	Year	Development status	Energy savings potential	Specific electricity use	Baseload or flex?	Ref. nr.
Ultrafiltration and reverse osmosis	Food	Separation	Royal FrieslandCampina (Leeuarden, Beilen, Veghel et cetera)	?	Study			Baseload	1
UF, NF and RO	Food	Separation	Cosun (Dinteloord, Vierverlaten)	2016	Research			Baseload	2
Electrostatic separation	Food	Separation	WUR		Research			Baseload	3

In conclusion, separation technologies form a smart application for electrification, especially in food industry. In the first stage, energy efficiency improvement is the driver, and not electrification. Further development to reduce fouling problems, upscaling and cost reduction of technologies is required.

References and acknowledgements

Annex D

D.1 Report references

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CPB, PBL, Nederland in 2030-2050: twee referentiescenario's – Toekomstverkenning Welvaart en Leefomgeving (2015).

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Fraunhofer Gesellschaft, 2013. Motor Challenge Program : Technischer Leitfaden : Lösungen zur verbesserung ihrer Motoren-systeme

Frontier Economics, *Scenario's for the Dutch Electricity System* (2015).

R.F.Schiffmann, 'Microwave and Dielectric drying', in A.S Mujamdar (ed.) Handbook of Industrial Drying (4th Edition, 2015).

Sequeira, C. A. C. and D. M. F. Santos, 'Electrochemical Routes for Industrial Synthesis', *J. Braz. Chem. Soc.*, vol. 20, 20 (2009), pp. 387– 40.

D.2 Gross list references (foreign examples)

Ref nr.	Source / URL
1	JRC BAT heat and cooling market in the EU http://www.industrialheatpumps.nl/en/practices/heat_pump_for_drying_of_fries/, http://www.industrialheatpumps.nl/en/applications/pasteurization/, http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/heatpump.pdf, http://www.ehpa.org/technology/best-practices/industry/, https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/publications/industry/Brewers_Guide_access_e.pdf, https://www.hptcj.or.jp/Portals/0/ahpnw/3rdmeeting/HPTCJ%20-%20Pioneering%20Industrial%20Heat%20Pump%20Technology%20in%20Japan%20rev1_130902.pdf
2	JRC BAT heat and cooling market in the EU http://parat.no/en/references/industry/parat-electrode-boiler/, http://www.elpanneteknik.com/Elpanne%20Competitive%20Analysis_5b%20_LeK2008-09-17.pdf, SE paper production
3	DSm plant Delft, Shell plant Pernis
5	België zie presentative Jan Grift België
6	http://www.micromilk.fraunhofer.eu/index.html, https://www.sciencedaily.com/releases/2013/11/131115104614.htm
7	BAT REF, p 174
11	Glass Melting Technology: A Technical and Economic Assessment Oct 2004
15	Kramer et al, 2009: https://www.energystar.gov/ia/business/industry/downloads/Pulp_and_Paper_Energy_Guide.pdf Bref 2010: Draft Reference Document on Best Available Techniques in the Pulp and Paper Industry (link is external), Apr 2010 http://eippcb.jrc.es/reference/BREF/PP_D1_0410.pdf
16	http://ietd.iipnetwork.org/content/air-impingement-drying
17	https://en.wikipedia.org/wiki/Ultraviolet#Applications
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21	https://www.nuon.com/nieuws/nieuws/2016/nuon-en-tu-delft-onderzoeken-opslag-windenergie-in-nieuwe-superbatterij/
22	Decarbonising industry in Sweden an assessment of possibilities and policy needs Report No. 77 September 2012
23	www.Conveavs.net/projects
24	www.carbonrecycling.is
27	LIchemical.com
28	C. A. C. Sequeira and D. M. F. Santos, D. M. F., Electrochemical Routes for Industrial Synthesis, J. Braz. Chem. Soc., 20, 387 (2009).
29	http://www.plasmaetch.com/plasma-polymerization.php
30	Prof. Peter Rem , TU Delft

D.3 Gross list references (Dutch initiatives)

Power to Heat: steam & hot water

Ref. nr	Source / URL
1	Running process. Direct supply of electricity from Germany. http://www.esd-sic.nl/ Heating by means of resistance heating of a mixture of sand and cokes. The conductivity is provided by the carbon element.
2	http://www.ispt.eu/media/Power-to-products-eindrapport1.pdf
3	http://www.ispt.eu/media/Power-to-products-eindrapport1.pdf
4	http://parat.no/en/products/industry/parat-ieh-high-voltage-electrode-boiler/
8	Stand by heating with electricity; not yet applied in Nl.
9	TAP = Thermal Acoustic Heat Pump.
10	http://www.bronswerk.com/nl/Radiax-Technology/SA50/
11	MVR for improving energy efficiency in salt production (evaporation)
12	Energy efficiency improvement of evaporation processes. In operation in PAVE2 at FC Leeuwarden.
13	Produced by ENGIE. 2 * 1,500 kWth + 2 * 400 kWth. Heat pump on CO2 / NH3. Project is initiated by out phasing R22.
14	For evaporation of water from sugar beets.
15	For application in potato frying processes (Aviko)
17	130 > 150°C
18	CRUISE project; CAPEX Reduction of Industrial Heat Pumps
19	Output LPS 120 - 200°C
20	http://www.ispt.eu/media/UH-20-10-Upgrading-Low-Temperature-Waste-Water-Streams.pdf
21	Approx. 150 kWth, 130°C
22	100 kWth scale yet? http://www.energiebusiness.nl/2015/06/23/thermo-akoestische-warmtepomp-voor-50-energiebesparing/
24	To be checked, observed on the Hannover Messe 2014.

Power to Heat: drying

Ref. nr	Source / URL
1	http://www.ispt.eu/media/Power-to-products-eindrapport1.pdf
2	Drying digestate of beet pulp with MVR at the sugar factory of SuikerUnie in Vierverlaten.
3	Microwave drying instead of convective drying Several projects, also in the Netherlands. http://www.flandersfood.com/crm/meam-microwave-energy-applications-management-2016-06-15t000000 www.meam.be
4	Electrical field processing, pre-treatment of materials to enhance drying speed and efficiency
5	Different advanced drying techniques, such as microwave drying, induction drying, contact drying.
6	Melting pans for production are dried with gas flames, in future maybe by microwave.
7	Closed loop dryers with heat pumps to condens vapour and heat up drying air. NWGD

Electro chemistry – power to hydrogen

Ref. nr	Source / URL
1	http://www.nedstack.com/ https://www.akzonobel.com/ic/innovation/ Up to 2 MWe scale PEM fuel cells. No electrolysis of water?
2	Hydrogen production with electrolysis to supply the deficit of hydrogen that arises when natural gas is no longer used as a feedstock (replaces hydrogen from steam reforming)
3	Draft R&D plan 2017 http://www.voltachem.com/ http://www.voltachem.com/research/power-2-hydrogen
4	Feasibility study 'Super wind', integrating wind energy with internal reforming fuel cells for flexible co-production of electricity and hydrogen (TUDelft 2008)
5	https://www.utwente.nl/tnw/mtg/mnt/Summer2016.pdf
6	https://www.portofrotterdam.com/en/news-and-press-releases/research-into-the-use-of-green-hydrogen-in-refinery-process

Electro chemistry – power to gas

Ref. nr	Source / URL
1	http://www.duurzaambedrijfsleven.nl/energie/2404/noord-nederland-wil-grootste-europese-power-to-gasfabriek Current status of this project is yet unknown; latest information is from 10th of April 2014.
2	http://topsectorenergie.nl/wp-content/uploads/2016/09/TerugblikTKI-Gas-2012-2016.pdf
3	CO2 neutral fuels – Adelbert Goede. Production of CO from CO2.

Electro chemistry – power to chemicals

Ref. nr	Source / URL
1	http://www.ispt.eu/media/Power-to-products-eindrapport1.pdf controllability is approx. 50-100%.
2	Study phase; operational people have strong opposition against flex operation.
3	Production of ammonia for storage of electricity from sustainable sources. http://www.tudelft.nl/onderzoek/thematische-samenwerking/delft-research-based-initiatives/delft-energy-initiative/onderzoek/energieopslag/ http://www.tudelft.nl/nl/onderzoek/thematische-samenwerking/delft-research-based-initiatives/delft-energy-initiative/nieuws/artikel/detail/tu-delft-en-nuon-onderzoeken-opslag-windenergie-in-gascentrales/ https://www.deingenieur.nl/artikel/nuon-gaat-stoken-op-ammoniak
4	-
5	Formic acid, the new energy carrier. Whitepaper: http://www.voltachem.com/images/ uploads/VoltaChem_Electrification_whitepaper_2016.pdf Pilot project with a small car (TU/e).
6	Preliminary study phase. In fact this can become a research project.
7	This has been mentioned by prof. Fokko Mulder in the interview.

Mechanical drive

Ref. nr	Source / URL
1	Interview Avebe
2	Vacuum drum drying instead of spray drying
3	Identical discussions have been noticed at Yara and DOW. E-drives will be limited to approximately max. 50 MWe.

D.4 References from BWK

Tech:	Issue:
Electric boiler Thermal energy storage Smart control Flexible dispatch of electric boilers together with thermal storage and integrated with steam system and generator. Model predictive Control	2016 nr. 10 pp 32-37
Electric boiler Thermal energy storage steam accumulator	2016 nr. 9 pp 6-11
Integrating heat pumps in industrial installations – call for cooperation in a new VDI directive	2016 nr. 9 pp 41
CHP policy in DE/fuel cells	2016 nr. 7/8 pp 53
Flexibility supply using “Virtual power plant” (Industry 4.0?)	2016 nr. 6 pp 29
Possibilities of RE for industrial heat: heat pumps 100 degr, geothermal 280 degrees	2016 nr. 6 pp 20
List of process heat to temperature level (PJ for EU28)	2016 nr. 6 pp 23
Stroomopslag DE	2016 nr. 5 pp 41
List of Power2X projects in DE +TRL	2016 nr. 5 pp 47
Power2Heat flexoptie industry +thermal energy storage; power prices	2016 nr. 4 pp 32
Flex challenge	2016 nr. 3 pp 49 ev
Energy efficient steel recycling with electric arc furnaces	2015 nr. 10 pp 34-37
Recovering electricity from waste heat with ORC	2015 nr. 7/8

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