Matching processes with electrification technologies

Final report of the E-match project

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Abstract

In the future the supply of renewable electricity will increase sharply, from 44 PJ in 2013 to 236 PJ in 2030 and increasing more thereafter. Being a large energy consumer, the Dutch chemical industry is expected to use a significant share of this renewable electricity, as it can help to reduce its carbon footprint. But which chemical processes can be electrified and what are the possible electrification options? What is a realistic potential of electrification of the chemical industry and what is the impact on the energy system? This report presents the results of a model-based merit order analysis, case studies analyses and a first impact assessment.

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Summary

Goal of the study

This study aims to identify processes in the Dutch chemical industry most suitable for electrification and to assess the potential impact of electrification on the Dutch energy system. Electrification of the chemical industry is not only important for the chemical industry itself, but also for other actors like the electricity sector and technology developers. The final goal is to provide input for strategic decision making for the actors involved in electrification.

Approach

The potential role for electrification in the Dutch chemical industry and the impact on the energy system is assessed using both a bottom-up and top-down approach. The bottom-up approach involves process scans with the four industrial partners, merit order calculations and four selected case studies. A hit list is made of the most promising generic electrification technologies and the opportunities for different chemical processes. A top-down approach was used to make a first estimate of the potential impact of electrification on the Dutch energy system in terms of amount of electricity that can be used in the chemical industry.

Conclusions

The findings of the merit order analysis, case study analysis and the first impact assessment give rise to the following conclusions:

1. Electrification of the olefin and ammonia production have the largest impact on the Dutch energy system.
2. Power-to-Chemicals and Power-to-Heat technologies for high temperatures (>200°C) have to be developed to use the potential of electrification for a large CO_2 reduction in the chemical industry.
3. Till 2020 only a limited number of Power-to-X technologies will be applied for demand side response.
4. In today's chemical plants Power-to-Heat technologies give an opportunity for a positive business case.

Recommendations

Based on the results of this study the following recommendations are made:

1. The additional benefits & applicability for the business cases for electrification at OCI Nitrogen and at Arkema should be further explored.
2. Extension of the merit order calculations with more possible future electrification options and benefits and costs
3. Detailed modeling of future balancing market & the role for electrification in the future Dutch energy system is needed from a techno-economic perspective: what should be the role for electrification in the mix of energy technologies in three different scenarios (security of supply, large CO_2 reduction, large supply of renewables) and with the least cost for society.

1

Introduction

1.1 Motivation and background of research

The energy demand of the Dutch chemical industry is significant. In 2013 it amounted to 1174 PJ, from which the share in electricity now is 107 PJ. In the future the supply of renewable electricity is expected to increase sharply, from 44 PJ in 2013 to 236 PJ in 2030 and increasing more thereafter (ECN/PBL/CBS 2014).

Being such a large energy consumer, the Dutch chemical industry is expected to use a significant share of this supply of renewable electricity. For this, three main drivers can be distinguished:

- Flexibility: Renewable electricity will predominantly originate from intermittent sources such as solar and wind. This will increase the fluctuations in the supply of electricity and will increase the need of flexibility. With its large scale use of electricity processes, the chemical industry can potentially play an important role in providing this flexibility, thereby contributing to the constantly required balancing of demand and supply.
- CO_2 emission reduction: The use of renewable electricity in the chemical industry replacing natural gas as an energy carrier or even as feedstock, is a very elegant method of reducing emissions.
- Security of supply: The Dutch chemical industry relies heavily on abundance of secure energy which is, on the long term, under threat due to depletion of national gas reserves, public concern on gas exploration and geopolitical developments.

Chemical industries in the Netherlands are aware of possible developments but are unsure what it means to their business. Recent studies that have been performed, in for instance the TKI Systeemintegratie and Deltalinqs, have focused on short and midterm business opportunities and on economic framework targeting specific electrification technologies. From these studies some promising opportunities arise, but there is a need for translation of opportunities to the strategic level of the chemical industry, the technology developers and the energy sector, which can be publicly shared.

1.2 Project objective, research questions

The project aims at identifying those processes in the Dutch chemical industry most suitable for electrification. This is done by a systematic scan applied on representative processes, by translating these to a list of best options for electrification potential for the total Dutch chemical industry in order to supply the relevant insights for strategic decision making within the chemical industry, for technology developers, electricity companies and for policy makers.

The project will also serve as a technology scan for a much more detailed study on the economic framework for electrification in the Dutch energy supply. This comprehensive assessment of the technical and economic potential of electrification technologies is needed to provide insights for the present business and innovation in the future energy system. Therefore, the study also includes an assessment of the effect of utilising this potential on the ability of the overall system to accommodate intermittent power production.

Different classes of electric processes (Power-to-Heat, Power-to-Hydrogen, Power-to-Products) are at various implementation levels (unit operation level, utility level). The project has addressed the following research questions:

- Which classes of electrification and which classes of chemical industries need to be considered in order to perform a systematic scan for the potential for electrification of processes?
- Which classes of electrification can be applied for the processes considered in the scanning study?
- What is a realistic potential of electrification of the chemical industry and what is the impact on the energy system in terms of flexibility, CO_2 reduction and diversification?

The project aims at providing input for strategic decision making for the actors involved in electrification. More specifically the study targets:

- Chemical industry corporate strategy: Identifying the processes that are most suitable for electrification at which level and type and what are the drivers for electrification. For the chemical industry as an end user this information helps in defining their long term technology portfolio strategy.
- Technology developers initiatives: A crucial step is the identification of promising electrification opportunities for technology developers in order to initiate R&D activities on those technologies that could serve the future demands of industry and society.
- Energy system perspective: Estimating the technical potential for electrification and giving an assessment of the contribution to flexibilisation, CO_2 emissions and diversification of the energy mix.

1.3 Reading guide

The remainder of this background report of the E-Match project is structured as follows:

- Chapter 2 describes the adopted methodological approach and strategy used in answering the research questions.
- In Chapter 3 an overview of the Dutch energy sector is given and the drivers for electrification of the chemical industry are discussed.
- Chapter 4 presents the results of the process scans and the marginal cost & merit order modelling.
- Chapter 5 reports on the top-down estimation of the potential for electrification.
- Chapter 6 gives the final hit list of promising electrification technologies.
- Chapter 7 contains the overall conclusions from this study and provides some recommendations.

2

Methodology

This chapter describes the adopted research methodology. Paragraph 2.1 describes the developed systematic approach of this study, which is a first step to a comprehensive assessment into the technical and economic potential of electrification technologies and the effect of utilising this potential on the ability of the overall Dutch energy system to accommodate intermittent power production in the long run.

2.1 Systematic approach of this study

For an analysis on the potential role for a particular technology or service in the Dutch chemical industry and its impact on the energy system important starting points are:

- characterization of the energy use of the chemical industry in the Netherlands.
- characterizing of the technologies.
- taking into account the impact of the drivers.

This section describes the developed systematic approach to identify processes in the Netherlands most suitable for electrification and the potential impact of electrification on the Dutch energy system.

In the study both a bottom-up and a top-down approach are used to address the research questions.

In the bottom-up approach the process scans with industrial partners are the main input for the analysis. Process scans are performed in which the electrification at various levels of typical processes brought forward by industry are discussed in workshops on site. For the workshops a multidimensional table was made in which a cross sectional view from various perspectives was applied. Next to that, a questionnaire was made for the industrial partners to provide background information on available processes for the workshops. Important elements of the questionnaire include a process description plus flow sheet with the main energy consumers and a utility consumption quantification. The questionnaire is given in Appendix A. During the individual workshops an assessment was held, to identify where and which electrification option can be potentially applied and the ease of implementation/time horizon for the given process. Next to that, the electricity requirement, intermittency and potential for repetition (MWhe/a) were identified. An important assumption in the process scans is that in 2030-2050 electricity has the same price as natural gas per Joule. Finally, the potential for a business case was calculated for the selected options and a merit order was made, based on marginal costs (paragraph 4.3). Based on these calculations a hit list was made of the most promising generic electrification technologies and the opportunities for different chemical processes (Chapter 6).

A top-down approach was used to make a first estimate of the potential impact of electrification on the Dutch energy system in terms of amount of electricity that can be used in the chemical industry and the flexible portion therein (Chapter 5). The top-down approach is based on data from literature and in-house data on production capacities.

3

Drivers for electrification

This chapter of the report gives an overview of the Dutch energy sector, the challenges for Distribution system operators (DSO’s) in the Netherlands and drivers for electrification of the Dutch industry from different points of view.

3.1 The Dutch energy sector

There has been a shift towards promoting increased competition within the energy sector in Europe and creating a European Energy Union is one of the European Commission’s priorities. This aim includes ensuring reliable energy supply at reasonable prices for businesses and consumers with the minimal environmental impact. During the 1990s, at a time when many national electricity and gas markets were still monopolised, the European Union and its member states decided to gradually open up these markets to competition, through:

a. Establishing a clear distinction between competitive and non-competitive parts of the industry.
b. Obliging the operators of non-competitive parts of the industry to allow third parties to have access to the infrastructure on a transparent and non-discriminatory basis.
c. ‘Freeing up’ the supply side of the market through the removal of barriers to enter for alternative suppliers.
d. Removing restrictions on customers changing suppliers.
e. Introducing independent regulators to monitor the sector.

This process began in the UK with the privatisation of British Gas in 1986. This was followed by the privatisation of the regional electricity boards in 1990 and the opening of the gas and electricity markets, in 1996 and 1998 respectively. This enabled electricity companies to directly compete for customers and therefore created competition within the market.

In the Netherlands there has been a phased approach of the opening the energy market in line with the EU policy. Currently, power is traded on different platforms that include three market segments on the APX: day-ahead, continuous intraday and strategic reserve, coupled with other power exchanges in the North West Europe, BELPEX, EPEX Spot FR, EPEX Spot DE and Nord Pool Spot. Participation of demand response applications will be crucial for a successful deployment of Power-to-X and further development of the energy system. As such, it is essential to assume demand response as an integral part of the imbalance system. The imbalance of the electricity grid is controlled under continuous basis matching demand and response.

Instead of having a power plants follow the demand for power, the demand (response) can also adjust generation to restrain peaking or to shave the demand profile. Dispatching demand response at a real-time dispatch basis, is very attractive since the highest value can be created for demand response applications. Real-time dispatch is the process of controlling the input of the electricity load or the output of flexible production capacity to deliver the required electricity load changes in the most economical manner. The process for demand response involves the following:

- converting scheduled power program input at 15 minute level into a smoothed ramping (load) profile
- adjusting the actual load in response to deviations to the scheduled program, so called regulatory (secondary) control
- monitoring the performance of the individual units
- sending discrete set-point and other control instructions to the flexible units.

3.1.1 Scenarios

For the different case studies historical hourly market prices (imbalance) has been used from 2013, 2014 and 2015. With these prices it is possible to construct a typical daily price curve of a specific day like Figure 2. To translate these prices in to future prices (daily price curves) the Frontier Dutch Energy Market study has been used. These results are open and reported and can be assessed in a transparent manner (Frontier, 2015).

The objective of this Frontier study was to analyse the long-term effects of future power market developments on the reliability and affordability of the electricity system in the Netherlands and the conditions that the market could offer for sufficient stimulus measures for investments in generation capacity, flexibility and system facilities. The study identifies the following future price scenarios for the electricity market:

- Base case “Dutch energie akkoord and EU target settings”.
- Sensitivity 1 “low CO_2-prices”: effect of substantial lower CO_2-prices.
- Sensitivity 2 “High fuel prices”: effect of substantial higher fuel prices for coal and gas-fired power plants.
- Sensitivity 3 “Slow growth of wind power”: effect of lower growth of wind-energy in the Netherlands.
- Sensitivity 4 “Increased foreign capacity”: effect of higher installed capacities in BE and FR e.g. due to higher capacity procurement in capacity mechanisms.
- Sensitivity 5 “Higher demand side response (DSR) potential”: effect of higher load shifting potentials in the Netherlands.

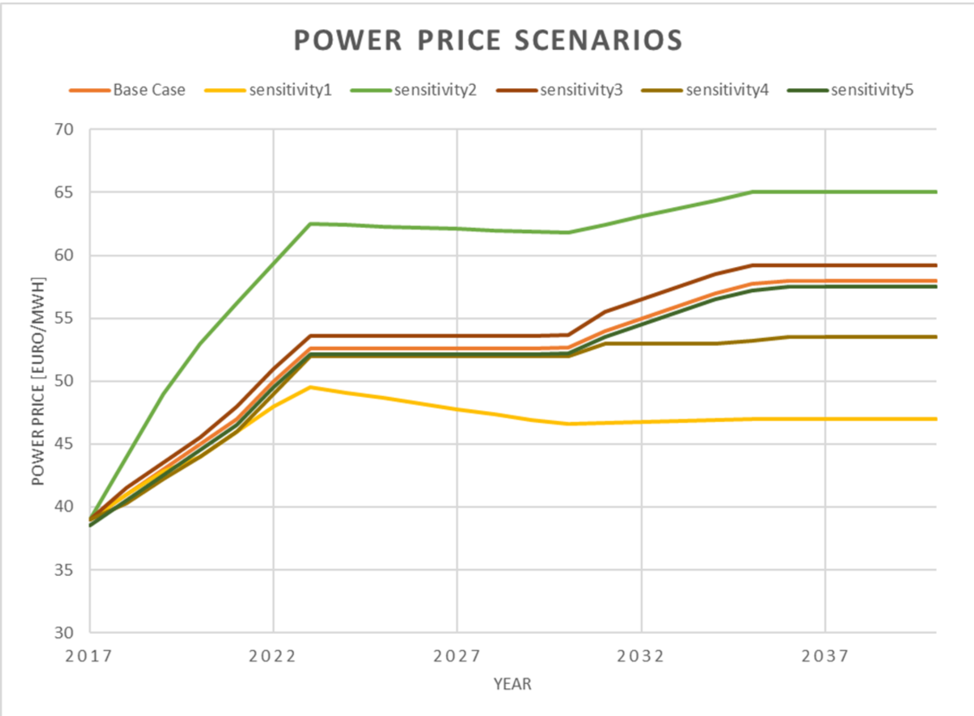

Figure 1: Power price scenarios used in the case studies.

By using these price forwards the daily price curves will be corrected accordingly as shown in Figure 2.

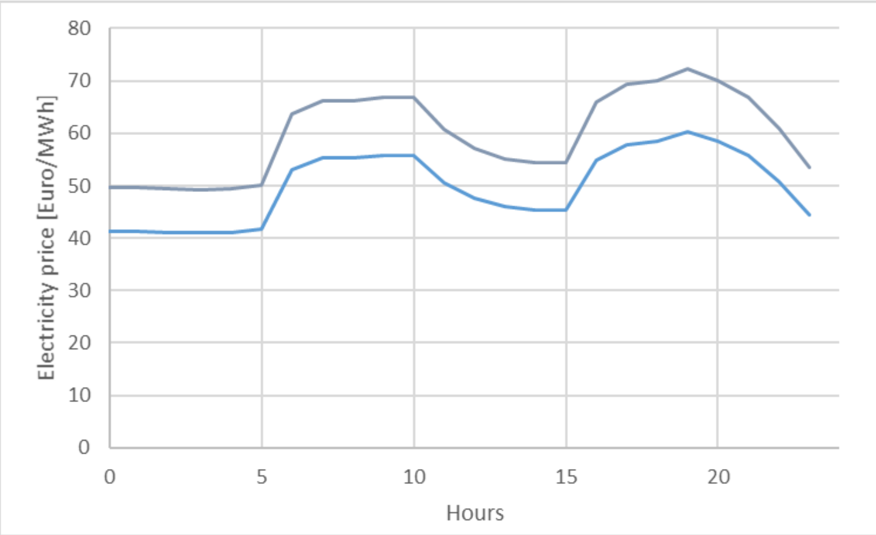

Figure 2: Daily power market price curve correction (off-set to a higher average daily price).

With a consistent set of underlying commodity prices taken from the Frontier study the case studies has been assessed with a forward look of 10 or 20 years. The commodity prices of Natural gas or Crude oil are used to index the future value of Hydrogen, Ammonia or Methanol etc, subject to the specific case.

3.2 Challenges for DSO's in the Netherlands

The quality and capacity strategic plan of Stedin states the following:

" The transition towards a renewable energy system has truly started. Our grids need to meet new standards. We need to invest in grids that are ready for the future and are able to facilitate flexibility in energy production and demand"

This statement hold true for all grid operators in the Netherlands. The Dutch energy grid operators are expected to meet this transition challenge with the same quality, safety and capacity standards that have become the norm in the previous 20 years.

One of the main risks associated with quality and capacity standards is that the grid operator will miss technological developments by end users. This can either create situation where the grid operator does not anticipate in time to facilitate this development or ends up with stranded assets. The electrification of the chemical industry presents such a technological development that can greatly influence the planning and maintenance choices for a DSO in order to meet the quality, safety and capacity standards of a future electricity, gas and maybe heat grids.

The electrification of the chemical industry in the Netherlands can become a major factor determining the planning and design of the gas, electricity and heat grids in the Netherlands. The main drivers for grid operators to be more engaged in future industry developments studies are the following:

1. Awareness and knowledge in order to develop strategic plans to accommodate these developments in the existing electricity and gas grid at the least social costs.
2. Identify the additional infrastructure connected to the traditional gas and electricity grid that are required to support the electrification of the chemical industry and define a changing role for the traditional DSO.

3.3 Drivers for electrification of the industry

In the whitepaper "Empowering the chemical industry; Opportunities for electrification" (TNO/ECN, 2016) the drivers for electrification from the perspective of the chemical industry are given for the different types of electrification based on the feedback from an industry consultation (see Table 1).

The main drivers for realising Power-2-Heat indicated by the chemical industry are cost efficiency and sustainability. Low electricity prices compared to natural gas prices make electricity a cost efficient alternative to natural gas, especially when combined with options to flexibly apply Power-2-Heat at moments when electricity prices are low. Electrically driven heat pumps can produce heat in a very cost effective way by upgrading waste heat to useable temperature levels. Recycling of waste heat leads to energy savings and CO_2 emissions reduction, and there for improved sustainability.
For Power-2-Hydrogen, in which electricity is used to produce hydrogen through the electrolysis of water, sustainability is indicated as the main driver. When renewable electricity is used to power the electrolyser, the hydrogen is a carbon-free energy carrier and chemical intermediate.
The main economic benefit of Power-2-Specialties lies in value creation around high value products. Power-2-Specialties is already being applied in companies to replace highly inefficient traditional production routes of high value products, mostly for cost reduction reasons.
Increased sustainability, whether due to a company's social responsibility commitment or in anticipation of future regulations, is a major reason for the current investigations into Power-2-Commodities processes. In some cases, cost reductions and positive business cases can also be achieved by electrochemically producing commodities.

Table 1: Drivers for electrification of the Chemical industry from Industrial perspective.

Industrial driver	Power-2-Heat	Power-2-Hydrogen	Power-2-Specialties	Power-2-Commodities
Cost reduction	Important	Relevant	Relevant	Important
Sustainability	Important	Important	Not relevant	Important
New products	Not relevant	Not relevant	Important	Not relevant

The interest and drivers for electrification of other stakeholders like the electricity sector and the national government is completely different. Being such a large energy consumer, the Dutch chemical industry is expected to use a significant share of the supply of renewable electricity. For this three main drivers can be distinguished:

- Flexibility: Renewable electricity will pre-dominantly originate from intermittent sources such as solar and wind. This will increase the fluctuations in the supply of electricity and will increase the need for flexibility. With its large-scale use of electricity processes, the chemical industry can potentially play an important role in providing this flexibility, thereby contributing to the constantly required balancing of demand and supply.
- CO_2-Emission reduction: The use of renewable electricity in the chemical industry replacing natural gas as an energy carrier or even as feedstock, is a very elegant method of reducing emissions.
- Security of supply: The Dutch chemical industry relies heavily on abundance of secure energy which is, on the long term, under threat due to depletion of national gas reserves, public concern on gas exploration and geo-political developments.

A first assessment of these drivers was made based on two characteristics (constant use and variable use) during the process scans. The driver flexibility (variable renewable electricity) is characterised by a variable use of electricity and it benefits from the large electricity price fluctuations. For CO_2 emission reduction, electricity can be used both continuously as variable. In this scenario the prices of renewable electricity are assumed to decrease to a level below the natural gas price. Security of supply becomes important the moment the Groningen gas field is closed and coal power plants are closed. The Netherlands will rely on import of natural gas. Electricity is produced from renewables, and is continuously used in the chemical industry. High peak prices for electricity and high natural gas prices are assumed in this scenario.
An overview of the characteristics and for which driver they are important is given in Table 2. Table 2 gives also the resulting market/scenario assumptions for the three drivers.

Table 2: Overview characteristics of the different drivers

Characteristics	Variable renewable Electricity	CO_2	Security of supply
Constant use		X	X
Variable use	X	X	
Resulting market / scenario / assumption	Large price fluctuations/ (high peaks, long lows)	Price use NG > price E	High NG price, high peak E, no power from coal. Groningen field closed.

3.4 Flexibilisation vs electrification

A distinction can be made between flexibilisation and electrification when it comes to applying electrical energy in industrial processes as replacement for applying fossil energy carriers.

Flexibilisation deals with the issue of providing flexibility to the demand side of the energy system in response to fluctuating electricity supply by renewable energy sources, therewith keeping the energy system balanced. Industrial end-users that apply flexibilisation technologies are willing to provide flexibility to the system in return for economic profits that can be obtained by price differences during high and low supply of electricity. Prerequisite for a flexibilisation option is that it is able to respond quickly to changes in the supply of electricity. Another aspect of flexibilisation options is, as with energy storage (another way to stabilise the energy system), that in most cases the number of operation hours will be limited. This, in turn, will lead to low allowable investment in order to achieve reasonable pay back times. However existing processes using electricity, like chlorine production, are good flexibility options since their overcapacity can be used for flexible production. They can also provide the needed system inertia, primary control actions, which will be more and more needed to maintain the voltage in the electricity network at a constant level.

Companies applying electrification technologies replace their fossil fuel based processes on processes that are driven by renewable electrical energy. This is done as a base load option, with no or limited flexibility. The drivers to make this change can be energy & costs savings, for instance by applying electrical heat pumps, but may also have to do with product quality, new products, safety, process control, or reducing O&M costs. Although energy savings are not always the main driver, electrification provides opportunities to make the industry more sustainable. Carbon-free electricity as replacement of fossil energy allows industry to decarbonize their processes. Since electrification options are intended as a base load option, the number of operation hours is large. This allows for a higher initial investment. In addition, response time is not an issue for these technologies.

4

Process scans & merit order

This chapter of the report gives a summary of the process scans and the results of the marginal cost & merit order modelling.

4.1 Electrification technologies & impact on the chemical process

In the past years different studies have been performed to identify technologies and business cases for the use and storage of (renewable) electricity in different sectors. A technology review was done by ECN and DNV KEMA for different energy storage technologies and power-to-gas technologies in particular. Based on different service applications for the integration of intermittent energy sources (IES), the assessed technologies were grouped according to the IES integration services (DNV KEMA, 2013). The Power-to-products project from ISPT (Berenschot/CEDelft/ISPT, 2015) looked at which technologies using flexible renewable electricity the process industry in Netherlands is willing and able to implement. An overview of potential technologies was made, the so-called 'staalkaart' and 10 most promising options were selected in consultation with project partners.

Based on these two studies and other literature an overview of electrification technologies was made in this study. Like in the Power-to-Product study a distinction was made between process applications, engines, heating, cooling, radiation, and storage systems. New innovations on a low technical readiness level (TRL) were added to complete the total picture for the process scans.
The different electrification technologies can be used at two different process levels (Table 3). The process levels give an indication of the level of impact the technologies have on the product and how generic the technologies can be implemented in the industry. We have distinguished two process levels, utilities and unit operations. Electrification technologies which are used at utility level have a lower impact on the final product, but are more generic and can be implemented in more processes. Often

utilities are supplied by one utility company at the industrial site and the influence of chemical companies on implementation of new technologies is limited. At unit operation level the electrification technologies are in the heart of the process. The impact is high and therefor the core business of the chemical company. Often the technologies have to be fine-tuned to the specific process, which makes them less suitable for wide application.

Table 3: Potential application of electricity.

Levels	Applications of electricity
Utility	Heat Electricity (direct) Process and demi-water Waste water treatment Cold Process gases (Hydrogen, Nitrogen, Oxygen)
Unit operations (within existing process)	Conversions (direct electrical consumption in reactor) Separations (direct electrical consumption in separation) Pressure change Heating and cooling

4.2 Summary of the process scans

DOW, OCI Nitrogen, Arkema and AkzoNobel are all big energy consumers: energy is a significant part of their variable costs. This is the main driver for these companies to find out what are the likely effects of replacing fossil energy by renewable electricity on their business and what opportunities this provides for the companies. Of the 11 options identified during the process scans, six are based on Power-to-Heat. These options use electricity instead of fossil fuels to produce heat. Five options are Power-to-Product options, ranging from ’peak shaving’ for AkzoNobel to microwave heating of PMMA for Arkema. The Power-to-Heat options from AkzoNobel, OCI Nitrogen and Arkema are good examples of electrification of industrial energy demand and a highly energy-efficient solution, because waste heat is upgraded to high temperature heat. The two Power-to-Heat options from Dow are examples of direct electrical heating.

In order to calculate the business cases the following steps were taken:

- In a process scan the companies together with ECN and TNO have determined which technology and in which part of their process their energy demand can be electrified and whether that could be made flexible or not.
- Efficiency calculations have been performed for selected cases using different prices scenario’s.
- The investment and operational costs are determined for the selected cases.

For the process scans, the companies have made the following choices:

- **AkzoNobel** has looked at two processes salt production and chlorine electrolysis. For the salt production the application of Mechanical Vapour Recompression (MVR) is an obvious way for electrification. AkzoNobel has already reviewed the chlorine process for providing swing capacity into the imbalance market. This option has been reported and indicated as a potential business case in the Power-to-Products project (Berenschot/CEDelft/ISPT, 2015). Another opportunity in the chlor-alkali process is the evaporation of caustic, which requires steam. This can potentially be substituted by an MVR comparable to the salt production process, but it should be kept in mind that the high boiling point of caustic makes the process less attractive than for salt. The option of using a MVR for the salt production was selected for a more detailed case study.
- **OCI Nitrogen**'s process scan was focused mainly on hydrogen production by electrolysis and the tie-in before the NH_3 synthesis loop. Another option which has been quickly reviewed was the electrical heating of heat transfer salts of the melamine process. A more detailed case study was done on the option of using electrolyzers to increase the ammonia production.
- The process scan at **Dow Benelux** was mainly focused on the cracking furnace for the production of ethylene from naphtha. Two options for electrical heating have been identified. One flexible option where part of the furnace is electrically heated if the electricity price is low and when the electricity price is high the furnace runs on fossil fuels. The second option for electrical heating and the options of electricity driven cracking and direct electrochemical synthesis of ethylene have a much lower technical readiness level (TRL), but a very large potential for electrification (up to 9875 GWhe per year). A more detailed case study has been performed on the option direct electrical heating.
- **Arkema**'s process scan was done on the PolyMethyl MethAcrylate (PMMA, also known with the brand names of Altuglas and Plexiglas) process to produce thick sheets of this transparent polymer. The electrification options identified for the Arkema Altuglas processes include microwave reactors and mechanical vapour (steam) recompression. The MVR option was selected for a more detailed case study.

A brief summary of the characteristics of different options is shown in Table 4.

Table 4: Characteristics of different electrification options (n.c. = not calculated)

Company	Process	Option	Option type	Est. Annual Potential of Electricity Consumption	Driver	TRL
				[GWhe/a]		
AkzoNobel	salt production	all MVR	P2Heat	775	CO_2 Emission reduction	9
AkzoNobel	chlorine Electrolysis	use overcapacity for flexible production of chlorine	P2Products	100	Flexibility	9
AkzoNobel	chlorine Electrolysis	caustic evaporation	P2Heat	n.c.		9
Dow	naphta cracking (ethylene production)	partly direct electrical heating	P2Heat	3200 - 8750	Flexibility	6
Dow	naphta cracking (ethylene production)	full electrical heating	P2Heat	6200 - 9875	CO_2-Emission reduction	5
Dow	naphta cracking (ethylene production)	electricity driven cracking	P2Products	n.c.	CO_2-Emission reduction	3
Dow	naphta cracking (ethylene production)	electrochemical production of ethylene	P2Heat	n.c.	CO_2-Emission reduction	3
OCI	ammonia production	adding 5% H2 by electrolysis before the synthesis loop.	P2Products, P2Hydrogen	149	CO_2-Emission reduction	7
OCI	melamine process	heating of heat transfer salt	P2Heat	145 (35 MWe peak)	Flexibility	8
Arkema	PMMA production	micro wave heating direct the PMMA sheets	P2Products	4.2	CO_2-Emission reduction	4
Arkema	PMMA production	mechanical vapour recompression.	P2Heat	0.2 - 0.55	CO_2-Emission reduction	9

4.3 Marginal costs & merit order for different electrification technologies

For the assessment of the different flexibility options a marginal cost & merit order model has been developed for the new demand response applications in conjunction to the current portfolio of large scale power plants, must run units and increase of renewable energy sources. The merit order provides insight into the operational margin in €/MWh for each option (vertical axis) and the capacity for load balancing (horizontal axis). The approach of the system analyses provides a good basis for reviewing a potential for business case, by assessing the position on the merit order (the operational hours when the application is marginally attractive to operate). Since the feedstock for demand response options is mainly electricity, it make sense to use a typical merit order, normally used for power plants, to rank the different electrification options. As such the merit order is the sequence of the de-activation of power loads of industrial processes and is determined by the system margin related to the cost of electricity. The approach considers the electricity purchase costs as variable costs, in consistency with other commodity and product prices. To generate a merit order all feedstock cost and sales price of the product steams will be needed including electricity price. For the marginal cost & merit order assessment prices assumption are listed in Appendix F.

Different classes of electric processes (Power-2-Heat, Power-2-Hydrogen, Power-2-Products) are reviewed resulting in the following different load response options for the materials industry and the petrochemical and basic chemical sectors. The load response merit order identifies the different load-shifting options of demand response. The merit order also includes the large scale power plants. Power plants will be switched on in case the electricity price is sufficient to make margin and demand response might be switched off in case the electricity price is too high to make any margin.

Based on the process scans the E-match project has reviewed different electrification applications, the options are highlighted in the merit order Figure 3:

Power-to-Heat:

- Mechanical vapour recompression (salt dryers).
- Steam recompression (reuse of low pressure steam).
- Electrical boiler (electrical tubular cracking furnace).

Power-to-Hydrogen / products:

- High pressure electrolysers (Ammonia production).
- For transportation (busses) assuming addition of a green bonus.

The merit order only shows the flexible capacity (power plant and the different new demand response applications) It does not shows the must run, existing industrial loads (e.g. chlorine production) and renewable assets. The assessment used all power production capacities and historical loads curves to determine the residual load duration curve for the Netherlands.

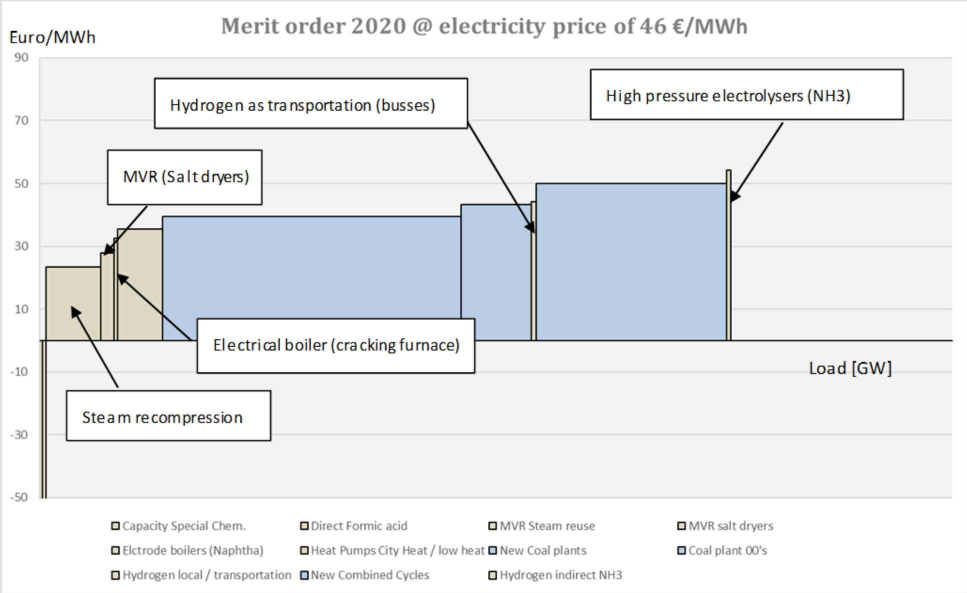

Figure 3: Demand response options and large scale power plants in 2020, assuming optimistic implementation of new Power-to -X technologies and renewable production capacity.

Table 5: The different load response options and large scale flexible production assets as part of the merit of Figure 3. The capacity is in [MW]. 1 =on, 0 = off.

Merit order	Technology	Normalized capacity	Full load hours
			# hrs
1	Capacity Special Chem.	27	1
2	Direct Formic acid	36	1
3	MVR Steam reuse	540	1
4	MVR salt dryers	135	1
5	Elctrode boilers (Naphtha)	38	1
6	Heat Pumps City Heat / low l	450	1
7	New Coal plants	2975	1
8	Coal plant 00's	700	1
9	Hydrogen local / transportati	45	1
10	New Combined Cycles	1900	1
11	Hydrogen indirect NH3	45	1
12	Cobined cycles 00's	1800	0
13	Hydrogen to refineries	180	0
14	In direct liquid fuels (MeOH	90	0
15	Direct liquid fuels	18	0
16	Hydrogen Natural Gas	45	0

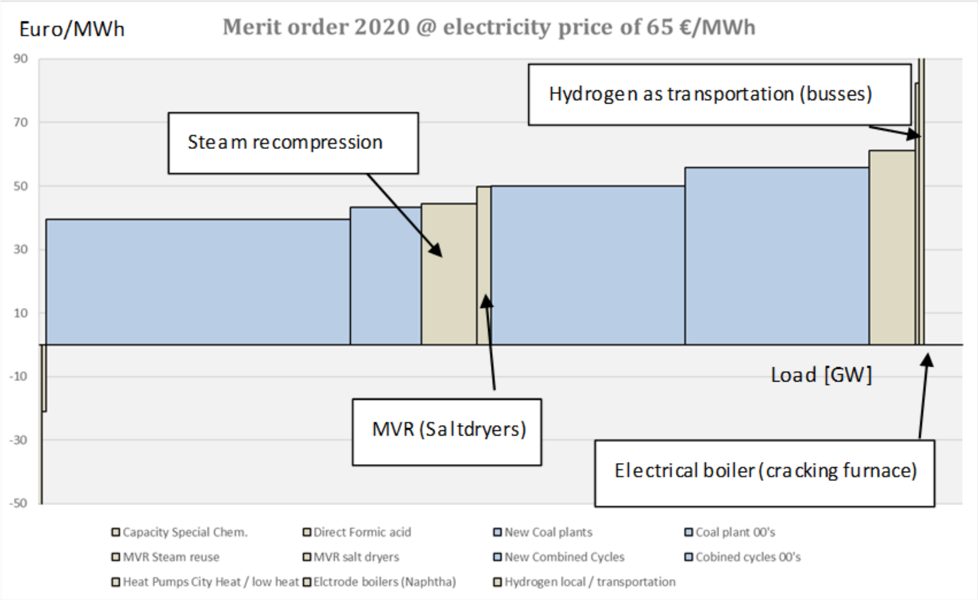

Figure 4: Demand response options and large scale power plants in 2020, during a peak hours.

According to the merit order assessment in Figure 4, it is worth noting that during peak hours most of the large scale power production might be running, switched-on or ramped-up. Only a limited number of Power-to-X options stay online: the niche applications Specialty chemicals / formic acid and the mechanical vapour recompression (MVR) application. This means that the E-match Power-to-X options will be switched off during peak hours:

- Electrical boiler (electrical tubular cracking furnace)
- High pressure electrolysers (Ammonia production)
- For transportation (busses) assuming addition of a green bonus.

5

Energy use of the Dutch industry

The total use of energy in the Netherlands is registered by the Dutch statistics office CBS (Centraal Bureau voor de Statistiek). The last couple of years, the total primary energy consumption is slightly more than 3000 PJ per year in the Netherlands. The Dutch industry has a total primary energy consumption of 1100-1200 PJ per year (excluding the oil refining sector), making it one of the most relevant sectors with respect to energy use. In Figure 5 the energy use for the relevant sectors in the Netherlands is depicted.

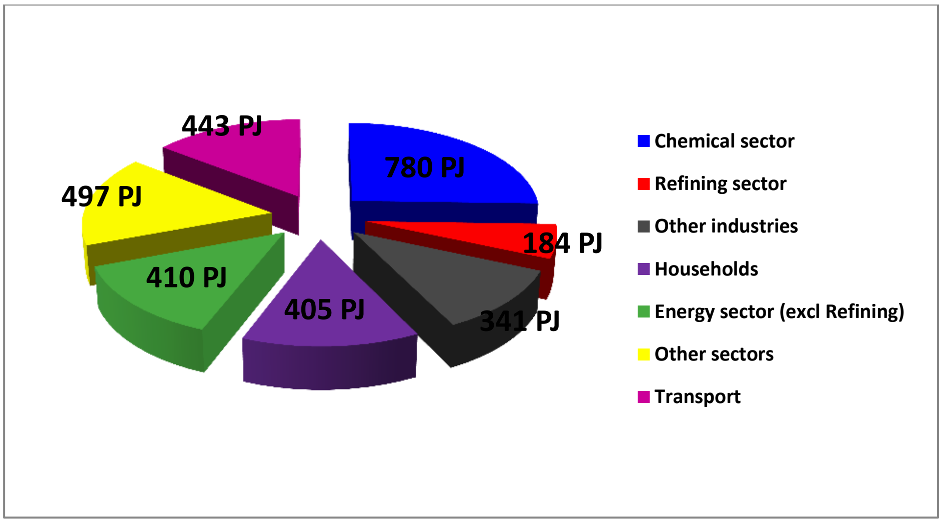

Figure 5: Primary energy consumption in the Netherlands in 2015 for various sectors. Total primary energy consumption was 3060 PJ. 'Energy sector' includes power plants and gas production, but excludes the refining sector. 'Other sectors' include Services, Agriculture and Greenhouse Horticulture

As can be observed from Figure 5, the energy use of the Dutch chemical sector is of major relevance. The primary energy consumption of the Dutch industry sector is decomposed in Figure 6. Traditional fossil fuels dominate the energy use, in particular for oil and natural gas.

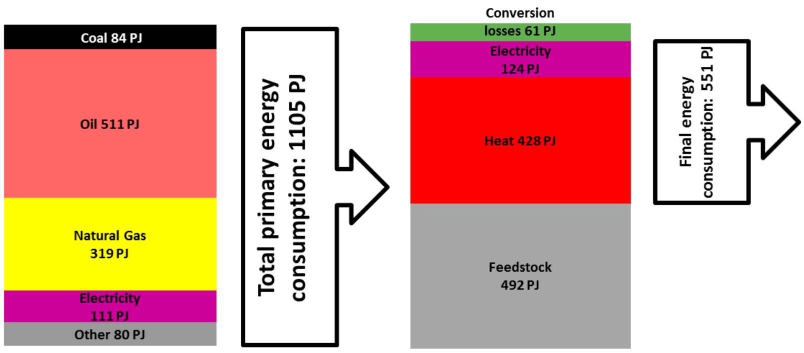

Figure 6: Decomposition of the primary energy consumption in the Netherlands in 2015 for the sector Industry into the various energy carriers and applications

As can be observed in Figure 6, application of energy for heat as well as feedstock dominate the energy use. If the energy use of the chemical industry is decomposed (see Figure 7), it is observed that the vast majority of energy use for feedstock is consumed in this sector. This is mainly the case for the oil-product naptha (for olefins production) and natural gas (in particular for ammonia production).

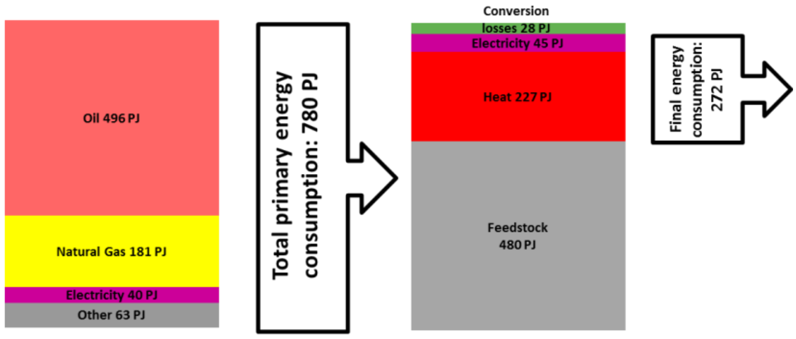

Figure 7: Decomposition of the primary energy consumption in the Netherlands in 2015 for the chemical sector into the various energy carriers and applications

5.1 Dutch potential Power-to-Chemicals

An estimate is made of the total potential for Power-to-Chemicals for the Dutch chemicals industry. This potential assumes that in particular the production of olefins and ammonia are electrified via hydrocarbon synthesis using (renewable) syngas to produce olefins and hydrogen production via water electrolysis to produce ammonia, in line with assumptions made in (Lechtenböhmer et al, 2015). Ethylene production is based on the ethylene production capacities as reported by (Koottungal, 2015). Ethylene production is recalculated to the production of High Value Chemicals (HVCs, i.e. light olefins (ethylene, propylene and butadiene) and non-olefins (aromatics and other C5+ compounds)) to be in line with assumptions made in (Lechtenböhmer et al, 2015). To that purpose, the ethylene production is assumed to be 30 wt-% based on naphtha-feed and HVCs-production is assumed to be 55 wt-% based on naphtha-feed (Ren et al, 2006).

Based on current production levels for ethylene and ammonia in the Netherlands, the required electricity consumptions to produce these chemicals is calculated up to around 215 TWh. Today's total Dutch Electricity consumption is 120 TWh (CBS, 2016).

Table 6: Total electrification potential Power-to-Chemicals

Sector	Production capacity	Electricity, required for production
Olefin production	4 Mtonnes ethylene or 7,4 Mtonnes High Value Chemicals (HVCs)	185 TWh
Ammonia production	2,9 Mtonnes ammonia	29 TWh

5.2 Dutch potential Power-to-Heat

An estimate is made of the total potential for Power-to-Heat in Dutch industry. This potential assumes that the processes that are carried out nowadays stay unchanged. The only thing that changes is the way in which the heat for the processes is generated. Energy saving measures, other than applying electrical heat pumps, will lead to a lower potential than presented below. In addition, this potential is calculated as a base load option where electricity is used continuously.
Table 7 presents the Dutch industrial final energetic energy use in 2015, as obtained from CBS. The refining sector has been added to industry, as opposed to the definition used by CBS. In addition to the total energy use, the final use of electricity has been added. The difference between the total energy use and the electricity use is calculated as energy used for heating. This underestimates the true energy use for heat, since electricity is nowadays also applied for heating purposes (heat pumps, refrigeration, electrical heating).

Table 7: Dutch industrial energy use in 2015.

Sector	Total (PJ)	Electricity (PJ)	Heat (PJ)
Food	85.3	23.3	62.0
Paper & board	23.3	8.5	14.8
Chemicals	278.9	44.4	234.5
Refining	132.2	9.6	122.6
Building materials	24	4.0	20.0
Metals	71.5	26.9	44.6
Miscellaneous	56.8	15.3	41.5
Total	**672**	**132**	**540**

The assumption is made that all heat demand below 200°C can be met by using industrial heat pumps. The heat demand above 200°C is covered by direct electrical heating. The main difference is of course the efficiency with which the heat is produced. The share of the heat demand below 200°C is based on information of a Dutch study (Davidse Consultancy, 2012) about companies in the refining, chemical, and paper & pulp sector, and the ECOHEATCOOL study (2005) for the food sector. The building materials & metals sectors are assumed to have a heat demand above 200°C.

Finally, the remaining companies (miscellaneous) are assumed to use only heat up to 200°C. This leads to o the two temperature regimes.
Table 8: , where the heat demand per sector is divided according to the two temperature regimes.

Table 8: Heat demand in Dutch industry in 2015 above and below 200°C

Sector	< 200°C (PJ)	> 200°C (PJ)
Food	62.0	0
Paper & board	14.2	0.6
Chemicals	82.1	152.4
Refining	18.4	104.2
Building materials	0.0	20.0
Metals	0.0	44.6
Miscellaneous	41.5	0.0
Total	**218.2**	**321.8**

The next step is to introduce heat pumps for temperature levels below 200°C and direct electrical heating above 200°C. Based on experience, a COP (Coefficient of Performance) of 4 is used for the application of a heat pump. Prerequisite for the application of a heat pump is the presence of waste heat of sufficient temperature level. The lower the temperature difference between waste heat and process heat, the higher the COP will be. Using a COP of 4 for temperature levels below 200°C and a COP of 1 for heating above 200°C leads to Table 9: .

Table 9: Electricity demand for Dutch industry for covering heat demand in 2015.

Sector	< 200°C		> 200°C	
	(PJ)	(TWh)	(PJ)	(TWh)
Food	15.5	4.3	0.0	0.0
Paper & board	3.6	1.0	0.6	0.2
Chemicals	20.5	5.7	152.4	42.3
Refining	4.6	1.3	104.2	28.9
Building materials	0.0	0.0	20.0	5.6
Metals	0.0	0.0	44.6	12.4
Miscellaneous	10.4	2.9	0.0	0.0

Total	**54.6**	**15.2**	**321.8**	**89.4**

6

Hit list promising electrification technologies

This chapter of the report gives the results of the business case calculations and the merit order assessment are discussed and the overall conclusions are drawn. Based on merit order and the business case calculations a hit list is made of the most promising generic electrification technologies & the opportunities for the Dutch chemical industry.

The results of the selected business cases are:

- **Arkema** and **Dow** see opportunities for a positive business case for their Power to Heat options. Both companies examine the possible next steps. Before these companies invest they need more detailed information on the profitability and the operational risks. For this reason detailed in-house profitability calculations have to be done. Next to that the new technologies have to be tested on pilot and demonstration scale before they will be implemented.
- **AkzoNobel** continues to investigate the increased use of MVR for salt production. A challenge is that replacing the existing multiple effect evaporators by MVR's is very capital intensive.
- The business case of **OCI Nitrogen** is not attractive with the projected ammonia prices for the year 2020. However if a premium is given for green ammonia this case would be a good starting point for carbon free ammonia production.
- The potential benefits of microwave reactors are very attractive. This makes it an interesting option for **Arkema** to further explore its applicability for the PMMA process on a small scale together with suppliers of microwave heating systems.

The four cases show that for every process/plant there is a different solution. However the question remains what is the general economic potential for different electrification options. Also the case studies give the business case of the electrification option if an investment decision has to be made. But what is the ranking of an option when it is already build and operational? According to the marginal cost & merit order assessment, used to rank the new demand response applications in conjunction to the current portfolio of electricity production units, only a limited number of Power-to-X options stay online during peak hours in the year 2020; the niche applications specialty chemicals and formic acid and the MVR application. The other electrification options like electrical boilers and high pressure electrolysers for ammonia & fuel production will be switched off during peak hours.

A number of things are important to keep in mind when interpreting the merit order results:

- Only the operational margin is considered. Often there are also other benefits, such as additional production (capacity) and security of supply, which is not included in the calculations. Also the CAPEX costs are not included.
- The benefits of saved alternative (fuel) costs have been included in all options.
- The value of the CO_2 emission reduction is not included in the marginal costs (the value of CO_2 has currently no major impact on the marginal costs).
- The different case analyses is based on an electricity connection of 10 MWe.
- The project only looked at selection of new demand response options for the chemical industry. In practice, these options "compete" with other innovative options such as batteries, compressed air energy storage (CAES) and pumped hydro storage. A useful next step would be to make the merit order including all of these techniques, so companies gain better insight into the potential of "their" demand response option in comparison with a wide range of other options.

Based on the case studies and the merit order calculations the most promising generic electrification technologies & the potential for the Dutch chemical industry have been summarized in Table 10.

Table 10: Hit list electrification technologies & potential for the Dutch chemical industry

Industrial Process	Electrification options	Total Dutch potential [TWh/a]	Impact on process	Driver
Specialty chemicals	Electrochemical production	low	High, unit operation level	New products
Low temperature heat (<200C)	MVR, heat pumps	5.7	Low, utility level	CO_2-Emission reduction
Formic acid production	Electrochemical production	0.5	High, unit operation level	CO_2-Emission reduction
Chlorine production	Electrolysis	2	High, unit operation level	Flexibility
High temperature heat (>200C)	Direct heating	42.3	Depending on the process	CO_2-Emission reduction
Olefin production	electricity driven cracking, electrochemical production of ethylene, micro wave reactors	185	High, unit operation level	CO_2-Emission reduction
Ammonia production	Water electrolysis, direct ammonia synthesis	29	High, unit operation level	CO_2-Emission reduction

7 Conclusions and recommendations

7.1 Conclusions

Based on this study the following conclusions are drawn.

1. **Electrification of the olefin and ammonia production have the largest impact on the Dutch energy system.**
   Today traditional fossil fuels dominate the energy use in the Dutch industry, in particular for oil and natural gas. The energy use is dominated by application of energy for heat as well as feedstock. The vast majority of energy use for feedstock is consumed in the chemical industry mainly for the oil-product naptha (for olefins production) and natural gas (in particular for ammonia production). The estimated total electrification potential for the production of olefins and ammonia is 214 TWh.

2. **Power-to-Chemicals and Power-to-Heat technologies for high temperatures (>200°C) have to be developed to use the potential of electrification for a large CO_2 reduction in the chemical industry.**
   The estimated potential for Power-2-Chemicals and Power-to-Heat technologies for high temperatures (>200C) is large. However a lot of those technologies, like direct electrochemical production of ethylene or ammonia, are at low TRL level. Also the application of direct heating has to be proven in high temperature applications in the chemical industry. Further development of those electrification technologies is there for needed to open this potential and use renewable electricity as continuous energy source in the Dutch chemical industry.

3. **Till 2020 only a limited number of Power-to-X technologies will be applied for demand side response.**
   The marginal cost & merit order assessment, used to rank the new demand response applications in conjunction to the current portfolio of electricity

production units, shows that in the year 2020 during peak hours only niche applications (specialty chemicals & formic acid production) and the mechanical vapor recompression application stay online. Other electrification options like electrical boilers and high pressure electrolysers for ammonia & fuel production will be switched off during peak hours.

4. **In today's chemical plants Power-to-Heat technologies give an opportunity for a positive business case.**
   The processes of four companies have been assessed whether and how their processes can be electrified and whether their processes can be used for demand side response. A good result of the project is that two companies (Arkema and Dow) see opportunities for a positive business case for their Power-to-Heat options. Both companies examine the possible next steps. Next to that the application of mechanical vapor recompression in the salt production is very promising.

7.2 Recommendations

This project shows that several issues need to be investigated further and that it is still too early to determine whether the companies should invest in electrification and flexibility of their energy demand. Outstanding issues include:

1. **Evaluation of additional benefits**
   The business case of OCI Nitrogen is not attractive with the projected ammonia prices for the year 2020. However if a premium is given for green ammonia this case would be a good starting point for carbon free ammonia production. A market study is needed to see if customers are willing to pay this premium.
   The potential benefits of microwave reactors are very attractive. This makes it an interesting option for Arkema to further explore its applicability for the PMMA process on a small scale together with suppliers of microwave heating systems.

2. **A wide merit order of all possible future electrification options**
   Only the operational margin is considered in the merit order assessment. Often there are also other benefits, such as additional production (capacity) and security of supply, which is not included in the calculations. Also the CAPEX costs are not included. Therefore it is advised to extent the merit order with more possible future electrification options and to add the mentioned benefits and costs.

3. **Modeling of future balancing market & the role for electrification in the future Dutch energy system from a techno-economic perspective**
   In the above assessment of the different electrification options a marginal cost and merit order model was used for the new demand response applications in conjunction with the current portfolio of large scale power plants, must run units and increase of renewable energy sources.
   Although the results give a first indication of the merit order for 2020 and the opportunities for the different chemical processes, the true potential of

electrification technologies remains uncertain because the restructuring of future energy markets is not well understood. Such an assessment would require (i) a more fundamental insight into the drivers for electrification mentioned above as these will determine the economic viability of electrification options and (ii) detailed accounting for the electricity supply and demand dynamics over the year on both the day-ahead spot and the balancing market. A crucial element in the economic assessment of electrification options is the characterization of both conventional and innovative electrification technologies (for instance novel electrolysers, electro synthesis), their possible operation strategies and the competition with alternative, non-electricity based, technologies.
The study should aim to explore the role for electrification in the future Dutch energy system from a techno-economic perspective: what could, or should, be the role for electrification in the mix of energy technologies in three different scenarios (security of supply, large CO_2 reduction, large supply of renewables) and with the least cost for society.

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Appendix A. Questionnaire

Note confidential

Petten, January 2015

From ECN/TNO

To E-Match industrial partners

Copy to

Subject [Title]

Introduction

This questionnaire has as objective to provide and document the relevant process information for the E-match project. Please return this document to boersma@ecn.nl. All provided information in this document will be kept confidential by ECN and TNO and will not be distributed amongst the other project partners, unless you give the specific permission to.

Information

Please provide the requested information in the fields below.

Process Name
Company
Confidentiality *Please specify if the provided information can be shared with other partners within the E-Match project.*
Yes/no
Process Information *Please supply below the requested information of the proces to provide an understanding what kind of conversions take place and what the key elements/operations in the process are.*
(Simplified) Flow Sheet *Please provide a (simplified) process flowsheet/block scheme, indicating the main unit operations. This information can also be provided in an attachment to this document.*

Short description of the process *(please provide a short summary of the process)*

Overall Mass Balance *Please specify the main in- and outgoing mass flows.*

MATERIAL IN		MATERIAL OUT	
Component	Flow rate [tonne/a]	Component	Flow rate [tonne/a
Raw material 1		Product 1	
Etc.		Etc.	

(Main) Reactions *Please specify the main reactions that occur in your process. Are they significantly endo- or exothermal? Please refer to the equipment ID in the process flow sheet, if available*.

- …

(Main) Separations *Please specify the (main) separation processes and indicate if they require significant amounts of energy (heat/power). Please refer to the equipment ID in the process flow sheet, if available*.

- …

Flexiblity of the process

- **Batch/continueously** *Please indicate if the process is currrently operated as a (semi) batch or continueous process.*

- **Turndown ratio** (expressed as % of maximum capacity) *Please indicate the possibility to have a variable production rate (turndown ratio) of the process and to what degree.*

Indication of Utility Consumption *Please provide information/indication on the existing fuel/energy used for for this process and on the main unit operations where they are consumed.*

	Annual consumption	Unit	Main unit operation(s)
Total fuel consumption by the process (also e.g. by steam generation)		GJ/a	• ……
Total cold/ refridgeration) requirements		GJ/a	• ……
Total electricity consumption		GWh/a	• ……
Other			• ……

Co-generation *Please indication of any co-generation (heat + power) occurs on site. Please indicate the annual fuel input plus output capacity).*

Remarks *If you have any additional information you can express it here.*

First Ideas for Electrification *If you take this process in consideration, do you have already ideas on where electricity can be used now or in the future? If this is the case, please indicate them.*

- …

Replication Potential *Please indicate if(you expect) there are similar processes in the Netherlands, where – if this process (or elements therof) could be electrified – a similar application can be potentially realised.*

Remarks *If you have any additional remarks you can express them here.*

Thank you for your cooperation!

Appendix B. Factsheet OCI Nitrogen

OCI Nitrogen BV is a subsidiary of OCI N.V. which is a worldwide producer of various types of fertilizers and industrial products. They produce fertilizers, methanol and other industrial products for agricultural use and industrial customers worldwide. OCI N.V. is one of the largest fertilizer producers with a capacity of almost 8.4 Mtons. Production facilities are located in the Netherlands, the USA, Egypt and Algeria.

OCI Nitrogen is one of the European market leaders in mineral fertilizers and the world's largest producer of melamine. The ammonia produced forms the basis for both fertilizer and melamine production.

OCI Nitrogen's history goes back more than eighty years. Established in 1927, it was initially known as Stikstofbindingsbedrijf. After changing owners a number of times, it continued in 2010 under its current name, OCI Nitrogen. The head office and primary production facilities are located at the Chemelot industrial site in Geleen (Netherlands). The company also has two port facilities: OCI Terminal Europoort (Port of Rotterdam), and OCI Terminal Stein, which connects OCI Nitrogen to the North Sea and Europe's inland waterways. They have approximately 500 employees in the Netherlands and 750 employees worldwide.

OCI Nitrogen is one of the larger energy consumers in the Netherlands, mainly used for the production of ammonia. Our facilities are among the most energy efficient facilities in Europe. Ammonia is the molecule from which all nitrogen based fertilizers are produced. OCI Nitrogen B.V. in Geleen produces 1.1 Mton/y ammonia, 1.5 Mton/y of fertilizers and over 120 kton/y melamine.

The main raw material for the production of ammonia is hydrogen. This is produced in a process called steam reforming. In this process natural gas (methane) is both the feedstock and the fuel. The production of hydrogen is the main contributor to the CO_2 emissions of the OCI Nitrogen plants producing over 1.8 Mton of CO_2/year.
There are some routes towards the production of a low CO_2-ammonia and derived products by electrification of process steps:
A: Hydrogen production using electrolyzers
B: Replace the fuel part in the reforming section by electrical heating (or hybrid),
C: Include hybrid – electric heating in the melamine process

The consequences in terms of required process modifications of option A and B are significant as an ammonia plant is very well heat integrated and some of the produced CO_2 is used as a feedstock for downstream processes.

Appendix C. Factsheet AkzoNobel

AkzoNobel Industrial Chemicals is a business unit of AkzoNobel. It produces and markets high purity salt, chlorine, caustic lye, hydrochloric acid, chloromethanes and monochloroacetic acid (MCA). These products are essential in daily life and are for example used in the manufacture of vehicles, glass, performance plastics, pharmaceuticals, feed and foodstuffs (e.g. Jozo, Nezo, OneGrain and KNZ), textiles and disinfectants for swimming pools.

Industrial Chemicals has approximately 1,900 employees employees based in the Netherlands (Rotterdam, Hengelo, Delfzijl, Arnhem and Amsterdam), Germany (Ibbenbüren, Bitterfeld and Frankfurt), Denmark (Mariager), Sweden (Gothenburg), USA (LeMoyne, Chicago) and China (Taixing, Shanghai). Major joint ventures are Delamine (Delfzijl, the Netherlands) and Denak (Ohmi, Japan). The businesses of Industrial Chemicals form a strong and integrated product chain of energy, salt, chlor-alkali, and chlorine derivatives as indicated in the figure below.

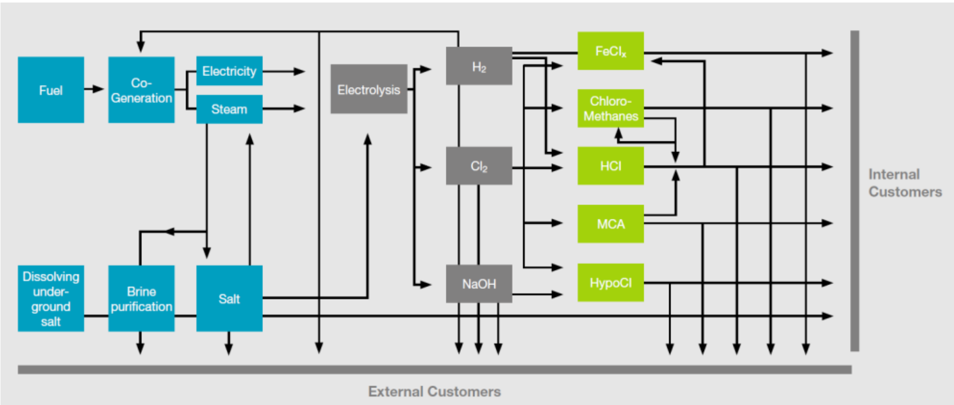

Figure 8: Product portfolio AkzoNobel

It all starts with energy, which counts for about 80% of the raw material used. Traditionally, cogeneration is used to generate steam and electricity. However, this has become less attractive due to negative spark spreads. AkzoNobel therefore looks to diversify its energy sources and make them more sustainable. Examples of such diversification include steam generation from waste and biomass.

Electrification provides another opportunity to make the energy more sustainable. This is basically already applied in the electrochemical chlor-alkali production process, which fully runs on electricity. Further opportunities for electrification include the use of mechanical vapor recompression (MVR) for salt evaporation and caustic evaporation, which are currently the main steam consumers within Industrial Chemicals. MVR technology enables complete replacement of steam consumption by electricity. MVR for salt evaporation is already being applied on a significant scale, although the majority of the salt production still occurs by the more traditional multiple effect evaporation (MEE). MVR for caustic evaporation is less attractive due to the higher boiling point elevation and is therefore not yet being applied.

Appendix D. Factsheet DOW Benelux

Dow Benelux BV is a subsidiary of The Dow Chemical Company. Dow Benelux worsk daily on innovations. We do this by combining scientific knowledge with our technological knowledge. We deliver sustainable contributions to solving the most pressing problems in the world such as the need for clean drinking water, renewable energy generation and improving agricultural productivity. The history of Dow Benelux begins in 1955 with the opening of a trade office. Meanwhile, Dow Benelux has become a leading player. Approximately 2,000 dedicated employees working from six offices and 20 factories in the Netherlands and Belgium to leading products and solutions. The plastics and chemicals that are produced in the UK find their way to customers and markets worldwide. The heart of Dow Benelux in Terneuzen, Zeeland. Dow Terneuzen has 17 plants and approximately 1,700 employees, the second largest production site of the Dow Chemical Company. As the largest employer of Zeeland Flanders, Dow contributes to the economic and social success of this region.

The main energy consuming process at the Dow facility is the well documented steam cracking process of hydrocarbons with the aim to produce olefins, crucial chemical building blocks for many products.
Dow Benelux B.V. in Terneuzen produces 1.7 Mton/y of ethylene, 800kton/y of propylene , as well as butadiene , BTX and heavier by products.

The primary reactors of these plants, also known as furnaces, create a high temperature environment by combustion of methane and hydrogen. This process is the main contributor to and source of CO_2 emissions on site.
The total thermal capacity of these units over the 3 crackers adds up to 1500 MWth.
A furnace consists of 2 main parts being a: the radiation section and b: the convection section.
In the radiation section the reactor tube is heated to a temperature at which the reaction takes place. The section B is used to pre-heat as well as mix the feedstock to the reactor tube.
Its top section is used to recover heat and generate steam. This steam is used in the downstream plant for traction (compressor drives) as well as heating purposes.

There are a number of fundamental choices to be made to develop technology towards low CO_2 processes. These are:
A: hybrid system with electrical as well as fuel gas flexibility.
B: electrically heated system
C: Totally new route towards the end products.

The consequences of each option will be significant as a cracker is very well heat integrated.

Appendix E. Factsheet Arkema

The Carling / Saint-Avold Arkema platform
The Arkema Carling / Saint-Avold platform integrates two of Arkema's three business segments: Coating Solutions, with Research and Process activities and with the production of acrylic acid and derivatives, as well as Industrial Specialties with Arkema's subsidiary's plant (Altuglas International) which produces PMMA sheets. Since 2008, Arkema also operates a superabsorbent production unit at the Carling / Saint-Avold site for the Japanese company Sumitomo Seika.

The Carling / Saint-Avold platform is one of the major players in the economic region and one of the most important industrial structures of Arkema in France. This position was further strengthened when Altuglas International supplemented this industrial site with its sheets production plant in the 1980s. The platform now includes:

- The Research and Acrylic Processes Center, which serves Arkema's customers and acrylic activities in Europe and around the world.
- Units for the production of acrylic acid and acrylic monomers
- A factory at Altuglas International

Figure 9: The Carling / Saint-Avold Arkema platform

The Altuglas International site of Saint-Avold
The Saint-Avold plant is one of Altuglas International's three European PMMA production sites. This subsidiary of the Arkema Group is a world leader in the manufacturing of PMMA (polymethylmethacrylate). This high-quality transparent thermoplastic, known as "acrylic glass", is produced at the Saint-Avold plant in the form of cast sheets and blocks (Altuglas® and Oroglas®). Thanks to its superior transparent properties, it is used in the building, healthcare, transport and visual communication sectors (signs, displays at points of sale).

Due to the integration in the site with other production units, the PMMA production benefits from an existing steam network. But its development will require either additional energy supply or energy savings technologies that would make it more independent from the platform. There are several choices that can be made to introduce low CO_2 emitting / lower fossil energy demand technologies:

- Process intensification with alternative heating process, like the use of microwaves
- Energy recovery (high temperature heat pumps or vapor recompression)
- Heat and Energy storage.

Each possible solution should have a significant impact on the process since the production is currently operated mostly batchwise. The use of completely new technologies, like microwaves, would still need to be demonstrated since it would correspond to a more drastic modification of the process.

Appendix F. Price assumptions

Table 11: Market prices

Market prices			
			sources
Electricity	[€/MWh]	46	APX
Natural Gas	[€/MWh]	14	Platts
CO_2	[€/t]	5	http://www.investing.com/commodities/energies
Hydrogen	[€/t]	2000	Subject to local situation
Ammonia	[$/t]	325	CHEME 4620: Chemical Process Design (Fall 2016): Chemical Prices
Ethylene	[$/t]	885	CHEME 4620: Chemical Process Design (Fall 2016): Chemical Prices
Methanol	[$/t]	210	CHEME 4620: Chemical Process Design (Fall 2016): Chemical Prices
Naptha	[$/t]	335	CHEME 4620: Chemical Process Design (Fall 2016): Chemical Prices
Propylene	[$/t]	1000	CHEME 4620: Chemical Process Design (Fall 2016): Chemical Prices

Appendix G. TRL levels

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

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