REPORT

Project 6-25 Technology Validation

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PDC Process Design Center

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Executive Summary

Project background and objective

In accordance with the **Climate agreement** the Dutch industry needs to reduce 14.3 Mtons of CO_2 emissions by 2030 (compared to 2015) additional to CO_2 reduction obligations of 5.1 Mtons from the EED[1] (total 19.4 Mtons). Most reduction measures require infrastructural changes that will not be realised before the end of 2025.

Innovative energy efficiency measures as presented by **Project 6-25**[2] offer a CO_2 emission reduction potential that can be realised **before the end of 2025** in a cost-effective way.
FME in cooperation with VEMW asked the consortium of Royal HaskoningDHV and PDC to perform an **independent validation study**. The study was supervised by a **steering group** with representatives of technology suppliers, industrial energy consumers and independent technology experts.

The **objective** of this project is to validate independently the cost-effective and proven CO_2 reduction potential that can be realised in the Dutch industry by applying 15 preselected innovative technologies. We call this the **Feasible economical reduction potential**.

The technologies are divided into **five technology groups**:
1. Motors and Drives;
2. Heat Integration;
3. ICT[3];
4. Separation technology;
5. Power flexibility.

A **sectoral approach** is used to determine the potential for the Dutch industry as a whole, being:
- Chemical Industries: Industrial gasses, Steam crackers, N-Fertilizer, Wider chemical industries;
- Refineries;
- Iron and Steel;
- Food;
- Paper and Board.

Together they cover 86% of the energy use of the Dutch industry. Savings in the other 14% are estimated by extrapolation to cover the total CO_2 reduction potential Dutch industry.

The main **boundary conditions** for the study are:
- Implementable before the end of 2025;
- Proven technology: Technology Readiness Level (TRL) 8 or 9;
- Cost effective: this is defined as a payback period of 5 years or less including subsidies[4] and a weighted average cost of capital (WACC) of 8%;
- Non-energy related savings are taken into account in this study for the determination of the payback time only in case they are verifiable and relevant for lowering the payback time to under 5 years;[5]
- Capital and skilled people are available.

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[1] *EED is the European Energy Efficiency Directive, implemented in the Netherlands as the Energy Agreement*
[2] *Website Project 6-25 https://6-25.nl*
[3] *Process automation and digitisation*
[4] *EIA and SDE++*
[5] *In practise, more non-energy benefits can apply to a certain situation e.g. lower maintenance cost, higher yields and better products. This allows the business case for certain technologies to improve. Payback times that are already lower than 5 years could be even lower.*

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Results

The **Feasible economical reduction potentials** are presented in the table below (for a larger version see Chapter 2, *Table 2-1*).

Table Executive Summary 1 - Overview of results: Feasible economical reduction potential (kton CO_2/y).

	Technology groups	Motors and drives		Heat integration				ICT			Separation		Power flex	Totals
	Industry sectors	High efficiency electro motors	Electrom. system opt.	Flue gas recuperation	HT heat pumps	Mechanical vapour recom-pression	Heat transformer	Advanced process control	Energy management analytics	Asset manage-ment analytics	Membrane separation of H2 from hydrocarbons	Pervaporation-based ethanol drying	Hybrid boilers	
Chemical industry	Industrial gasses	0	11	5	0	0	0	26	14	16	0	0	90	162
	Steam crackers	0	29	55	4	15	29	74	36	39	0	0	0	281
	Ammonia & N- fertilizer	0	5	10	1	2	0	49	21	19	3	0	10	120
	Wider chemical industry	1	32	59	52	127	86	58	25	57	0	0	90	587
	Refineries	0	20	85	6	23	76	65	31	29	73	0	0	409
	Iron and Steel	2	47	49	2	8	0	46	23	17	0	0	0	194
	Food	5	49	67	165	165	16	106	63	62	0	0	130	828
	Paper & Board	1	39	20	38	88	0	23	14	14	0	0	50	287
	Other industries *)	-	-	-	-	-	-	-	-	-	-	-	-	467
	Correction for overlap)**	-	-	-	-	-	-	-	-	-	-	-	-	-515
	Totals	**9**	**232**	**350**	**268**	**428**	**207**	**447**	**227**	**253**	**77**	**0**	**370**	**2820**

Conclusions

The main conclusions[6] are:

1. The 15 technologies validated in this study allow for a **Feasible economical reduction potential of roughly 3 Mton up to and including 2025**. This potential can be realised without additional infrastructure (as with e.g. CCS, H_2) or new legislation provided that there is no limitation of capital and/or manpower. This is 20% of the industry obligations in the Climate agreement, or 15% of the 19.4 Mtons total CO_2 reduction obligation for the Dutch industry.
2. If the **payback time** is allowed to increase from 5 to 10 years, the feasible economical reduction potential increases with 1 Mton/year.
3. We identified the following **7 'hotspots'** that together represent the validated feasible CO_2 reduction potential:
   - A wide range of technologies with implementation potential applies to the sectors 1) Food, 2) Wider chemical industry and 3) Refineries;
   - Technologies with cross sectoral implementation potential are: 4) ICT, 5) Heat Integration and 6) Motors and Drives;
   - Technology with implementation potential at specific industrial sites is 7) Hybrid boilers.
4. Materializing the feasible potential is not "business as usual" and requires a **programmatic approach** to address specific challenges like the complexity of heat integration on complex Industrial sites and ICT knowledge and awareness.

Recommendations

The main recommendations are:

1. To developing ways to increase the access of stakeholders to:
   - **Knowledge**, this can be realised by creating a Living Lab environment, in which several pilots based on the 7 hotspots, share best practices so that this ultimately leads to a reproducible approach that is widely applicable to the industry;
   - **(Wo)manpower** by intensification of cooperation between industry, suppliers and service providers in the value chain. For example, by developing consortia of specialised companies and service providers that can quickly and (cost) effectively implement new technology in a specific market segment;
   - **Capital**, for example by ESCO[7]'s, bridging the gap between large international funds (e.g. pension funds) and the relatively small-scale investments in this study. This may also increase the feasible economical potential for the measures with a payback period of 5 to 10 years;
2. To invest in capacity and knowledge of **enforcement of energy regulations**.

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[6] *For more results, conclusions, observations and recommendations please refer to Chapter 2.*

[7] *Energy Service Company*

1 Introduction

1.1 Project background and objective

Project 6-25
The Dutch Industry needs to significantly reduce CO_2 emissions. Most reduction measures require infrastructural changes that are not realised before 2027. Innovative energy efficiency measures as presented by Project 6-25 offer a CO_2 emission reduction potential that can be realised before the end of 2025 in a cost-effective way, also because these techniques do not require this infrastructure.

The realisation of this potential requires broad support for Project 6-25 over the whole value chain. To gain this support the CO_2 emission reduction potential of Project 6-25 is to be validated by an independent party. This validation study has been assigned by FME to a consortium of Royal HaskoningDHV and PDC. This report is the first step in this validation.

The study is to bring insight on how to focus the CO_2 reduction efforts of suppliers, industry and government and thus help to make the first and most cost-effective step towards the 2030 climate targets: implementation of the feasible reduction potential.

The objective of this project is to validate independently the cost-effective and proven CO_2 reduction potential that can be realised in the Dutch industry by applying 15 preselected technologies.

In this introduction we discuss:

- Scope; CO_2 reduction potential 15 technologies, 5 technology groups, boundary conditions
- The project approach, activities task 1, 2 and 3, theoretical and feasible potential, technical and economical potential
- Energy use and CO_2 emission by industry
- Calculations of payback time and CO_2 reduction potential based on energy saving potentials
- An overview of the technologies and suppliers studied for this report.
- Reading guide for the report

1.2 Scope

To meet the objective, we have to calculate the CO_2 reduction potential based on the energy savings that can be realised in Dutch industry by the 15 preselected technologies, while taking into account the boundary conditions that apply to this potential. When calculating the CO_2 reduction potential we focus on significant effects.

Below we first describe the boundary conditions for the calculation of the CO_2 reduction potential, followed by a description of what we mean with focussing on significant effects and an overview of the 15 preselected technologies.

1.2.1 Boundary conditions

Six boundary conditions apply to the validation of the CO_2 reduction potential:

1 Dutch industry

The CO_2 reduction potential is to be realised in the Dutch industry. Paragraph 1.4 describes which sectors belong to the industry and on which sectors this study focusses.

2 Capital is available

Aim of project 625 is to set up structures that make sure that capital limitations are not limiting the implementation of energy efficient technologies.

3 Skilled people are available

The assumption is that work can be out sourced to third parties. Therefore, no limitations for the availability of skilled people are taken into account.

On such a short time scale only proven technology can be applied. We defined proven technology as technology proven to be reliable in an industrial context on a relevant scale. This compares to Technology Readiness Level (TRL) 8.

4 Realisable before the end of 2025

We found two types of limitations that may limit the implementation before 2025:

- the lack of maintenance stops that allow for implementation before the end of 2025,
- the time required change your organisation in such a way that it is capable of structurally improving energy efficiency by applying ICT.

The second limitation may seem to contradict the assumption that skilled people are available. However, we think that successfully outsourcing a far-reaching topic that touches every aspect of your business operations is only feasible if you have enough in-house knowledge to manage this outsourcing. So, in case of companies that already have such in house knowledge the second limitation does not apply. Only in case of companies that currently have no or very limited experience with ICT this limitation applies.

5 Cost-effective

Cost effective is defined as a payback period of 5 years or less including subsidies and a weighted average cost of capital (WACC) of 8%. Paragraph 1.5 describes how these calculations are made.

6 Brand-independent

The potential of the 15 technologies is assed using the information of a selected number of suppliers. However, we aimed to this in such a way that the CO_2-reduction potential of the technology is determined, not the attractiveness of a certain brand to a specific industrial sector.

Meeting conditions 2 and 3 is not self-evident. Therefore, it is important to create conditions to make these assumptions valid and capital and skilled people sufficiently available. We come back to this in the recommendation section.

1.2.2 Significant effects

This study provides an overview of the emission reduction for the Dutch industry as a whole. Due to the energy intensity of the industry we express results in thousand tons of CO_2. Thus, if a result is zero that does not mean that there is no emission reduction but that it is less than 499.999 kg of CO_2 and therefore 0 kton CO_2.

This means that secondary effects that reduce CO_2 emission are not relevant to this study as the following calculation will show.
An example of a secondary effect that is often mentioned is less emissions by cars or maintenance engineers since they have to come less often to the site. To illustrate the insignificance of this effect we calculate the contribution to the CO_2 emission on the scale of all the industrial EU-ETS companies
Let's assume a very big effect:
A measure reduces this traffic with 1,000 km per year for each of the 248 EU-ETS factories in the Netherlands and the cars they are driving with are old gasoline cars that drive 1 on 10.

Using the numbers in table 1-1 we calculated the saving that results from 1000 km less driving by maintenance engineers per Dutch industrial EU-ETS company. Together this is 248,000 km less per year. Even in that rather extreme case this would mean that the total CO_2 reduction is only 0,065 kton CO_2/year.

Therefore, we calculated savings based on savings that are reported from applications of technologies in industry. If effects are strong enough to be measured as a saving, they are significant and taken into account, if savings are too small to be reported they are not relevant to this study.

Table 1-1: Numbers used to calculate effect of CO_2 reduction by less km driven by maintenance engineers.

	Quantity	Unit	Source
Reduction in km driven for maintenance	1,000	km/company	
Nr or industrial EU-ETS companies in NL	248	companies	NEA, see 1.4
Car efficiency	10	km/l	
Emission factor gasoline	72.5	kg CO_2/GJ	Nederlandse lijst van energiedragers en standaard CO_2 emissiefactoren, versie januari 2019
Energy content gasoline	43.2	MJ/kg	
Density gasoline	0.84	kg/l	

1.2.3 15 Pre-selected technologies

The CO_2 reduction is to be realised by energy savings due to the application of 15 technologies divided over 5 technology groups. In chapter 3 to 7 these technologies are described in detail:

- Efficient electro-motor systems:
  - Replacement of electro-motors by more efficient electro-motors;
  - Optimisation of electro-motor systems driving pumps, fans and compressors;
  - Nano-lubricants.

- Heat integration 2.0
  - Flue gas recuperation until below the condensation point;
  - Heat pumps;
  - Mechanical vapour recompression;
  - Heat transformers;
  - Heat storage.

- ICT
  - Asset Management Analytics;
  - Energy Management Analytics;
  - Advanced Process Control.

- Separation technology:
  - Membrane separation of H_2 from hydrocarbons;
  - Membrane separation of N_2 /O_2 from Air;
  - Pervaporation-based ethanol drying.

- Power flexibility:
  - Fly wheel technology;
  - Hybrid boilers.

1.3 Project approach and results

The project is divided in 2 tasks flanked by a reporting task. At the end of each task the outcomes and the approach for the next task are presented to the Technology Validation Steering Group. This approach is presented in Figure 1-1.

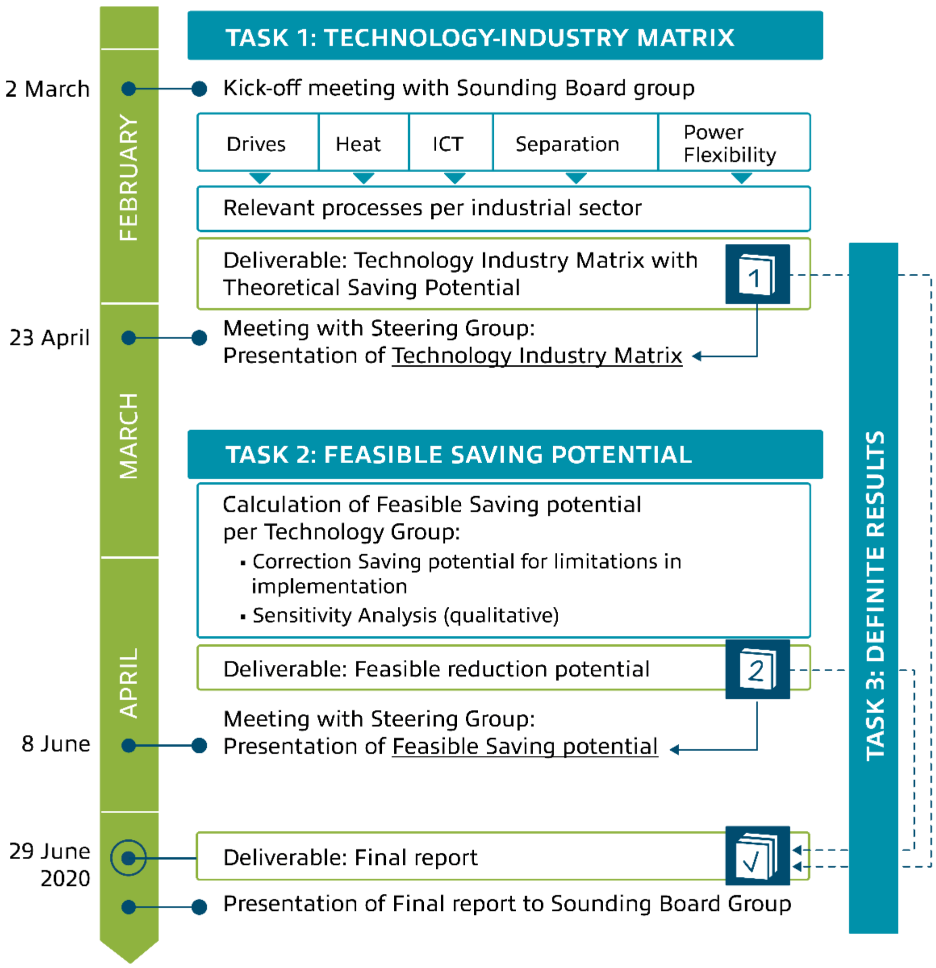

Figure 1-1: Project approach

In this study we look for agreement on the robustness of method, assumptions and data sources. We do not strive for consensus on outcomes, since it is crucial for the trust building that we deliver an independent result.

1.3.1 Activities and results in Task 1

The aim of task 1 is to have a first order estimate of the technical and the economical CO_2 reduction potential before the end of 2025. **To indicate that these numbers were only indicative we called them the theoretical potentials**. The difference between the theoretical technical potential and the theoretical economical potential was that the latter meets the requirement of a payback period of 5 years or less. This purpose of the theoretical potentials is twofold:

1 Have an impression of high potential technology-industry combinations. To get this impression we presented the Technology-Industry matrix as the main result of Task 1.

2 Check in discussions with technology suppliers and technology users whether full potential and potential limitations are considered.

Task 1 included the following activities:

- Quick scan, to qualitatively assess the completeness of the current technology portfolio,
- Literature review on the technologies,
- Interviews, meeting report and approval with external experts
- Assessment of the general payback time per technology
- Determination of the CO_2 emission per relevant industrial process
- Development of the Technology -Industry matrix resulting in a theoretical and economical reduction potential per technology – industry combination.

1.3.2 Activities and results in Task 2

In **task 2** the **Feasible Economical CO_2 Reduction Potential** was determined. This potential meets the brief for the validation of the CO_2 reduction of Project 625. In addition, we calculated the feasible technical potential.

When interpreting these results, one should take into account the different levels of information that we are working on:

- The potential of a technology for a **specific company**. This level is too detailed for this study. Nevertheless, a specific company can use this study as a guide for technologies that may or may not be of interest in the quest for lower the CO_2 emissions. In principle technologies with a high saving potential in a specific sector should be of interest to the individual companies in that sector.
- The potential of a technology for a **complete sector**. For this situation the accuracy of the outcomes depends a bit on the number of installations considered in a sector. In most cases we expect the average accuracy to be approximately +/- 50%.
- When it comes to the reduction potential of the **total industry** the effect of large numbers works in our advantage. Therefore, we expect that the accuracy of the feasible economical potential is much higher with a deviation of maximally +/- 30% on industry level.

Based on the above we can conclude that the difference between the feasible technical and the feasible economical potential is rather large. This difference is caused by economic considerations.

To assess how a larger part of the feasible technical potential may become feasible economical potential we did a sensitivity analysis on the influence of the maximum payback period and the height of the WACC. We determined the feasible economical potential in two ways:

- increase the maximal payback period from 5 → 10 years
- decrease the WACC from 8% → 4%

Activities in task 2 were:

- Determination of **technical limitations and their effect on the technical and economical** CO_2 **reduction potential per industrial sector**. The limitations and the effect on the CO_2 reduction potentials are described in chapter on the respective technology group.
- **Correction for overlap** in saving potential between technologies.
- **Extrapolation** of the results to the whole of the Dutch industry.
- Evaluation of assumptions with a **sensitivity analysis** on the technical and economic potential.
- We use the insights gained in this study to give an indication of the potential of CO_2 reduction by means of insulation[8].

The overall result of Task 2 is the 'Feasible Economical CO_2 emission reduction potential per 2025'.

1.4 Energy use and CO_2 emissions by industry

This paragraph describes **CO_2 emissions and energy use by the Dutch industry**, in order to provide **background to the choices** made regarding which sectors are studied in more detail and which are not.

1.4.1 SBI codes to indicate industrial sectors

The energy use in industry is in general reported per category of companies, the so-called SBI categories[9].
However, for reasons of **confidentiality** there are a few limitations to the use of this SBI categories:

- Energy use is not always subdivided to the same level of subcategories;
- There are no official lists of which companies have which SBI codes there are only the general SBI code description.

Nevertheless, based on the general description of the SBI codes we know that the sites of Dow, Shell Moerdijk, and Sabic Chemelot are in 20.14, the refineries of BP, ExxonMobil, Gunvor, Koch, Shell Pernis and Zeeland Refinery in Refineries, Tata Steel in Iron and steel, N-fertiliser producers OCI and Yara are in 20.15, industrial gasses producers Air Liquide, Air products and Linde are in 20.11, the 22 paper production sites in the Netherlands in 17 and Avebe, Cosun, Friesland Campina, Mars and a whole lot of other companies in SBI code 10 for Food.

1.4.2 CO_2 emission numbers

The largest CO_2 emitters in industry are part of the European Emission Tranding System (EU-ETS). In this framework the CO_2 emissions of these emitters are registered. In the Netherlands the Nederlandse Emissie Autoriteit (NEA) registers and published these CO_2 emissions. This register is public.
In Table 1-2 we summarised the CO_2 emissions per sector and the number of installations.

[8] Based on the saving potential of insulations as presented by Ecofys in 2012. The calculation of the actual saving potential of insulation is however not part of this study.
[9] The SBI code applied by the CBS is SBI 2008 versie 2018 update 2019, this documents provides a qualitative description of the type of business that belong in each SBI category

From this table it is clear that 480 installations are registered by the NEA. Normally one site counts like one installation, but some large sites like Dow and Shell Moerdijk have several installations that are separately reported. At the same time all EU-ETS plants on the Chemelot site are registered as one installation. Therefore, the number of installations is not the same as the actual number of sites.

When looking more closely at the activities of these sites approximately 50% of the EU-ETS installations are industrial installations. The other installations are universities, hospitals, greenhouses, asphalt production facilities for road construction, etc.

Only 248 installations on the EU-ETS list are actual industrial installations.

To bring some focus in our study we selected 8 industrial sectors that are known as the most energy intensive industrial sectors: industrial gasses, steam-crackers, N-fertilizer, Wider chemical industry, refineries, iron and steel production, food and paper.

When we focus on the companies in the 8 selected industries, we see that these industries cover 95% of the EU-ETS emissions in industry.

Although the register by the NEA provides an overview of the scope 1 emissions per location of the largest CO_2 emitters in industry, it has some serious limitations:

- The CO_2 registration gives the total of scope 1 emissions, meaning all emissions on the site. This also includes process emissions that are not reduced when reducing energy use. Not included are emissions related to purchased electricity (scope 2);
- Furthermore, all activities at Chemelot are reported under one Chemelot permit, making it impossible to determine which emissions are from which type of activity;
- Only the largest CO_2 emitters are registered under EU-ETS. The other 40% of emissions due to industry are not taken into account.

Therefore, we choose to use final energy use as registered per sector by the CBS instead of the CO_2 as registered by the NEA.

Table 1-2: Scope 1 CO_2 emissions *per sector based on NEA data per installation [B11]*

2018 [ton CO_2 eq]	ETS-NL		Total industry		In the 8 selected industries	
Sectors	Emission [ton CO_2]	Nr of permits	Emission [ton CO_2]	Nr of permits	Emission [ton CO_2]	Nr of permits
10 food	2,075,919	49	2,075,919	49	2,075,919	49
11 drinks	160,107	7	160,107	7		
12 tabacco	23,267	1	23,267	1		
13 textile	47,149	4	47,149	4		
17 paper and board	1,017,868	20	1,017,868	20	1,017,868	20
19 refineries	10,078,096	5	10,078,096	5	10,078,096	5
20 chemicals	12,369,653	66	12,369,653	66	12,369,653	66
20.11 industrial gasses	2,023,109	7	2,023,109	7	2,023,109	7
20.14 N-fertilizer	3,620,890	7	3,620,890	7	3,620,890	7
20.15 steam crackers	4,155,693	10	4,155,693	10	4,155,693	10
22 rubber and plastic	57,478	3	57,478	3		
23 building materials	1,559,110	55	1,559,110	55		
24 iron and steel	6,616,886	3	6,616,886	3	6,616,886	3
24 non-ferro	441,694	6	441,694	6		
25 metal products	20,303	1	20,303	1		
26 ICT production	8,252	1	8,252	1		
28 machinery	14,957	1	14,957	1		
29-30 transport vehicles	51,885	2	51,885	2		
52 tank storage	100,808	11				
agro	400,171	31				
energy system	42,171,976	117				
other	276,975	37				
road construction	121,114	36				
Grand Total	**87,413,360**	**480**	**44,342,316**	**248**	**41,958,114**	**167**
Part of CO_2 emission industry in 8 sectors					*95%*	

1.4.3 Energy use in Industry

Table 1-3: Final energy use (scope 1 and 2) per industrial sector [B7]

Industry sector		Final energy use [PJ]
Food (10 Voedingsmiddelenindustrie)		**83,7**
Drinks (11 Drankenindustrie)		4,1
Tabacco (12 Tabaksindustrie)		0,4
Textile (13 Textielindustrie)		4,1
Clothing (14 Kledingindustrie)		0,1
Leather and shoes (15 Leer- en schoenenindustrie)		0,4
Wood (16 Houtindustrie)		2,3
Paper (17 Papierindustrie)		**22,9**
Graphical (18 Grafische industrie)		2,8
Refineries (19.2 Aardolie industrie / Raffinaderijen)		**128,6**
Chemical (20 Chemische industrie)	**Industrial gasses (20.11 Industriële gassenindustrie)**	**12,5**
	Steam crackers (20.14 Organische basischemie)	**172,6**
	N-fertilizer (20.15 Kunstmestindustrie)	**30,2**
	Wider Chemical Industry (SBI 20 – (20.11+20.14+20.25))	**75,8**
Pharmaceutics (21 Farmaceutische industrie)		4
Rubber and plastics (22 Rubber- en kunststofproductindustrie)		10,6
Building materials (23 Bouw-materialen)	Glass (231 Glas- en glaswerkindustrie)	8,2
	Ceramics (233 Keramische bouwproductenindustrie)	9,3
	Concrete, gypsum and cement (236 Beton-, gips-, cementwaren)	3,6
	Other building materials	2,6
Iron and steel (24.10 IJzer en staalindustrie)		**40,1**
Non-ferro metal (24.4 Non-ferrometaalindustrie)		12,4
Metal products (25 Metaalproductenindustrie)		11
Electro technics (26 Elektrotechnische industrie)		1,7
Electric appliances (27 Elektrische apparatenindustrie)		1,5
Machinery (28 Machine-industrie)		5,8
Transport vehicles (29-30 Transportmiddelenindustrie)		5,1
Furniture (31 Meubelindustrie)		1,9
Other industries (32 Overige industrie)		0,8
Total		**659,6**

1.4.4 Final energy use

The **final energy use means the actual energy consumption** per energy carrier. So, if in a certain industry electricity is purchased from the grid and produced on-site for example based on natural gas, this means that the final electricity use is the sum of the purchased electricity, the produced electricity and the sold electricity. It also means that the amount of natural gas mentioned under final consumption is lower than the total amount of gas consumed, because part of the natural gas is used to produce electricity. The final energy use is therefor as electricity and not as gas.

This makes final use of energy very suitable for this study since you now quite precise how much of each energy carrier is used per industrial sector. For each industrial sector CBS publishes the final energy use in the so-called **Energy balance per sector** [B7].

These numbers cannot be compared to the numbers of the NEA because of the following differences:

- Final energy use comprises electricity consumption of purchased electricity, CO_2 emissions by NEA do not comprise electricity consumption of purchased electricity;
- Final energy use comprises energy consumption by all companies in a certain sector, CO_2 emissions by NEA comprise only EU-ETS companies;
- NEA numbers include CO_2 emissions from feedstock conversion (process emissions), final energy use only includes energy use not used as feedstock.

1.4.5 Energy use in the 8 selected industrial sectors

When looking at *Table 1-3* the top 8 industrial energy consumers: Steam crackers, N-fertiliser, Industrial gasses, Remainder of Chemical industry, Refineries, Steel, Food and Paper. Together they cover 86% of the final energy use in industry, see *Table 1-4*.

Table 1-4: Final energy use scope 1 and 2 per energy carrier for top 8 industrial sectors [B7]

Final Energy use per sector [PJ]		Natural gas	Waste	Electricity	Crude oil derivatives	Renewables	Coal derivatives	Heat	Grand Total
Total industry		194,1	0,5	132,9	205,2	4,9	21,2	100,8	***659,6***
Chemical industry	Industrial gasses	3,7		6	2			0,8	***12,5***
	Steam crackers	18,6		13,1	112,6			28,3	***172,6***
	N-Fertilizer	24,2		2,6	0			3,4	***30,2***
	Remaining chem industry	20,5	0,5	23,3	3,3	0,2	0	28,5	***76,3***
Refineries		20,7		9,3	86,4			12,2	***128,6***
Iron and Steel		9,9		9	0,2		18,8	2,2	***40,1***
Food		44,6		23,1	0,1	2,1	1,3	12,5	***83,7***
Paper and Board		6,2	0	6,4	0	1,8		8,5	***22,9***
Total 8 industrial sectors		**148,4**	**0,5**	**92,8**	**204,6**	**4,1**	**20,1**	**96,4**	***566,9***
		76%	**100%**	**70%**	**99,7%**	**84%**	**95%**	**96%**	***86%***

In Table 1-4 we present the final energy use of the 8 selected industrial sectors in more detail. When we look at the second row, we see that the total final energy of the 8 selected industries covers 86% of the final energy consumption in the whole industry. The largest contributions to the final energy consumption are made by; crude oil derivates (205 PJ), natural gas (148 PJ), heat (96 PJ) and electricity (93 PJ). The consumption of these energy carriers is covered by this selection for respectively 99,7%, 76%, 96% and 70%.

The subdivision of energy use over these different carriers is useful, because some energy sources are available as waste stream of the process. For example, the derivatives of crude oil and coal, strongly relate with the use of respectively crude oil, naphtha fraction and coal as raw material. These fractions are available and do not have another outlet yet. The development of such outlet were these waste streams are reused as raw material and not as fuel, is not feasible with a payback time of 5 years or less before the end of 2025, and therefore out of scope. This implies that only the fraction of the final energy based on natural gas, electricity and partially heat can be reduced.

Another aspect that makes this subdivision interesting is, that some measures only affect one energy carrier for example the amount of electricity used. This limitation applies to the measures in the technology group efficient electro-motor systems. These measures reduce electricity use, but do not affect the consumption of other energy carriers. Thus, to get an indication of which industries are relevant for this type of technologies, the amount of electricity consumption is a good indication of the potential in a sector.

1.4.6 Electricity consumption

When we look in more detail at the individual (sub)sectors we see that the “Steam-crackers” have the highest total final energy use (173 PJ) and “Refineries” the second highest total final energy use (129 PJ), while “Wider chemical industry” and “Food” consume by far the most electricity (23 PJ for Wider chemical industry and Food compared to 13 PJ and 9 PJ for respectively Steam-crackers and Refineries). Apparently, the use of electricity is not proportional to total final energy use. This is easily explained by the fact that at very large plants some equipment like large compressors are steam driven instead by electromotors. As part of electrification of industry this may change in the coming years but for now this is the situation.

In remaining industry there is a special situation. Normally chemical industry uses natural gas or oil derivates as an energy source to provide the chemical reactions the energy required to take place. The other energy use is to run rotational equipment, lights, computers, elevators, electric heating. To have a good indication of electricity use that is available for energy saving measures listed in this study, we have to correct the electricity consumption in Wider chemical industry for the high electricity use to provide the reaction energy in the production of chlorine, which is particularly large in the Netherlands. Therefore, we assumed that 350 MW is 8000 hours per year applied for electrolysis in the production of chlorine and therefore not relevant for the electricity saving measures for rotational equipment. Thus, **when calculating the potential for energy saving in the sector Wider chemical industry we used the number listed in table 1-4 corrected for electricity required for electrolysis = 23 PJ - 10 PJ = 13 PJ.**

1.4.7 Temperature range of energy consumption

Apart from differences in the division of final energy use over energy carriers, there are also differences in the temperatures of the processes in which these energy carriers are applied.

For example, temperatures in the food industry and the paper industry are in general below 250 °C, while temperatures in steel production tend to be much higher. The temperature range at which energy is used is very important to the heat integration potential. Heat pumps, mechanical vapour recompression, heat transformers, heat storage and to a lesser extend flue gas heat recuperation depend for their working on a specific temperature range at which the heat can be recovered and the heat can be re-used.

There are no official statistics on consumption of heat per temperature range. However, some years ago an overview was made based on several sources [B9]. We used this format and updated the numbers from 2013 to 2018, see *Table 1-*. We checked with a number of companies whether the ratio of fossil energy used to meet the demand for heat in the range below 250 ºC compared to total energy use was in line with our assumptions.

Table 1-5: Estimates of industrial heat consumption per temperature range per industrial sectors

Heat demand 2018 (PJ)	Total heat demand	Steam from CHP	<100 ºC	100-250 ºC	250-500 ºC	>500 ºC
Food industry	61	12	30	30	0	0
Paper Industry	17	7	0	17	0	0
Chemical industry	247	44	12	28	66	141
Industrial gasses	7	0	0	0	0	7
Steam crackers industry	160	0	0	4	47	109
Ammonia and N-fertiliser	28	0	0	0	3	24
Wider chemical ind	33	0	12	24	16	1
Steel	31	2	0	1	7	23
Refineries	119	10	0	2	50	68

1.5 Calculations of payback time and conversion of energy saving potentials to CO_2 reduction potentials

The calculation of the saving potential is very technology specific and therefore described in the technology chapters. However, some aspects of the calculation apply to all technologies like the energy data do you use as basis to convert the energy saving potential to an energy saving in kWh of electricity or gas, the conversion of energy saving potentials to CO_2 reduction potentials and the calculation of the payback period are calculations that apply to all technologies. Therefore, we decided to set up an approach that is applied by all technology group experts to ensure that no differences were introduced by these calculations. Therefore, we made the following standardisations:

1 we use the final energy use data for 2018 as representative for the yearly energy use,

2 we prescribed the way in which energy savings are converted to CO_2 emission reduction,

3 we prescribed the calculation of the payback time and

4 we used standardised values for energy prices, CO_2 price, emission factors, tax reduction on energy savings, weighted average cost of capital.

Below we describe each of these standardisations.

1.5.1 Energy data 2018

We assume that the energy consumption for 2018 is representative for 2020 and later. This introduces a small overestimation since overall efficiency of industry is likely to have increased a little between 2018 and 2020. But that error is negligible compared to the uncertainty over the actual energy consumption. Unforeseen global effects may strongly affect the energy consumption of industry in the next ten years. As is illustrated by the expected effect of the Corona crisis on the energy consumption of 2020.

1.5.2 Standardised values

A number of aspects that are the same for all technologies: the conversion of energy saving in a CO_2 saving potential and the approach to calculation of costs. The relevant numbers are in *Table 1-6*. Below an overview of description of these numbers is provided. If we have values that change per year for example the gas and electricity price, we provided the value for 2020. The other values can be looked up in the sources listed.

Table 1-6: values used to calculate savings and their sources.

Main Assumptions	Value 2020	Source
Gas price 2020-2030	0,02 €/kWh	KEV 2019- voorgenomen beleid [B1]
Gas price 2031-2050		WEO 2019- Sustainable development scenario [B6]
Wholesale Electricity price 2020-2030	0,05 €/kWh	KEV 2019- voorgenomen beleid [B1]
Wholesale Electricity price 2031-2050		WEO 2019- Sustainable development scenario [B6]
EU- ETS CO_2 price 2020-2030	22 €/ton CO_2	KEV 2019- voorgenomen beleid [B1]
EU- ETS CO_2 price 2031-2050		WEO 2019- Sustainable development scenario [B6]
Electricity emission factor	0,582 kg CO_2/kWh	CO_2-emissiefactor elektriciteit referentiepark KEV2019 Voorgenomen beleid [B1, B8]
EIA	45% (=11% reduction)	[B3, B4, B5]
Natural gas emission factor	0,20376 kg CO_2/kWh	[B1, B12]
Electricity tax 2020-2050	0,00055 €/ kWh	[B5]
Natural gas tax 2020-2050	0,00143 €/ kWh	[B5]
WACC	8%	
1 USD to Euro	€ 0,85	[B6]

1.5.3 The conversion of energy savings in CO_2 savings

To convert energy savings into CO_2 reductions, we calculated the net change in electricity and gas used by application of a technology in a certain industry and converted these net changes to CO_2 savings. To do so we use in principle the emission factors for 2020 as listed in table 1-6.

- This means that to convert savings on gas consumption to CO_2 savings, we used the emission factor for 2020 provided by RVO of 56,6 kg CO_2/GJ = 0,20376 kg CO_2/kWh gas consumption [B1, B12];
- For the conversion of electricity to CO_2, we used the reference park emission value for intended and current policies for 2020 0,582 kg CO_2/kWh elektricity. This emission value decreases per year. We

used for this first exploration the emission factor for 2020 as mentioned by PBL in the Klimaat en Energieverkenning 2019 [B1, B8]. We used the emission factor for intended and current policies because that is the only way to get close to the climate goals. Some people worry that these intended measures require time to be implemented. We can reassure that PBL has taken this into account. In 2020 the emission factor for intended and current policies are the same, from 2024 they start to diverge. We used the *referentiepark* value and not the *integrale* value for emissions, since RVO advises to use this value to calculate savings [B10].

As mentioned above in principle we used the CO_2 emission factors for 2020 there are a few exceptions to this rule. We met two reasons for using other values:

- In the technology group ICT savings are the cumulative result of all savings between 2020 and 2025. Thus, the savings have to be calculated using the CO_2 factors in the years the savings are realised. This is the case of the ICT savings since we assume that each year an incremental improvement occurs compared to the previous year. The reported saving is the result of the total of incremental improvements and is therefore calculated using the CO_2 emission factors of 2025.
- In the technology group power flexibility savings occur only in 2025 or later because savings depends on low electricity prices due to high availability of renewable electricity. This requires renewable energy capacity that is not available yet. This technology only uses electricity if the mix consists almost completely of renewable electricity. This means that the emission factor of the electricity used is significantly lower than the average CO_2 emission of the electricity in this year.

1.5.4 Calculation of the payback time

The payback time is a simple payback time taking into account the costs of financing with a WACC of 8% and substraction of subsidies like EIA and SDE++.
The payback period is calculated by calculating per year the outstanding sum + cost of capital (WACC) – subsidies – income from lower energy costs (nett saving of energy costs and CO_2 rights/tax). The number of years required to make this sum zero or below zero is the payback period.

EXAMPLE
For example we have a hat pump with a total cost of installation of 6 million euros (€ 6,000,000.-). So, we have to calculate the costs of investment and the savings due to energy saving.

Investment costs
Per year we have to determine the investment costs. In the first year this is the total cost of the implementation of the measure + the costs of capital (costs of implementation of the measure * WACC) – subsidies.
In the second year there are no longer implementation costs but still costs of capital and possibly incomes from exploration subsidies like SDE++: the cost of capital (net sum of first year *WACC) – subsidies.
In third year the cost of capital (net sum of second year *WACC)- subsidies, etc, etc.

In this study a WACC of 8% was prescribed. In the technical chapters we have looked if and to what extend a WACC of 4% increases the feasible economical reduction potential.
Subsidies taken into account are EIA and SDE++.
In principle the EIA is a tax deduction and therefore only applies, if sufficient tax is paid in the Netherlands. Nevertheless, we assumed for all measures maximum applicability of the EIA, i.e. 11% deduction of the investment costs over the first year.
SDE++ is not official yet but probably there will be an exploitation subsidy for heat pumps with a COP of 4.5, for MVR with a COP of 7.5, and for a limited number of hours for electric boilers [B14, B15].

Savings due to energy saving
An installed capacity of 5 MW, at 8000 full load hours and a COP of 4.5.
This means that the yearly energy saving has two components:
The amount of natural gas saved (in this case 5*8,000 = 40,000 MWh) and the extra consumption of electricity (in this case 5/4.5*8,000 = 8,889 MWh). From these numbers we can calculate the costs for natural gas and electricity by multiplying with the respective prices per MWh.
In addition, we calculate the amount of CO_2 emission prevented from natural gas consumption and multiply this amount with the costs of CO_2.
The amounts of gas saved, and extra electricity required do not change per year, but the costs per MWh gas and electricity and the cost of CO_2 do change per year and therefore are calculated per year.
We do not calculate the costs of CO_2 of electricity use since we assume overall that the saved CO_2 emission is the reference park emission, thus we treat the electricity saved as electricity from a power plant and companies do not pay directly CO_2 rights for electricity from power plants.
From this analysis, a simple payback period is obtained using capital costs of 8% WACC and a nett income from EIA of 11% of the implementation costs in the first year.
The technologies which demonstrated a payback period ≤5 years are considered economically feasible.

1.6 Technologies and suppliers

Table 1-7: Overview of all suppliers in this study given per Technology Group and Technology.

Technology	Suppliers in this study
Motors and drives	
High efficiency electromotors	ABB
Drives	ABB
	Zytec
	Bronswerk
	Schneider
Nano-lubricants	DexOil
Heat	
Flue gas heat recuperation	HeatMatrix
Heat pumps	Siemens
	Viking
	Spilling
	Bronswerk
Mechanical vapour recompression (MVR)	Siemens
	Viking
	Spilling
Heat transformer	Qpinch
Heat storage	EnergyNest
ICT	
Advanced process control	Duiker/ Yokogawa
	Emerson
Energy management analytics	Emerson

	EnergyQ
	Energy21
Asset management analytics	Emerson
	Semiotic
	Schneider
	Sorama
	ABB
Separation	
Membrane separation of H_2 from hydrocarbons	AirProducts, Air Liquide, MTR
	Air Liquide
	MTR
Membrane separation N_2 /O_2 from air	Parker Hannifin
	Generon
	Air Liquide
	AirProducts
Pervaporation based ethanol drying	Pervatech
	MTR
Flexibility	
Flywheel technology	S4Energy
	Pentadyne Power Corporation
	Beacon Power
	Active Power
	ELYTT ENERGY
	Stornetic
Hybrid Boiler	Parat Halversen
	Elpanne
	Cleaverbooks
	Vapec
	ESG Corporation

1.7 Reading Guide

In chapter 1 the context, objective and present status of the Project 6-25 Technology Validation is described.

Chapter 2 presents a **summary** of the main results, the conclusions, observations and recommendations.

In the chapters 3, 4, 5, 6 and 7 the innovative **technologies** for energy saving are described, the input data, the calculation methodology and the results. Chapter 8 deals with the correction for overlap in reduction potentials between technologies. We end the report with Literature and Appendices.

2 Summary results, Conclusions and Recommendations

This chapter deals with the summary of the results, our conclusions, observations and recommendations.

2.1 Results

As described in Section 1.3, in this study we calculated different types of reduction potentials. Relevant for the results are the Feasible technical reduction potentials and the Feasible economical reduction potentials. These are presented in the overall results tables in this chapter[10].

2.1.1 Feasible economical reduction potential

The main results of this study are the Feasible economical reduction potential as presented in Table 2-1. This is the potential that meets all the requirements for this validation study (refer to Chapter 1).

Note that this potential represents the Feasible reduction potential of each individual technology, so some double counting might be included if technologies compete for the same reduction potential. This applies for example within the heat technology group. This double counting is corrected for in the final row of the table.

Please refer to Chapter 3 to 8 for more details on the calculations.

[10] As a first step in this study we also calculated the ‘theoretical reduction potentials’. These intermediate results can be found in the chapters on the different technologies.

Table 2-1 Overview of results: Feasible economical reduction potential.

B. FEASIBLE ECONOMICAL reduction potential (kton/y)

	Technology groups	Motors and drives		Heat integration				ICT			Separation		Power flex	Totals
	Industry sectors	High efficiency electro motors	Electrom. system opt.	Flue gas recuperation	HT heat pumps	Mechanical vapour recom-pression	Heat transformer	Advanced process control	Energy managemen t analytics	Asset manage-ment analytics	Membrane separation of H2 from hydrocarbons	Pervaporation-based ethanol drying	Hybrid boilers	
Chemical industry	Industrial gasses	0	11	5	0	0	0	26	14	16	0	0	90	162
Chemical industry	Steam crackers	0	29	55	4	15	29	74	36	39	0	0	0	281
Chemical industry	Ammonia & N- fertilizer	0	5	10	1	2	0	49	21	19	3	0	10	120
Chemical industry	Wider chemical industry	1	32	59	52	127	86	58	25	57	0	0	90	587
	Refineries	0	20	85	6	23	76	65	31	29	73	0	0	409
	Iron and Steel	2	47	49	2	8	0	46	23	17	0	0	0	194
	Food	5	49	67	165	165	16	106	63	62	0	0	130	828
	Paper & Board	1	39	20	38	88	0	23	14	14	0	0	50	287
	Other industries *)	-	-	-	-	-	-	-	-	-	-	-	-	467
	Correction for overlap)**	-	-	-	-	-	-	-	-	-	-	-	-	-515
	Totals	**9**	**232**	**350**	**268**	**428**	**207**	**447**	**227**	**253**	**77**	**0**	**370**	**2820**

**) We note that in our approach the figures for the industry sector "Others" have been addressed as a group. We estimated the group 'others' by extrapolation based on the industrial energy usage of the 8 sectors (in total 86% of the energy usage, others being 14%). We accounted for this potential in the column totals only to avoid misinterpretation of the potential per technology.*

***) Refer to Chapter 8 for details and on the distribution of the overlap between technologies.*

In *Figure 2-1* the results are presented per technology group.

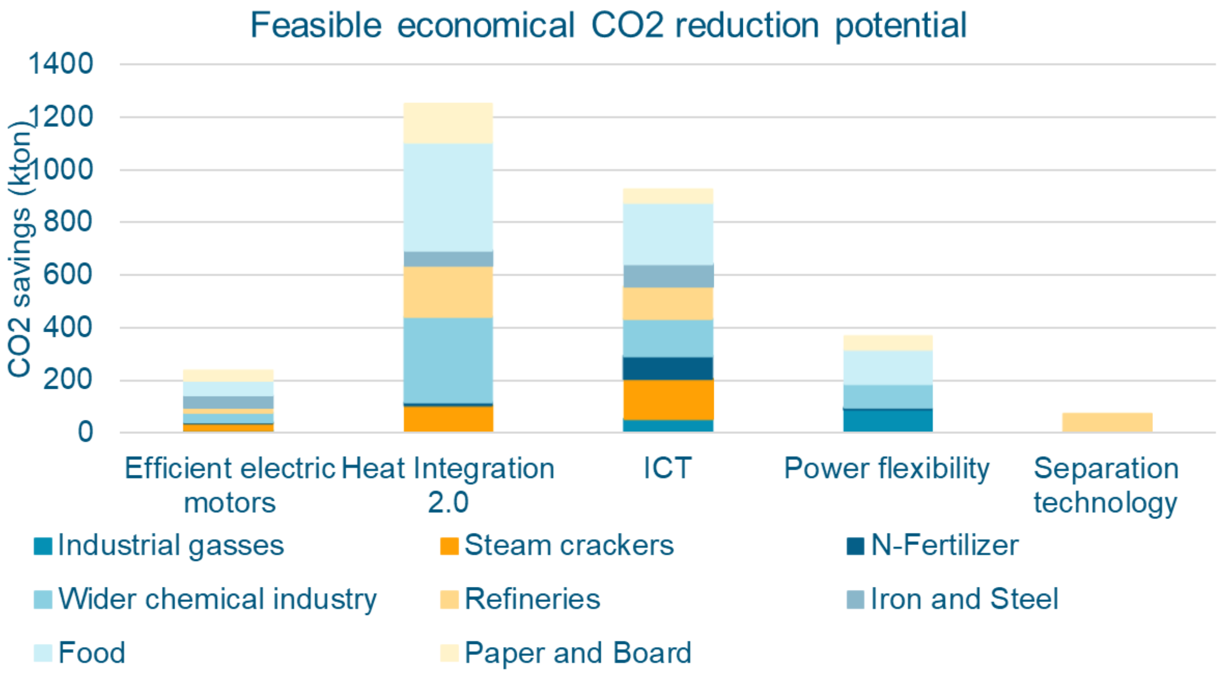

Figure 2-1: Feasible economical reduction potential per technology group and per sector.

2.1.2 Feasible technical reduction potential

The results for the Feasible technical reduction potential are presented in Table 2-2. These numbers are in general higher as no economical limitation (payback time) is applied to these calculations. Part of the difference between this technical and the economical reduction potential could be made feasible by policy measures (aimed at reducing the limitation of payback time).

Table 2-2 Overview of results: Feasible technical reduction potential.

A. FEASIBLE TECHNICAL reduction potential (kton/y)

	Technology groups	**Motors and drives**		**Heat integration**				**ICT**			**Separation**		**Power flex**	**Totals**
	Industry sectors	High efficiency electro motors	Electrom. system opt.	Flue gas recuperation	HT heat pumps	Mechanical vapour recom-pression	Heat transformer	Advanced process control	Energy managemen t analytics	Asset manage-ment analytics	Membrane separation of H2 from hydrocarbons	Pervaporation-based ethanol drying	Hybrid boilers	
Chemical industry	Industrial gasses	14	51	5	0	0	0	26	14	16	0	0	90	216
Chemical industry	Steam crackers	30	112	55	16	24	29	74	36	39	0	0	0	415
Chemical industry	Ammonia & N- fertilizer	6	22	10	3	4	0	49	21	19	3	0	10	147
Chemical industry	Wider chemical industry	41	146	59	208	212	130	78	33	76	0	0	90	1073
	Refineries	21	80	85	25	38	76	65	31	29	73	0	0	524
	Iron and Steel	48	221	49	8	13	0	46	23	17	0	0	0	425
	Food	160	322	67	287	189	27	213	125	123	0	0	130	1643
	Paper & Board	27	157	20	58	98	0	45	28	28	0	0	50	511
	Other industries *)	-	-	-	-	-	-	-	-	-	-	-	-	806
	Totals	**347**	**1111**	**350**	**605**	**578**	**262**	**596**	**311**	**347**	**77**	**0**	**370**	**5760**

**) We note that in our approach the figures for the industry sector "Others" have been addressed as a group. We estimated the group 'others' by extrapolation based on the industrial energy usage of the 8 sectors (in total 86% of the energy usage, others being 14%). We accounted for this potential in the column totals only to avoid misinterpretation of the potential per technology.*

A comparison between the technical and the economical reduction potential is given in Figure 2-2.

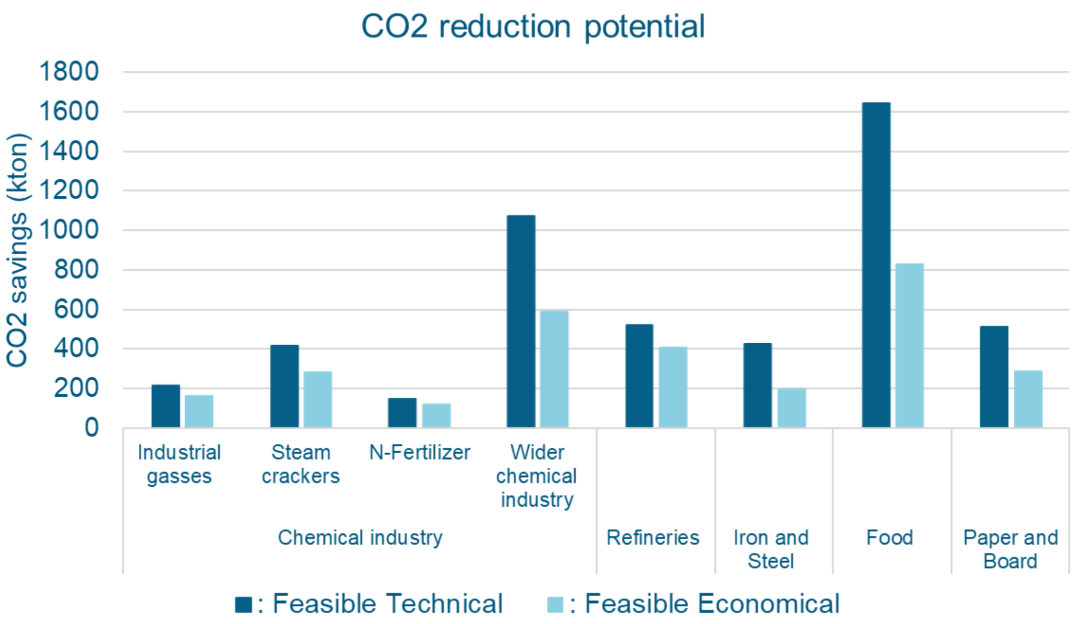

Figure 2-2: Overview of Feasible technical and Feasible economical reduction potentials per sector.

2.1.3 Sensitivity analysis

The results of a **high-level sensitivity analyses** are presented in the results tables at the end of each technology paragraph in Chapters 3 to 7. The sensitivity analysis focusses on the impact of a lower WACC (4% instead of 8%) and a longer payback time (10 years instead of 5 years). The graph below gives an overview of the overall effect. From this it shows that an increase of the payback period to 10 years increases the Feasible economical reduction potential with 1 Mton.

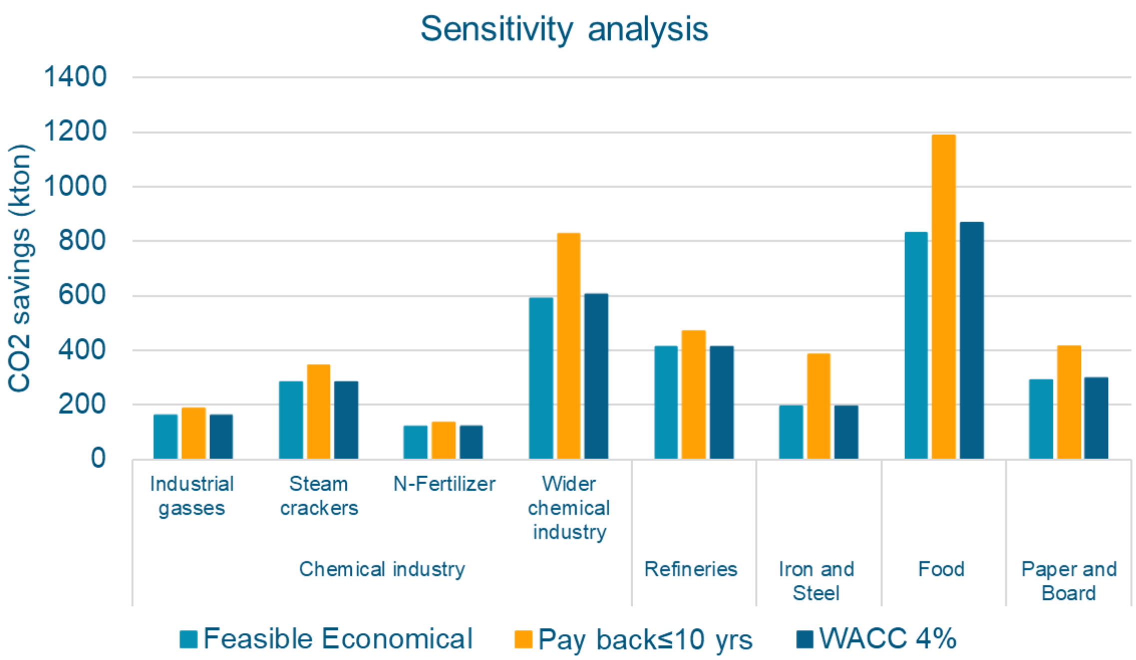

Figure 2-3: Sensitivity analysis per sector.

2.1.4 Other studied technologies

In this chapter and tables we only represent the technologies that have a theoretical technical Reduction potential of more than 50 kton for the studied sectors combined. The technologies “Industrial lubricants” (Motors and Drives), “Heat storage” (Heat), “Membrane separation of N_2/ O_2 from air” (Separation technology) and “Flywheel” (Power flex) are described in the respective Chapters. Application in specific sectors or situations can be interesting from a reduction perspective.
The technologies “Data infrastructure” and “Digital Twin” (ICT) are described as well, however, standalone they do not result in CO_2 reductions.

2.2 Conclusions, observations and recommendations

In this section the consortium Royal HaskoningDHV/PDC shares the main conclusions, observations and recommendations of this validation study. The conclusions are directly related to the scope and results of this validation study. In addition to that, our observations are worthwhile mentioning as contextual to the results. The recommendations represent our view on how to materialize CO_2 emission reduction by innovative energy efficiency technologies as envisaged in Project 625.

2.2.1 Conclusions

1 For the portfolio of innovative techniques examined, a feasible CO_2 reduction potential of roughly 3 Mton/year has been validated up to and including 2025. This is 20% of the industry obligations in the Climate agreement, or 15% of total CO_2 reduction obligation for the Dutch industry[11].

2 We see this 3 Mton as a realistic estimate of the potential provided that there is no limitation of capital and/or (wo)manpower. This can be realized without time-consuming additional infrastructure (as with e.g. CCS, H_2) or new legislation.

3 Materializing this feasible potential is not "business as usual" and requires a programmatic approach to address specific challenges.

4 If the payback time is allowed to increase from 5 to 10 years, the feasible economical reduction potential increases with 1 Mton/year. A lower WACC (from 8 to 4%) however has a marginal impact.

5 At present, knowledge of, and experience with, innovative technology is still insufficiently shared, as a result of which effective scalable implementation of innovative, CO_2 and cost-saving technology proceeds slower than possible.

6 In the industry sectors with the largest feasible CO_2 reduction potential, Food and Wider chemical Industries, a broad range of technologies contribute to the potential. Each sector consists of a broad range of industries for which a case by case implementation is required.

7 The technologies with the largest feasible CO_2 reduction potential, Heat integration and ICT, have potential in a broad range of industries.

8 We identified the following 7 ‘hot spots’ that together represent the validated feasible CO_2 reduction potential:

- A wide range of technologies with implementation potential applies to the sectors 1) Food, 2) Wider chemical industry and 3) Refineries;
- Technologies with cross sectoral implementation potential are: 4) ICT, 5) Heat Integration and 6) Motors and Drives;

[11] In accordance with the Climate agreement the Dutch Industry needs to reduce 14.3 Mtons of CO_2 emissions by 2030 (compared to 2015) additional to CO_2 reduction obligations of 5.1 Mtons from the EED[11] (total 19.4 Mtons).

- Technology with implementation potential at specific industrial sites is 7) Hybrid boilers.

9 The main technical limitations for reduction potential are:
- Some technologies can only be implemented during Turn Arounds. This is most significant for the technology group heat integration;
- At many sites abundant high temperature residual heat is available. Investments in low temperature heat recovery are not useful in those cases;
- At some industries ICT infrastructure and knowledge are limiting factors;
- Overlap and / or displacement: multiple technologies can achieve the same effect in different ways.

10 Further CO_2 reduction potential: The Feasible technical CO_2 reduction potential of this portfolio is almost 6 Mton per year up to and including 2025. Part of the difference between this technical and the economical reduction potential could be made economically feasible by policy measures (aimed at reducing the limitation of payback time).

2.2.2 Observations

1 Given the principles of this validation, the reported Feasible economical potential of about 3 Mton is realistic. Regarding the feasible potential with innovative technologies as targeted in this study, for the entire industry, the following comments can be made:

1.1 The industry's wider CO_2 reduction potential can be **higher** in case:

1.1.1 The examined portfolio covers more of the available techniques (TRL 8 or 9) for improving process efficiency (like process modifications at existing sites e.g. with membranes, reactive distillation, divided wall column technology, optimization of heat transfer or insulation);

1.1.2 For some advanced technologies (TRL 7, in this specific context), more practical proof can be found for CO_2 reduction and therefore can be quantified. These may still be deployable with a focused approach for 2025;

1.1.3 The potential of process innovation can be demonstrated and realized.

1.2 The CO_2 reduction potential, on the other hand, may be **lower** in practice if the basic starting points of this assessment are not met:

1.2.1 It is not certain that all subsidies from this study (EIA, SDE ++) are actually granted.

1.2.2 No restrictions are included due to capacity (resources) or access to capital.

1.3 The business case for certain technologies can improve in case more non-energy related savings are taken into account[12].

2 We notice that some potential with a payback time of less than 5 years has not been realized yet, although the technology is already available for quite some time (for example in Motors and Drives). This is not according to present legal requirements.

3 The potential that cannot be realized before 2025 due to lack of a turnaround in this period, could still be realized up to 2030. However, after 2025, overall changes in process configurations (e.g. due to electrification, H_2, CCUS) are expected to drastically change reduction potentials, both in positive and negative way.

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[12] Non-energy related savings are taken into account for the determination of the payback time only in case they are verifiable and relevant for lowering the payback time to under 5 years. In practise, more non-energy benefits can apply to a certain situation e.g. lower maintenance cost, higher yields and better products. This allows the business case for certain technologies to improve. Payback times that are already lower than 5 years could be even lower.

4 The implementation of the proposed technology are no-regret investments and don't interfere with other longer-term CO_2 reduction technologies due to the short payback time (5 years).

5 Concerns related to perceived business continuity risks are an important limiting factor in management decisions for implementation of innovative technologies new for the industry.

6 Feedback from various industries: "This study refreshes our focus on already existing technologies and adds new technologies to be assessed".

7 By removing barriers, the feasible CO_2 reduction potential can be further increased over 3 Mton. These barriers are in the field of business operations as well as in the field of legislation and regulations, policy instruments, financing and knowledge sharing between companies.

2.2.3 Recommendations for follow up

1 Investigate and evaluate creative and effective measures to facilitate implementation of the Project 6-25 technologies.

2 Develop a specific and focused implementation program per 'hot spot':

2.1 The sectors Food and Wider chemical industry;

2.2 The technology groups ICT, Heat Integration and Motors & Drives;

2.3 The specific technologies membrane separation and hybrid boilers.

3 This program should unburden companies, share knowledge of and experience with the application of innovative technology and systematically helps companies to move from analysis to economically responsible implementation:

3.1 Living Lab environment, based on the hot spots in which several pilots to form a learning environment, share best practices so that this ultimately leads to a reproducible approach that is widely applicable to the industry to establish a fast and effective platform for this;

3.2 Use the identified hot spots to form consortia of specialized companies and service providers that can quickly and (cost) effectively implement new technology in a specific market segment;

3.3 Continuation and intensification of cooperation between industry, suppliers and service providers in the value chain;

3.4 Provide training and support to actors in the value chain. Invest in the entire value chain so that it has sufficient state-of-the-art knowledge to be able to quickly evaluate, assess and apply innovations.

4 Investigate the opportunities to facilitate realization the potential of technologies with a pay back time between 5-10 years

5 Install proper instruments:

5.1 Evaluate the existing instruments based on the results of this research and strengthen or adapt them where necessary;

5.2 Develop new financial instruments that form an addition - earmarked for CO_2 reduction - to the existing capex budget of companies;

5.3 Explore the potential to mitigate limiting factors like business continuity risks and the availability of capacity and resources.

6 Invest in the level of knowledge and capacity of supervision and enforcement in order to arrive at an appropriate company and / or sector-specific approach.

7 Broaden the 625 portfolio with additional innovative & deployable technologies to further enlarge the CO_2 saving potential through process efficiency

3 Efficient Electric Motor Systems

3.1 Introduction and overview of results

Electromotor-systems consume 69% of electricity in industry according to EU wide studies [E1, E4]. Additionally, these studies further divide the use per motor application and per industry and reveals a significant saving potential for pumps, and ventilation.
For a specific case on a specific site the best way to determine the saving potential of an electromotor system is to make an integral analysis of the whole electromotor-system including the application like a pump, fan or a compressor. However, since the main goal for this task is to determine the CO_2 reduction potential for these technologies on a sector level we focus in this task on a top down analysis per system element. This also meets our brief to analyse the following elements:

- CO_2 reduction potential of replacing electro motors by more efficient electromotors;
- CO_2 reduction potential of optimising electromotor-systems driving compressors, fans and pumps, by means of variable speed drives and/or optimisation/replacement of the application. Optimisation of other electromotor applications like conveyor belts and mills is considered part of the saving potential under ICT measures;
- CO_2 reduction potential of adding nano lubricant to gear boxes in electromotor-systems.

In the tables below the main results are summarised.

- Overview of technologies, with a description of the energy saving principles and main conditions to allow for the CO_2 reduction;
- Overview of results: main economical parameters;
- Overview of results: CO_2 reduction potential (technical / economical) in kton/y.

Table 3-1: Overview of technologies, saving principles and main conditions

High efficiency electromotors	
Technology	Electromotor-systems consume 69% of electricity in industry according to EU wide studies. Energy efficiency of electro motor is constantly improved according to worldwide accepted standards.
Savings principle	By replacing an electromotor by a more efficient electromotor you receive the same output but at a lower energy use.
Main conditions and sectors	Highly efficient electromotors can be applied across all industries. We distinguish two options for saving: 1 a less efficient motor is replaced with the most efficient IE5 motor type (in case application of a frequency control does not limit application) 1 A less efficient motor is replaced with the most efficient AC induction IE4 motor without frequency control (in case application of a frequency control would limit the feasibility of the replacement).
Motor system optimisation	
Technology	1. Optimisation/replacement of the compressor, fan or pump, possibly in combination with a better matched electromotor 2. Install a variable speed drive (variable frequency drive or magnetic coupling). Variable speed drives are applied, if the motor application requires a variable shaft speed or when the shaft speed is too high for the application
Savings principle	1. Replacement of a equipment that is too large, or for another reason not efficient, with an equipment that is better fit for the duty, and therefore uses less energy 2. The total system efficiency is on general more efficient with variable speed drives than with other types of control
Main conditions and sectors	The main infrastructure required for variable speed drives is a connection to the factories' operating system. Magnetic couplings can operate without such connection
Nano-lubricants	
Technology	All motors with gear boxes use lubricants to decrease friction and increase efficiency. The use of nano structures in lubricants has proven to improve physical characteristics of the lubricants without changing the chemical composition.
Savings principle	The nano structures form a smooth layer between the gear components and the lubricants, reducing the friction and thus lowering the peak temperatures in the lubricants
Main conditions and sectors	There need to be parts that need lubrication, in electromotor systems that are mainly gear boxes. No known limitations for using nano-lubricants

Table 3-2: Overview of results: main economical parameters.

	High efficiency electromotors	Motor system optimisation	Nano-lubricant
Payback period	>3	>1	<5
TRL	8-9	8-9	5-8

Table 3-3: Feasible economical CO_2- reduction potential given per technology and sector (kton/y)

Total top 8 industrial sectors		Feasible Economical	Feasible Economical
		Electric motors	*Drive*
Chemical industry	Industrial gasses	0	11
	Steam crackers	0	29
	N-Fertilizer	0	5
	Wider chemical industry	1	32
Refineries		0	20
Iron and Steel		2	47
Food		5	49
Paper and Board		1	39
Total		**9**	**232**

The feasible CO_2 reduction potential of nano-lubricants is not presented for three reasons:

- Given the lack of information to validate the saving potential;
- The very small theoretical CO_2 reduction potential calculated based on the limitedly available data.

3.2 Application of high efficiency electromotors

There is a large number of electromotor suppliers. Some of the most well-known are: ABB, Nidec, Rockwell, Siemens and Toshiba.

3.2.1 Working principle of energy saving by applying high efficiency electromotors

By replacing an electromotor by a more efficient electromotor you receive the same output but at a lower energy use. How much you save is determined by the difference in energy efficiency and the power size of the new motor and the motor you replace.

Worldwide governments oblige producers and users of electromotors to increase the efficiency of the electromotors they respectively produce and use. To discriminate between more and less efficient electromotors the motors are divided over International Efficiency classes, currently ranging from IE1 standard efficient to IE5 Ultra-premium efficient. All motors that are less efficient than the 1E1 motors for example most electromotors built in 1990 and earlier are indicated as IE0.

The energy saving that can be realised by replacing motors by more efficient electromotors depends on the difference in efficiency class between the old and the new motors, motor size distribution and the number of motors per industrial sector:

1. The difference in efficiency class: for example, an IE5 motor is more efficient than a IE4 motor. So when an IE0 motor is replaced by a new IE5 motor, the saving is bigger than when it is replaced by a IE4 electromotor with the same shaft power output;
2. Motor size: the motor efficiency defined for each efficiency class (IE1-5) increases with the power rating of electromotors up to rated power of 160 kW. Also, the difference between the defined efficiency for classes (IE1-5) decreases with increasing motor power. For example, the efficiency gain between IE0 and IE4 is 9.7% for a 7.5 kW motor and only 3.8% for a 200 kW motor.

3 The full load hours that motors are used per year;

4 Number of motors replaced in the sector. One way to determine the number of motors that can be replaced is to estimate how many motors are at the end of their lifetime. However, when a motor is at the end of its lifetime can be disputed. Therefore, we determine the number of motors, that makes such an efficiency gain that replacement has a simple payback time of less than 5 years.

Summarizing, to calculate the technical saving potential of motor replacement we combined the following data:

- Electricity use in a sector [CBS, 2020];
- Electricity consumption by electromotors per industry [E1];
- The total energy consumption by electromotors in the industry is divided over motor efficiency classes as follows: IE0 (10%), IE1(46%), IE2(34%), IE3(10%) and IE4(0%) [E2];
- The distribution of the energy consumption per motor sizes for each sector, see table 3-4;
- Increase in energy efficiency by replacement the motors of certain power rating from a lower efficiency class by a motor of energy efficiency classes IE4 or IE5. To calculate this increase we used energy efficiency classes definition or all motor sizes [E5, EU standard 60034-30-1].

Table 3-4: Overview of motor size and electricity use [E1].

AC Motor size by electricity use [kW]	Percentage of total electricity consumption by electromotors			
	Chemical industry& Refineries[13]	Iron and Steel	Food[14]	Pulp and Paper industry
>0, <0.75			3%	0%
>0.75, <4	2%	4%	16%	3%
>4, <10	5%	5%	12%	5%
>10, <30	6%	7%	9%	12%
>30, <70	13%	14%	34%	20%
>70, <130	12%	10%	5%	19%
>130, <500	30%	34%	20%	33%
>500, –	33%	26%	3%	8%

For each motor size (power rating), the calculations resulted in 9 numbers, describing the energy efficiency gain of an IE5 motor replacing respectively an IE0, IE1, IE2, IE3 and IE4 motor and an IE4 motor replacing respectively an IE0, IE1, IE2, and IE3 motor. For ,example, the efficiency increase by replacing an IE1 motor of 30 kW by an IE5 motor of 30 kW results in an efficiency gain of 4.6%. However, we do not have insight in the energy consumption for individual motor sizes but we do have data on the energy consumption per range of motor sizes per industrial sector, see table 3-4. Therefore, we calculated the average energy saving per motor power size range as indicated in table 3-4. For example, the average energy saving of replacing all IE1 30-55 kW by IE5 motors results in an energy saving of 4.1%.
In this way we calculated the average energy efficiency gain of replacing all electromotors in an industrial sector by more efficient electromotors.

[13] *the numbers are reported for the chemical industry we also apply them to the refineries.*
[14] *The numbers are reported for the Food, beverages and tobacco industries*

The results of these calculations are listed in the table in 3.2.7, under theoretical technical CO_2 reduction potential.

3.2.2 TRL level of by high efficiency electromotors

IE motor classes are currently required for most electric motors.To be precise it is required for all electric motors that meet the following criteria [E12]:

- Single speed electric motors (single and three phase), 50 and 60 Hz;
- Line-start permanent magnet motors;
- 2, 4, 6 or 8 poles – Rated output PN from 0.12 kW to 1000 kW;
- Rated voltage UN above 50 V up to 1 kV;
- Motors, capable of continuous operation at their rated power with a temperature rise within the specified insulation temperature class.

Electromotors for ATEX surrounding and non-integrated brake motors are excluded under the current EU directive 640/2009 [E12].

The IEC standards IEC 60034-1 & 60034-2 already include electromotors for ATEX surrounding and non-integrated brake motors. These standards allow for the calculation of which electromotors are compatible with IE4 and IE5 criteria.

Since 2015 IE3 efficiency is the minimal efficiency class for middle size motors [E12], from 2021 all most all electromotors in power sizes from 0.75 kW to 1 MW have to meet the IE3 efficiency criteria [IE6].
Motors in the class from 0.12-7.5KW have to meet the IE3 efficiency class from 2021 onwards [E6].
IE4 and IE5 motors are commercially available for the full range from 0.7-375 kW [E4], i.e. TRL 9.

3.2.3 Conditions to allow for high efficiency electromotors

All electromotors require a power connection. For most electromotors this is a 400 Voltage 50 Hz AC connection. For some motors a higher voltage connection may be required.
The most efficient IE5 motor types require a control cable to connect with the data management system of the plant.
The most efficient motors that do not require a control cable connection are the IE4 induction motors.

3.2.4 Costs and benefits of high efficiency electromotors

OPEX and CAPEX

The price of electromotors depends on the motor capacity. For example, the cost of IE5 motors in standard surroundings is circa 70 €/kW (recommended end-user price). In ATEX surroundings this price may increase. If a motor can be replaced by a smaller sized model than this reduces investment costs.

In addition to the motor costs come the costs of installation; power connection, control cable, motor frame. We assume that existing motors are replaced by more efficient types. This means that a power cable with sufficient capacity is already there.
The most efficient IE5 motor types are of synchronous-reluctance type and as opposed to most commonly used induction motors, synchronous-reluctance require a variable speed drive (VSD) for operation. The VSD needs to be connected to the control system hardware (e.g. PLC). Most of the time VSD can be installed close to the control system hardware. However, in case VSD cannot be easily installed this may increase costs significantly. In such cases or if for another reason an IE5 motor cannot be applied an IE4

induction motor still may provide a very efficient solution. Therefore, we calculated both the saving by replacement of the current electromotors by IE4 and IE5 motors.

In the cost calculation we assume two different situations (our expert judgement):

1. A less efficient motor is replaced with the most efficient IE5 motor type and there is already a VSD, thus there is already a control cable;
2. A less efficient motor is replaced with the most efficient AC induction IE4 motor without frequency control.

In both situations it is further assumed that the surroundings is non-ATEX and the motor frame and the power cable can be reused. Therefore, we calculate with installation costs of € 1,000.00 + 6%(CAPEX+1000) (installation within a day and minimal engineering/process management). We will look further into the limitations posed by ATEX requirements and spread in the installation costs in the next paragraph on the feasible CO_2 reduction potential

To calculate the theoretical economical saving potential, we determined for which motor classes a payback time of maximal five years is applicable at the operational cost assumptions mentioned above. We concluded that under these circumstances all IE0 motors larger than 4 kW can be replaced with an IE5 motor with a payback time ≤ 5 years, if the required connection for the VSD of the IE5 motor is available. Approximately 10% of the current motors in industry are IE0 motors [E2]. When assuming that for 50% of these IE0 motors a VSD connection does not significantly raise the total costs of installation (either because the replaced motor already had a VSD or that the VSD can be connected to the control system without raising cost significantly), this implies that in theory 5% of all motors in industry can be replaced cost effectively.

3.2.5 Feasible saving potential

In task 1 we made a first estimate of the technical and economical CO_2 reduction potential when replacing existing motors (independent of they are still functioning or not) by the most efficient electromotor. Since these estimates were not affected by practical considerations, we refer to them as theoretical reduction potentials.
In this task we will take practical considerations into account and thus calculate the feasible reduction potentials.

The only technical limitation that we found is the turnaround planning or lack of maintenance stops.
The feasible technical CO_2 reduction potential is based on the efficiency increase that is possible based on the current efficiency of the electromotors per sector corrected for the part of the motors that cannot be replaced due to a lack of maintenance stops (turn around planning):
In formula form this is summarised as:

$$TP_{feas} = TP_{theo} * L1 \text{ (Equation 1)}$$

In which TP_{feas} is the feasible technical potential, TP_{theo} the theoretical technical potential, and L1 the limitation due to the turnaround planning.

In task 1 (paragraph 3.1.1) we explained how the theoretical technical potential is calculated. The outcomes of this calculation are listed under theoretical technical potential in the table in paragraph 3.2.7. In addition, we found three other limitations that affect the payback time of this measure; low runtime hours due to seasonal effects or spare units (L2), additional costs due to ATEX (L3), replacement is only cost effective if it is a relatively straight forward installation (L4). Therefore, we calculate the theoretical economical potential (EP_{theo}) as a basis to calculate the feasible economical potential (EP_{feas}) using the following approach:

$$EP_{feas} = EP_{theo}(L1*L2*L3*L4) \text{ (Equation 2)}$$

In which L1 to L4 are the limitations mentioned above. Below we will describe the calculation of these limitations.

Limitation 1: planning of maintenance stops (L1)
When looking at the different industrial sectors we see the following practices regarding maintenance stops:

- steam crackers, industrial gasses, N-fertilizer and refineries only have very few stops, typically 1 in 6 years.
- Wider chemical industry, offers a range of situations, part of the companies also have stops limited to1 in 6 years, some 1 in 4 years and some more often.
- steel stops only 1 in 10 years the blast furnaces, but all other processes are stopped for maintenance on a regular basis.
- food and paper stop regularly for maintenance, hygienic and /or commercial reasons.

Based on the above and our expert judgement we assume that the potential for the steel, food and paper sectors is not affected by the planning of maintenance stops.
The potential of the Wider chemical industry reduces with 20% and the potential of the steam crackers, industrial gasses, N-fertiliser and refineries reduces with 50% by the lack of stops that still can be used before 2026.

Therefore, we calculate the limitation factor (L1) according to the following formula:

$$L1 = 100\% - (\%\text{loss of potential due to turn arounds}) * (100\% - E_{pump\%})$$

In which L1 stands for the factor L1 in equation 1, $E_{pump\%}$ is listed in table 3-5.

This results in the following limitation factor (L1) per sector:

- 63% of the theoretical economical potential of in case of steam crackers, industrial gasses, N-fertilizer sectors;
- 85% of the theoretical economical potential in case of Wider chemical industry sector;
- 100% of the theoretical economical potential of the steel industry;
- 63% of the theoretical economical potential of the refineries;
- 100% of the theoretical economical potential of the food industries;
- 100% of the theoretical economical potential of the paper and board industry.

Table 3-5: Part of the energy used by electric motors driving pumps and fans [E1, E10, E16]

	Motors ($E_{motor\%}$)	Pumps ($E_{pump\%}$)	Fans ($E_{fan\%}$)
Paper, pulp and print	75%	56,9%	21,7%
Food[14]	90%	9,8%	11,5%
Chemical industry and Refineries[13]	72%	26,4%	10,6%
Iron and steel	100%	19,0%	22,0%

Limitation 2: limited runtime of 5500-4000 hours per year (L2).
A runtime of 4000-5500 hours appears to be insufficient for almost all motor power ranges to have a payback period below 5 years.
There are two reasons to have a low runtime: redundancy and seasonal influences.

Redundancy indicates the practice to have additional capacity on standby. For most sectors applies that most pumps have a spare on 1 or two pumps running, and that the exceptions are compensated by another type of equipment that has a spare. This results in an average runtime for pumps of 4000-5500 hours. Apart from the paper industry where at least 50% of the pumps does not have a spare.

Seasonal influences refers to the situation that the required duty varies with seasonal effects. This is the case for most fans (cooling applications) that work at maximum capacity in summer and approximately 50% in winter.

Therefore, we corrected the theoretical economical saving potential for the percentage of electromotors driving pumps and fans per industry:

$$L2 = (100\% - E_{pump\%} - E_{fan\%}).$$

In which L2 stands for the factor L2 in equation 2,
$E_{pump\%}$ stands for the part of electromotors driving a pump,
$E_{fan\%}$ stands for the part of electromotors driving a fan see table 3-5.

In case of the paper industry we use a slightly different formula since 50% of the pumps do not have a spare in this sector:

$$L2(paper) = (100\% - E_{pump\%} * 50\% - E_{fan\%}).$$

This results in the following values for L2 per sector.

- 77% of the theoretical economical potential in case of chemical industry (4 sectors);
- 59% of the theoretical economical potential of the steel industry;
- 77% of the theoretical economical potential of the refineries;
- 79% of the theoretical economical potential of the food industries;
- 50% of the theoretical economical potential of the paper and board industry.

Limitation 3 (L3): ATEX
In the chemical industry, refineries and part of the food sector explosion safety is an issue, requiring special adaptations on equipment to prevent that switching on and off, or switching gear may spark an explosion. Such measures may be required in chemical industry and refineries. Our expert judgement is that approximately 75% of electromotors should be ATEX compatible in steam crackers and refining, 50% of industrial gasses, 50% in N-fertilizer and 50% in Wider chemical industry and 10% in food industry. ATEX compatibility adds 50% to the price of these motors and therefore is no longer economically feasible.
Therefore, we calculate this limitation according to:

$$L3 = (100\% - ATEX) + ATEX * R_{ATEX}$$

In which L3 stands for the factor L3 in equation 2, ATEX stands for the part of the equipment that needs to meet ATEX requirements and R_{ATEX} for the part of the motors that remains cost effective when meeting ATEX requirements.
Since $R_{ATEX} = 0$, this simplifies to:

$$L3 = (100\% - ATEX)$$

Table 3-6: ATEX % and calculated ATEX factor (L2) per industrial sector

Sector	ATEX [%]	Remaining % of economical potential due to ATEX (L2)
Food	10%	90%
Paper and Board	0%	100%
Industrial gasses	50%	50%
Steam crackers	75%	25%
N-Fertilizer	50%	50%
Iron and Steel	0%	100%
Refineries	75%	25%
Wider chemical industry	50%	50%

Limitation 4: Electromotors are only replaced by motors that fit the same frame
Replacement of the motor frame or the foundation is too cost intensive to allow for a payback period of 5 years or less. Motor frame size in relation to power and speed has been standardized in CENELEC standards for decades. Interchangeability of old motors with new motors is usually no problem unless the old motor is older than the CENELEC standardization or in case of the latest IE5 motors that tend to be a bit larger than the current motors. Sometimes this can be resolved by using one size smaller motor (only applicable if motor is oversized), or by choosing an IE4 instead of an IE5 motor.
The option of an IE4 instead of an IE5 motor is taken into account in the theoretical potential. So this does not significantly limit the potential.

Conclusions
In 3.2.7 the feasible technical and economical CO_2 reduction potential per sector is listed in a table together with the theoretical potentials.

The feasible technical potential consists of the replacement of all electrical motors that can be replaced outside large maintenance stops (redundant potential) or within maintenance stops that occur before the end of 2025.

Even in the theoretical economical potential calculated in task 1 only 5% of the motors could be replaced in an economically feasible way. After application of the limiting factors a very small portion remains, ranging from 3.5% in food to 1% in steam-cracking and refineries. Therefore, the feasible economical potential is negligible.

3.2.6 Sensitivity analysis

In the previous paragraphs we described how we calculated the theoretical and feasible technical and economical CO_2 reduction potential of replacement of the electromotors. In this sensitivity analysis we determine the effect of three policy measures/aspects on the CO_2 reduction potential.

1 The variable varied in the sensitivity analysis are the payback period varied from 5 → 10 years

2 The WACC varied from 8% → 4%

Payback time 5 → 10 years
This measure increases the CO_2 reduction potential strongly. The replacement of all IE0 and IE1 motors by IE4 and IE5 motors that run full time (8000 hours) outside ATEX zone becomes cost effective.
In ATEX zones only the IE0 motors smaller than 132 kW that run >8000 hours can be replaced by IE0 or IE5 motors. The same applies to motors that are not under ATEX but have a limited runtime.
This makes that the feasible economical potential under payback period of maximally 10 years:

$$EP_{feas} = \quad TP_{theo} \text{*(part of motors IE0 and IE1)*L1*L2*L3*L4 +}$$

$$TP_{theo}\text{* (part of motors IE0\&<132 kW}\rightarrow\text{IE4+ part of motors E0}\rightarrow\text{IE5)*L1*L2* L3*L4}$$

The term (part of motors IE0&<132 kW→IE4+ part of motors IE0→IE5) represents the part of the motors that have energy efficiency class IE0 and have a power size smaller than 132kW and are replaced by IE4 motors and the part of motors that are IE0 and are replaced by IE5 motors.
Together the feasible economical potential is still only approximately 25% of the feasible technical potential. The part that is not economically feasible is explained as follows:

- The total energy consumption by electromotors in the industry is divided over motor efficiency classes as follows: IE0 (10%), IE1(46%), IE2(34%), IE3(10%) and IE4(0%) [E2];The replacement of IE2 and IE3 motors by IE4 and IE5 motors remains economically unfeasible even at a payback period of 10 years.
- All motors smaller than 7.5 kW remain unfeasible due to the assumption of installation costs of € 1,000. Especially in case of food motors with a potential below 7.5 kW cause a significant part of the energy consumption by electromotors.

We did not find a significant effect of WACC on the feasible economical potential (only at payback periods much larger than 5 years the WACC changed the payback period in a significant way).

3.2.7 Overview of all CO_2 reduction potentials

1. Using the above described approach, we calculated the amount of CO_2 emission that can be reduced when replacing in 2020 all electromotors by more efficient motors. The numbers presented are the average of two situations, i.e. replacement by IE4 and replacement by the more efficient IE5 motors.
2. As mentioned above the economical feasible potential at a payback time of 5 years is negligible. It strongly increases at a payback period of 10 years. The effect of the WACC on the feasible economical potential is not significant (the lower WACC does significantly reduce the total costs of ownership and thus improves the business case).
3. Since the CO_2 reduction is the result of saving on the electricity, use the CO_2 reduction decreases with decarbonisation of the electricity production by increasing wind power generation. This means that in 2030 the feasible CO_2 reduction potential is only half the reduction potential that it is in 2020. Nevertheless, these measures are helpful for the energy transition since they reduce the amount of renewable energy that needs to be produced.

Table 3-7: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	22	2	14	0	4	0
	Steam crackers	48	3	30	0	8	0
	N-Fertilizer	9	1	6	0	2	0
	Wider chemical industry	48	3	41	1	13	1
Refineries		34	2	21	0	6	0
Iron and Steel		48	3	48	2	18	2
Food		160	6	160	5	42	5
Paper and Board		27	2	27	1	9	1
Total		396	22	347	9	102	9

3.3 Optimisation of electromotor systems with pump / fans/compressors

Motors drive a large number of applications. The main applications are pumps, fans, and compressors. The energy use per application varies greatly between industrial sectors, see Table 3-8.

Table 3-8: Energy use per application per sector [E1] & [E10]

	Pumps	**Fans**	**Air compressors**	**Cooling compressors**	**Conveyors**	**Other motors**
Paper, pulp and print	56,9%	21,7%	13,2%	0,4%	0,9%	6,9%
Food[14]	9,8%	11,5%	8,7%	30,3%	0,0%	39,7%
Chemical industry and Refineries[13]	26,4%	10,6%	28,1%	5,7%	2,6%	26,6%
Iron and steel	19,0%	22,0%	2,0%	2,0%	11,0%	44,0%

In this section we describe the optimisation of the combination of electromotors with respectively a compressor, fan, or pump.

Apart from replacement of an inefficient electromotor as described in a previous paragraph there are basically three situations in which a motor system consisting of at electromotor and a compressor pump or fan, respectively, can be improved in the energy efficiency:

1 Efficiency of compressor, pump or fan is low although the flowrate is according to the design flowrate (e.g. best efficiency of pumps corresponds to 60-70% maximal pump flow rate). In this situation the compressor, pump and/or fan should be replaced by a more efficient pump and/or fan.

2 The compressor, fan or pump varies between the optimum design flowrate a significantly lower flowrate as compared to design optimum efficiency throughput and there is no efficient load control mechanism like a variable speed drive or efficient control as on-off cycling in case of fans or compressors is not possible in that specific application. In this situation the recommended practice is to install a variable speed drive, magnetic coupling or some specific efficient flow control options available to compressors.

3 The compressor, pump or fan is systematically oversized and there is no efficient control mechanism like a variable speed drive or some specific control techniques as on/off cycling are not applicable for that application.

   In this situation the recommended practice for pumps is to change the impeller, adjust the angle of the impeller blades, trim the blades or replace the pump completely. These changes are irreversible, so this is only possible if the flow demand is consistently low. Analogous actions may be considered on fans and compressors if applicable (based on the type of the compressor or fan)

   An alternative solution is to install a variable speed drive (VSD) to increase the efficiency of fans and compressors in this situation. For compressors, other efficient control mechanisms are available as well.

As described above there are basically two generic types of approach:

1 Optimisation/replacement of the application: compressor, fan and or pump. This can be coupled with a better matched electromotor to reflect the lower power consumption of the new system. In this case the equipment that is too large, or for another reason not efficient, is replaced with new efficient equipment of size that is better aligned with required duty and therefore uses less energy;

2 Install a variable speed drive (VSD), i.e. a variable frequency drive or magnetic coupling. A VSD is applied in situations when the motor application requires a variable load delivered via variable shaft speed or when the delivered constant shaft speed is too high for the application requirement. By applying a VSD the application provides the required duty, and the friction losses of various inefficient load control mechanisms are eliminated. Therefore, the motor power consumption decreases. Both the application of a variable frequency drive and a magnetic coupling causes energy loss, but the overall system efficiency (VSD + motor +application or motor + MC + application) is in general higher than with less-efficient (friction based) types of load control.

Technology description variable speed drives:
There are several suppliers of variable speed drives, amongst others: ABB, Schneider and Zytec. There are basically two working principles for variable speed drives: magnetic coupling and frequency converters.

Technology description frequency converters:
Frequency converters are equipment that regulate the speed and rotational force delivered from electric motor, via the control of the AC supply frequency delivered to the motor. Therefore, they are often indicated as variable frequency drives (VFD). There are several suppliers of variable frequency drives, amongst others: ABB, Schneider.

Technology description magnetic coupling:
Magnetic coupling is a contact free coupling on the shaft between motor and application (e.g. pump) translating power between an electromotor and an application by means of induction. The coupling is realised by applying a copper disc (Inductor) at the rotating motor side and a magnet rotor at the load side to transfer torque.
The permanent magnet, mounted in the magnet rotor, changes the magnetic fields in the inductor creating loops of electrical current resulting in a drag force.
The magnet rotor rotates under the influence of the magnetic field with no physical contact between the inductor and the magnet rotor.
Speed of the load can be controlled by varying the air gap between the inductor and the magnet rotor resulting in variable slip between the two parts of the equipment. The magnetic coupling can be operated as a fixed coupling or as a variable speed drive, depending on the type of coupling installed. Magnetic couplings are produced by Zytec.

3.3.1 Working principle of energy saving by optimisation of motor systems driving a compressor

Technical saving potential by replacing compressors by more efficient compressors
The efficiency of the compressors varies between types / applications / considered number of compressor stages, intercooling system and age of the compressor (e.g. polytropic efficiency of centrifugal compressors was improved from 70% to 85% between 1970 and 1990 and further to ~87-89% as presently standard. The aerodynamic limit is ~91%). Efficiency of compressor acquisition is one of the main topics assed in energy audit/permit studies and this needs to be carefully evaluated in context of the wider parameters of the application.

Utilization of the saving potential by replacement of a whole compressor for a new more efficient is significantly affected by the specific application and economy of the project. We expect that the maximum efficiency gain that can be (technically) realised on a sector wide approach is 5%.

Technical saving potential by improving compressor control
There is a large number of different compressor types used in industry, but the four types used most, are the following:

1 Reciprocating (double acting);

2 Screw;

3 Centrifugal;

4 Axial.

For each of these compressor types different control options may apply:

- Pump around recycles (loss proportional to not-used flowrate, power = constant);
- Load-unload;
- On – off switching (some minor loss during switching, efficiency depends on how often it happens, too often is a reliability problem);
- VFD (small loss on VFD, efficiency of compressor may change a bit, but practically POWER = constant x FLOW);
- Hydrocom (no-loss, power proportional to flowrate, POWER = constant x FLOW);

- 50%-75%-100% switching (no loss at the three operation points) standard combined with pump around recycle for point between three operation points;
- [15]Inlet butterfly valve (IBV)/inlet guide vanes (IGV), 20% flow reduction leads to 5% loss of power efficiency for IGV. Better efficiency for IGV than IBV, IGV comparable to additional VFD inefficiency.

In appendix A2 on compressors we show a matrix of the different compressor types and the control types that apply. Based on that analysis, our expert judgement is that the potential power savings by more efficient performance control hardware is maximally 3-5% for air and refrigeration compressors. For large continuously operating compressors in chemical industry and refineries, it is maximally 1-2 %.
We use a 3% saving potential for control optimisation in compressors.

We estimated the technical saving potential of the optimisation of electromotor systems driving fans as follows:

$$TS_{comp} = TS_{rep} + TS_{VSD}$$

Where TS_{comp} stands for saving by optimisation of electromotor-systems driving compressors (excluding replacement of the electromotor system since we discussed that in the previous chapter), TS_{rep} stands for saving due to replacement of the compressor by a more efficient compressor and TS_{VSD} stand for optimisation of the control system. We assume an increase of 5% for example by replacing a compressor of 81% efficiency by a compressor of 85% efficiency.

$$TS_{rep} = E_{sector} * E_{motor} * E_{comp\%} * 5\%$$

In which TS_{rep} the saving due to replacement of the compressor per sector, E_{sector} the electricity use in the sector, E_{motor}* $E_{comp\%}$ the % of the electricity consumed by motors driving compressors per sector and the saving of 5% by replacing a compressor by a more efficient compressor.

$$TS_{VSD} = E_{sector} * E_{motor} * E_{comp\%} * (100\% - 5\%) * 3\%$$

In which TS_{VSD} the saving due to optimisation of the control of the compressor per sector, E_{sector} is the product of the electricity use in the sector, E_{motor}* $E_{comp\%}$ the % of the electricity consumed by motors driving compressors per sector, (100% - 5%) the factor to correct for reduced saving potential due to replacement of the old compressor by a newer more efficient compressor and 3% the average saving by adding a VSD.
The above-mentioned approach results in the following theoretical technical saving potential for optimising electromotor systems driving compressors.

[15] unlike throttling for pumps affects more flowrate & power via density change and momentum impact of compressor blades rather than pressure – much more efficient as compared to choking of pumps

Table 3-9: Theoretic Technical CO_2 reduction potential of electromotor systems driving compressors

Total top 8 industrial sectors		Theoretical Technical CO_2 Reduction Potential compressors [kton CO_2/ year]
Chemical industry	Industrial gasses	11
	Steam crackers	25
	N-Fertilizer	5
	Wider chemical industry	24
Refineries		18
Iron and Steel		3
Food		64
Paper and Board		5

3.3.2 Working principle of energy saving by optimisation of motor systems driving a fan

Technical saving potential by replacing fans by more efficient fans. Fans can be replaced by more efficient fans. The last years more efficient fans are brought to the market. An example of such a high efficiency fan is the Whizz wheel by Bronswerk. Due to optimised fan design the overall efficiency is 85% compared to 30-50% for regular fans (mainly low head fans of propeller type typical for air coolers, air condensers, cooling water towers exhibit lower efficiency). This presents a significant potential for improvement, higher as compared to other types of rotating equipment (pumps / compressors) that already have a fairly high efficiency by state-of-art mechanical design. Therefore, savings can be up to 60%. In general, we our expert judgement is that the saving for the replacement alone, is 50% (from 40% → 80% efficiency) in all sectors.

Technical saving potential optimisation fan controls

Figure 3-1 shows the difference in power input between the different types of control as a function of motor speed (=air flow) for fans.

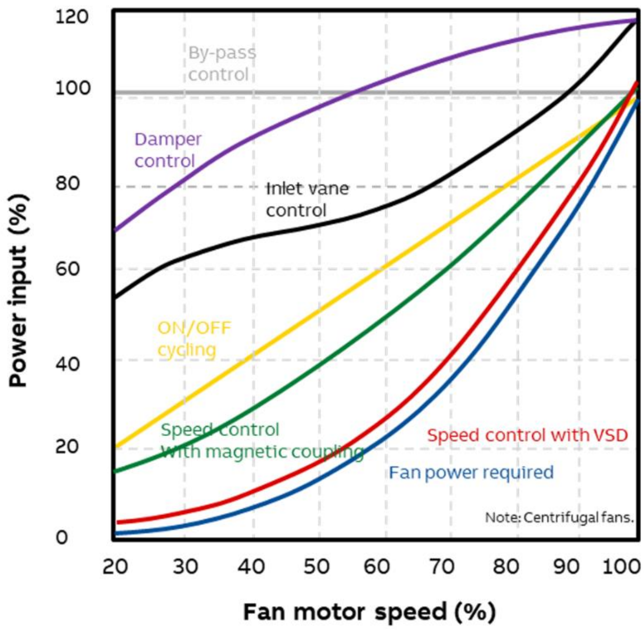

Figure 3-1: Effect of different controls on power input in case of fans [E3]

This picture shows that the required power reduces with a power three with the degree of flow reduction in case of centrifugal fan (lowest blue line). Industrial fans are centrifugal. This means that if the flowrate through the fan is only 80% of the design flowrate, the required power is only 80% x 80% x 80% = 51%.

According to the picture a 20% oversized motor means that the required flow in a fan is 90% of the design flow. Based on experience we assume that approximately 75% of fans is oversized and therefore need 70-90% of the design flow that is 10-30% less than the motor provides. Of these an estimated 50% already has an effective control in the form of on/off cycling or a VFD.
According to figure 1 application of a motor control on the fans without an effective control results in a saving of 10%-60% in power input, depending on the actual flow and the type of control applied. This implies that at a flow rate of 90% the energy saving is 10%-20% while at 70% flow compared to design flow the potential energy saving is 40-60%. On average this results in a 30% saving.
We calculate the saving potential of the optimisation of electromotor systems driving fans as follows:

$$TS_{fan}=TS_{rep} + TS_{VSD}$$

Where S_{fan} stands for saving by optimisation of electromotor-systems driving fans (excluding replacement of the electromotor system since we discussed that in the previous chapter), S_{rep} stands for saving due to replacement of the fan by a more efficient fan and S_{VSD} stand for optimisation of the control system.

$$TS_{rep} = E_{sector} * E_{motor\%} * E_{fan\%} * 50\%$$

In which TS_{rep} is the saving due to replacement of the fan per sector, E_{sector} the electricity use in the sector, $E_{motor\%}$*$E_{fan\%}$ the % of the electricity consumed by electromotors driving fans per sector and 50% the saving of resulting from an efficiency increase from 40 to 80%.

$$TS_{VSD} = E_{sector} * E_{motor\%} * E_{fan\%} * (1- 50\%) * F_{sizing} * F_{control} * 30\%$$

In which TS_{VSD} is the saving due to optimisation of the control of the fan per sector, E_{sector} the electricity use in the sector, $E_{motor\%}$*$E_{fan\%}$ the % of the electricity consumed by electromotors driving fans per sector, (1-50%) the correction for the optimisation of the fan, F_{sizing} the part of fans that are oversized (75%), $F_{control}$ the part of the fans that have inefficient control (50%) and the saving of on average 30% by adding a VSD.

The above-mentioned approach results in the following theoretical technical saving potential for optimising electromotor systems driving fans, of which approximately 75% of the savings is due to the replacement of fans.

Table 3-10: Theoretic Technical CO_2 reduction potential of electromotor systems driving fans

Total top 8 industrial sectors		Theoretical Technical CO_2 Reduction Potential fans [kton CO_2/ year]
Chemical industry	Industrial gasses	41
	Steam crackers	90
	N-Fertilizer	18
	Wider chemical industry	87
Refineries		64
Iron and Steel		178
Food		215
Paper and Board		94

3.3.3 Working principle of energy saving by optimisation of motor systems driving a pump

The optimisation of motor systems driving a pump has three components:

1. replacement of the electromotor by an electromotor of higher efficiency, as discussed in the previous paragraph,
2. the replacement/optimisation of the pump to the application
3. the improvement of the control.

The technical saving we calculate in this paragraph focusses on the latter two elements:

$$TS_{pump} = TS_{rep} + TS_{VSD}$$

Where TS_{pump} stands for saving by optimisation of electromotor-systems driving pumps (excluding replacement of the electromotor system since we discussed that in the previous chapter), TS_{rep} stands for saving due to replacement/optimisation of the pump to better fit the application and therefore function more efficiently, S_{VSD} stand for optimisation of the control system.

Technical saving potential by replacing pumps by more efficient pumps

For years the efficiency standard for pumps was in general 65-75% and it has increased to 75-80% lately. Assuming replacement of a 70% efficient pump by a 75% efficient pump yields a saving of 7% (we deem the 5% efficiency gain as generally representative). Therefore, we added 7% saving due to pump efficiency gain in case of a new pump.

This results in the following formula to calculate the technical saving potential by replacing pumps by more efficient pumps:

$$TS_{rep} = E_{sector} * E_{motor\%} * E_{pump\%} * 7\%$$

In which TS_{rep} is the saving due to replacement of the pump per sector, E_{sector} the electricity use in the sector, $E_{motor\%}$*$E_{pump\%}$ the % of the electricity consumed by motors driving pumps per sector and 7% the saving of resulting from an efficiency increase from 70-75%.

Technical saving potential optimisation pump controls

Pumps are often reported to have over-capacity that is controlled by control means like recycle streams, bypasses, throttle valves. The industry survey in several European countries that was used as the basis for the large European Motor Challenge programme reports that 75% of pumps is 20% oversized [E1]. This means that 75% of the pumps receives at least 20% too much power. For most industries, only an estimated 10% of flow is controlled by a variable speed drive, in all other cases a throttling valve or a recycle valve is used. Exceptions are paper and food industries due to the high variation in product ranges we estimate that approximately 50% of situations with an oversized pump flow is controlled by means of a VSD

This results in the following formula to calculate the technical saving potential by optimising the control on pump systems:

$$TS_{VSD} = E_{sector} * E_{motor\%} * E_{pump\%} * (100\% - 7\%) * F_{sizing} * F_{control} * S_{pump\%}$$

In which TS_{VSD} is the saving due to optimisation of the control of the pump per sector, E_{sector} the electricity use in the sector, $E_{motor\%}$*$E_{pump\%}$ the % of the electricity consumed by motors driving pumps per sector, (100%-7%) the correction in case of optimisation of the pumps (to avoid double counting with the pump replacement potential), F_{sizing} the part of pumps that are oversized (75%), $F_{control}$ the part of the pumps that have inefficient control (in general 90%, food and paper: 50%) and $S_{pump\%}$ the saving percentage that is feasible when adding a VSD.

Determination of the saving potential of adding a VSD

As shown above the only variable that we do not have yet is $S_{pump\%}$ the percentage saving that is feasible when adding a VSD.
Using the physics governing power consumption in pump systems we calculated the saving potential as a function of flow rate and static pressure for applying a VSD to replace throttling valve.
The saving potential feasible by applying a VFD is shown in table 3-11. (In Appendix A3 also the saving potentials feasible with a MC are shown).

The columns in table 3-11, show the saving potential at different flow rates, expressed as percentage of the design flow rate. The rows in these tables show the saving potential for the different static head as contribution of total head.

The saving potentials in table 3-11 show a strong correlation with flow rate and the contribution of static pressure to total pressure head. It is therefore important to determine the flow rate compared to design flow rate and the contribution of static pressure to total pressure head that are representative for the pump systems in the different industrial sectors.

*Table 3-11: Saving potential as a function of flow rate and static pressure for **VFD** [see appendix A3]*

		Flow/design flow [%]					
		100%	**90%**	**80%**	**70%**	**60%**	**50%**
Static head/Total head [%]	**0%**	0%	18%	37%	50%	58%	62%
	10%	0%	17%	34%	46%	54%	58%
	20%	0%	15%	31%	42%	50%	53%
	30%	0%	13%	28%	38%	45%	49%
	40%	0%	11%	25%	34%	41%	44%
	50%	0%	9%	21%	30%	36%	39%
	60%	0%	8%	18%	26%	31%	33%
	70%	0%	6%	15%	22%	26%	28%
	80%	0%	4%	12%	17%	21%	22%
	90%	0%	2%	8%	13%	15%	16%

**Single value of VFD efficiency of 94% was assumed in this document, as an average of range of efficiencies due to minor influence of the rotation speed and the power rating of the VFD. The selected value is in a good correspondence to the defined IEC standards for VFD.*

Determination flow rate compared to design flow rate
Given the observation that 75% of pump systems has at least 20% to large power consumption, this indicates that 75% of the pumps have a flowrate of maximally 90% of design flowrate. Pumps tend to become severely unreliable under 70% of the design flowrate. Therefore, we assume that 75 % of pumps has a flowrate between 70-90% of design flowrate.

Determination of contribution of static pressure to total pressure head
The numbers in table 3-11 show that an indication of the static head contribution to the total head is required to estimate the saving potential we used the pressure in the steam systems as a first approximation of the static pressure. The following typical pressures apply for the steam systems per industry sector according to our expert judgement confirmed by interviews with industry experts:

- 90-120 bar in steam systems of steam cracker sector;
- 80-100 bar in steam systems of N-fertilizer sector;
- 25-75 bar in steam systems of industrial gasses sector;
- 10-65 bar in steam systems chemical industry;
- 80 bar in steam systems of the steel sector;
- 40-100 bar in steam systems of the refineries;
- 5-15 bar in steam systems of the food sector;
- 5-10 bar in steam systems of the paper and board sector.

We assume the following relation for the dynamic head [m]:

$$H_{dyn} = P_{steam}\,[bar]+50$$

The 50 stands for the average 50 m of dynamic losses of head in piping/fittings.

From the representative pressures in the steam systems of the different industries we calculated the static head contribution to total head, se second column in table 3-12. The column next to the calculated static head shows the assumption on static head we used. It shows that the maximum static head we assumed was 70-90% even if we calculated 80-90%, see table 3-12.

Table 3-12: Static head per sector

Sector	Calculated Static Head based on steam system	Assumption on static head
Steam crackers	87-88%	70-90%
N-fertilizer	86-87%	70-90%
Industrial gasses	77-86%	70-90%
Wider chemical industry	63-85%	60-90%
Refineries	82%-87%	70-90%
Steel	86%	70-90%
Food	48%-70%	40-70%
Paper and Board	48%-63%	40-70%

Using the numbers of static pressure and the flow rate from table 3-12 we can look up the value for $S_{pump\%}$ in table 3-11. A complication is that we have a range for the flow rate and a range for the static pressure instead of two exact numbers.
This means we have to work with average values.
To calculate the theoretical technical saving we use the following formula:

$$TS_{pump} = TS_{rep} + TS_{VSD}$$

$$= E_{sector} * E_{motor\%} * E_{pump\%} * 7\% + E_{sector} * E_{motor\%} * E_{pump\%} * (1 - E_{pump\%} * 7\%) * F_{sizing} * F_{control} * S_{pump\%}$$

To take the effect of the different flow rates fully into account we used the following approach:

$$TS_{pump,theo} = 1/3 * (TS_{pump70\%theo} + TS_{pump80\%theo} + TS_{pump90\%theo})$$

In which $TS_{pump,\ theo}$ is the theoretical technical saving potential, $TS_{pump70\%theo}$, $TS_{pump80\%theo}$ and $TS_{pump90\%theo}$ the theoretical technical saving potential at a flow rate of respectively 70%, 80% and 90% of the design flow rate.

*TSpump90%theo= Esector*Emotor%*Epump%*7%+ Esector*Emotor%*Epump%*(100%-7%)*Fsizing*Fcontrol*Spump%VFD90%*

*TSpump80%theo= Esector*Emotor%*Epump%*7%+ Esector*Emotor%*Epump%*(100%-7%)*Fsizing*Fcontrol*Spump%VFD80%*

*TSpump70%theo= Esector*Emotor%*Epump%*7%+ Esector*Emotor%*Epump%*(100%-7%)*Fsizing*Fcontrol*Spump%VFD70%*

In which $S_{pump\%VFD70\%}$, $S_{pump\%VFD80\%}$, $S_{pump\%VFD90\%}$, stand for the saving percentages by replacing a throttling valve by a VFD at a flow of respectively 70%, 80% and 90%. Using these formulas, we calculated the theoretical technical savings listed in table 3-13.

Table 3-13:Theoretical technical CO_2 reduction potential for electromotor systems driving pumps

Sector	Theoretical technical CO_2 reduction Potential for electromotor systems driving pumps [kton CO_2/year]
Steam crackers	25
N-fertilizer	55
Industrial gasses	11
Wider chemical industry	57
Refineries	39
Steel	40
Food	44
Paper and Board	59

3.3.4 TRL level of optimisation of electromotor systems

The TRL level of variable speed drives, and optimisation of electromotor-systems is 9. VSD are applied from the smallest to the largest applications. The power scale for off-the-shelf variable speed drives (frequency control) comes from very small to up to 1 MW, but VSD as large as a 100 MW are reported. Magnetic couplings are available as a VSD for 7.5 kW to 375 kW as a fixed control from: 7.5 to 2000 kW.

The practice of optimising existing pumps is widely established, and more efficient compressors, pumps and fans are commercially available.

3.3.5 Conditions to allow for optimisation of electromotor systems

The main infrastructure required for variable speed drives is a connection to the factories' operating system. In all systems were a variable flow is operated by for example a throttle control, the infrastructure to support such a connection is already available.

Fixed variable speed drives do not require any supporting infrastructure.

3.3.6 Costs and benefits of optimisation of motor system driving a compressor

Economical saving potential by replacing compressors by more efficient compressors
Economically, diminishing efficiency gains need to be further balanced against additional costs for each individual project. In general, due to large CAPEX of compressors affecting economic considerations of the whole installations, the payback time of replacement of compressors is far longer than 5 years. For comparison, the CAPEX for replacement of compressor is 5 to 20x larger than CAPEX for pump of the same power rating. This implies that there is no significant economical reduction potential by replacing well-functioning compressors by more efficient versions.

In case of replacement of compressors at the end of their lifetime, efficiency of the new compressor is one of the main topics assed in energy audit/permit studies.

Economical saving potential by improving compressor control
CAPEX of variable speed drives varies between 1,000 and 70,000 for VSD varying in size between 7.5 kW and 900 kW for non-ATEX surroundings.
Cost of installation involve the installation of the motor control. We assume that installation costs of €5.000 and 6% over CAPEX and installation for design, engineering and project management. In practice this may vary between 1,000 and 10,000 depending on the local situation.

The total costs of installation of magnetic couplings vary between 10.000 and 65.000 for 7.5 kW to 375 kW fixed motor controls in-non ATEX surroundings and 14.000 to 114.000 in ATEX surrounding.

The saving for a VSD on a 55 kW motor to be cost effective in case of 8000 hours runtime is 10. The larger the motor the smaller the required saving. For motors of 250 kW-500 kW at 8000 hours runtime is 5% sufficient. For larger motors the percentage needs to be higher again. About 5% of the motors are in the range of 250-500kW. To have an energy saving of 5% or more in the compressor by applying a VSD, the flow needs to be significantly lower than the design flow rate and the current control needs to be inefficient. Thus no IGV, on-off switching, no HYDROCOM, or long unload periods need to be the case. In case of compressors the combination of the right motor size and a flow rate so much lower than the design flow rate without an efficient control occurs so limited that the theoretic economical saving potential is severely reduced to few isolated outlying cases, which are not expect to bring significant savings considering the global numbers of the total potential.

3.3.7 Costs and benefits of optimisation of motor system driving a fan

As described in 3.3.2 we have the following definition for the economical saving potential in fans

$$ES_{fan} = ES_{rep} + ES_{VSD}$$

Where S_{fan} stands for saving by optimisation of electromotor-systems driving fans (excluding replacement of the electromotor system since we discussed that in the previous chapter), S_{rep} stands for saving due to replacement of the fan by a more efficient fan and S_{VSD} stand for optimisation of the control system.

Economical saving potential by replacing fans by more efficient fans
High efficient fans, come at a certain cost (approximately 1500 €/kW total costs of installation [E16]). Only when the fan is a bottle neck in noise reduction or production (insufficient capacity at hot days) there is a payback time below 5 years. Both these aspects are likely to become more acute in the coming years. However, since there is no way to make an accurate estimate of the part of the fans that need to be replaced for noise reduction or form a bottleneck for production during hot days, we assume that 0% of this potential can be economically implemented.
This means that ES_{rep} =0

Economical saving potential by improving fan control
We assumed in paragraph 7.3.2 that 75% of fans is 10-30 % oversized in air flow compared to the design air flow. Of these an estimated 50% already has an effective control in the form of on/off cycling or a VSD.

Costs of CAPEX and installation of VSD are listed in 3.3.6. The saving for a VSD on a 55 kW motor to be cost effective in case of 8000 hours runtime is 10%. The larger the motor the smaller the required saving. With an average fan saving potential of 30%, applications of a VSD on a fan that runs 8000 hours per year is cost effective for all fans of 15 kW and larger. This means that the saving potential due to improving controls on fans (S_{VSD}) is reduced by the part of the fans that are 11 kW and smaller. To account for that reduction, we calculated per sector this reduction (F_{ECO}), see table 3-14.

Table 3-14: Correction factor to account for the part of the fans that is not economically feasible at the average saving of 30%

Sector	% of fan optimisation that remains cost effective (F_{ECO})
Chemical industry and refineries	93%
Steel	91%
Food	86%
Paper	92%

Since the replacement of fans is not economically feasible the saving of the VSD does not need to be corrected for the higher fan efficiency (thus 100%-50% becomes 100%-0%=100%).
This means that formula for the saving due to adding a VSD simplifies to:

$$ES_{VSD} = E_{sector} * E_{motor\%} * E_{fan\%} * F_{sizing} * F_{control} * F_{ECO} * 30\%$$

Resulting in the following formula for the total theoretical economical saving potential for the fan:

$$ES_{fan} = ES_{rep} + ES_{VSD} = E_{sector} * E_{motor\%} * E_{fan\%} * F_{sizing} * F_{control} * 30\%$$

Using this formula, we calculated the theoretical economical saving potential. We converted the calculated electricity saving to CO_2 reduction as described in chapter 1, see table 3-15.

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Table 3-15: Theoretical Economical CO_2 reduction potential for electromotor systems driving fans

8 industrial sectors		Theoretical Economical CO_2 Reduction Potential fans [kton CO_2/ year]
Chemical industry	Industrial gasses	8
	Steam crackers	18
	N-Fertilizer	4
	Wider chemical industry	18
Refineries		13
Iron and Steel		36
Food		43
Paper and Board		19

3.3.8 Costs and benefits of optimisation of motor system driving a pump

In this chapter we look how we can apply the formulas used in 3.3.3 to calculate the theoretical economical saving potential.

Economical saving potential by replacing pumps by more efficient pumps
Optimisation or replacement of the pump is only cost effective if the pump has reliability issues due to a too low flow rate. In case of 30% less flow compared to the design flow rate this may cause serious reliability issues with the pump, as shown in Figure 3-2.

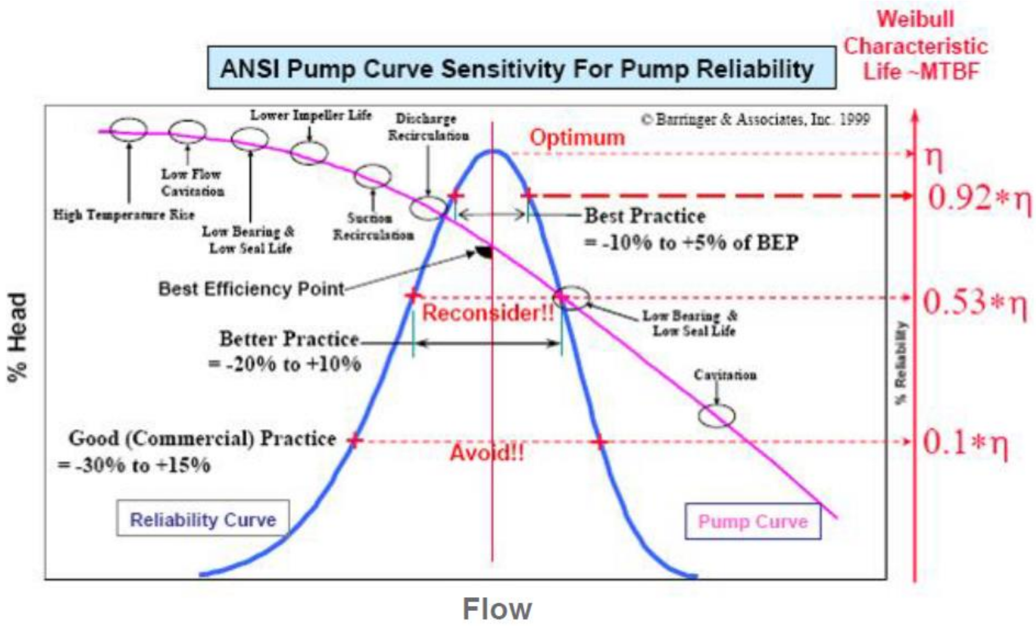

Figure 3-2: Ansi Pump curve sensitivity for pump reliability combined with Weibull Characterisitic Life [E15]

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Economical saving potential by improving pump control
Costs of CAPEX and installation of VSD are listed in paragraph 3.3.6. Depending on the static pressure and the flow rate the average saving due to adding a VSD varies, see table 3-12.
The relation between motor size and cost effectivity of the VSD needs to be considered due to economy of scale. At 20% power savings. VSDs are cost effective from 22 kW and up, for 14% savings from 37 kW and up and for 12% savings from 45 kW and up, for 9% they are cost effective from 75 kW and up and for 5% they are cost effective between 250 kW and 300 kW. Taking the energy consumption per motor size for each sector into account (listed in table 3-4). Considering the distribution of the motor sizes and static pressure distribution in the industry sectors, this results in factors which need to be applied to technical potential, S_{VSD}, see table 3-16.

From the above it becomes apparent that we need to calculate the theoretical economical saving potential per flow rate and use the average to calculate the theoretical economical CO_2 reduction potential. Therefore, we used the following approach:

$$ES_{pump} = 1/3*(ES_{pump70\%theo}+ES_{pump80\%theo}+ES_{pump90\%theo})$$

Table 3-16: Saving percentage due to addition of a VSD at relevant flow rates and static pressures (S_{VSD})

Sector	Static pressure contribution	Saving at flow rate of 70% ($S_{pump\%VFD80\%}$)	Saving at flow rate of 80% ($S_{pump\%VFD80\%}$)	Saving at flow rate of 90% ($S_{pump\%VFD90\%}$)
industrial gasses, steam crackers, N-fertilizer, refineries, steel	70%-90%	17%	12%	4%
Wider chemical industry	60%-90%	20%	13%	5%
paper and food	40%-70%	28%	20%	9%

In which, ES stands for economical saving potential.

$$ES_{pump90\%theo} = ES_{rep} + ES_{VSD} = E_{sector}*E_{motor}*E_{pump\%}*F_{sizing}*F_{control}*F_{ECO90\%}*S_{pump\%VFD90\%}$$

ES_{rep} is set to zero, since the replacement of the pump by a more efficient pump is not economically feasible at a flow rate of 90% of the design flow rate without additional benefits that are too process specific to estimate on the scale of an industrial sector. The placement of a VSD is cost effective for part of the motors on pumps with a power of 37-45 kW or larger in case of the chemical industry, refineries and steel and 22 kW and larger in the food and paper industry. To correct for the part that it is not cost-effective we add the factor $F_{ECO90\%}$. The values for $F_{ECO90\%}$ are listed in table 3-17. Relatively smaller factor in the food sector as compared to other industries is caused by large number of small motors in this industry.

Table 3-17: Correction factor in calculation of theoretical economical saving potential (S_{VSD})

8 industrial sectors		Correction factor ($F_{ECO80\%}$)	Correction factor ($F_{ECO90\%}$)
Chemical industry	Industrial gasses	81%	0%
	Steam crackers	81%	0%
	N-Fertilizer	81%	0%
	Wider chemical industry	87%	21%
Refineries		81%	0%
Iron and Steel		77%	0%
Food		64%	25%
Paper and Board		86%	60%

$$ES_{pump80\%theo}= ES_{rep} + ES_{VSD} = E_{sector}*E_{motor}*E_{pump\%}*F_{sizing}*F_{control}*F_{ECO80\%}*S_{pump\%VFD80\%}$$

ES_{rep} is set to zero, since the replacement of the pump by a more efficient pump is not economically feasible at a flow rate of 80% of the design flow rate without additional benefits that are too process specific to estimate on the scale of an industrial sector. In which $F_{ECO80\%}$ is the factor to correct for the part of the motors that is too small to place a VSD in a cost-effective manner, see table 3-17.

$$ES_{pump70\%theo}= ES_{rep} + ES_{VSD}$$

$$= E_{sector}*E_{motor}*E_{pump\%}*7\%+ E_{sector}*E_{motor}*E_{pump\%}*(100\%-7\%)*F_{sizing}*F_{control}*S_{pump\%VFD70\%}$$

Since both replacement of the pump by a more efficient pump and placement of a more efficient control are economically feasible at a flow rate of 70% of the design flow rate.

Applying these formulas, we calculated the theoretical economical power saving potential that we consequently converted to the theoretical economical CO_2 reduction potential for pumps using the emission factor for electricity as described in chapter 1.

Table 3-18: Theoretical Economical CO_2 reduction potential for electromotor systems driving pumps

Total top 8 industrial sectors		Theoretical Economical CO_2 Reduction Potential pumps [kton CO_2/ year]
Chemical industry	Industrial gasses	15
	Steam crackers	32
	N-Fertilizer	6
	Wider chemical industry	36
Refineries		23
Iron and Steel		24
Food		24
Paper and Board		37

3.3.9 Feasible saving potential

In the previous paragraphs we calculated the theoretical CO_2 reduction potentials for the optimisation of electromotor systems driving compressors, fans and pumps.

The only limitation we found on the feasible technical potential is the lack of maintenance stops in a number of industrial sectors. Therefore, we calculate the feasible technical potential (TP_{feas}) as the part of the theoretical technical potential (TP_{theo}) that is not affected by the lack of maintenance stops ($L1$):

$$TP_{feas}= TP_{theo}*L1=(TP_{theo}*L1)_{compressor} + (TP_{theo}*L1)_{fan} + (TP_{theo}*L1)_{pump} \quad (Equation\ 3)$$

In addition, we found a number of limitations that affect the payback time.
To calculate the feasible economical potential (EP_{feas}) based on the theoretical economical potential (EP_{theo}) we used the following approach:

$$EP_{feas}= EP_{theo}*L1*L2*L3*L4 =$$

$$EP_{feas}= (EP_{theo}*L1*L2*L3*L4)_{compressor} + (EP_{theo}*L1* L2*L3*L4)_{fan} + (EP_{theo}*L1* L2*L3*L4)_{pump} \quad (Equation\ 4)$$

In which EP_{theo} Is the theoretical economical potential and L1 to L4 are the factors resulting from the limitations described below.

Limitation 1: planning of maintenance stops

When looking at the different industrial sectors we see the following pattern for maintenance stops:

- steam-crackers, industrial gasses, N-Fertilizer and refineries only have very few stops, typically 1 in 6 years,
- Wider chemical industry, the picture is less clear, part of the companies also have stops limited to1 in 6 years, some 1 in 4 years and some more often,
- steel stops the blast furnaces only 1 in 10 years, but all other processes are stopped for maintenance on a regular basis,
- food and paper stop on a regular basis for maintenance, hygienic and /or commercial reasons.

Based on the above we assume that the potential for the food, steel, and paper and board sectors is not affected by the planning of maintenance stops.
The potential of the Wider chemical industry reduces with 20% and the potential of the steam crackers, industrial gasses, N-fertiliser and refineries is 50% reduced by the lack of stops that still can be used before the end of 2025.

Since the maintenance stops are not a limitation for the sectors paper, food and steel, and redundant systems, this implies that the **feasible potential of pumps is not affected ($L1_{pump}$=100%).** For simplicity we assume here that all pumps outside the paper industry are redundant. This is in line with the outcome of the interviews we held.
Thus, only the savings by optimisation of electromotor systems driving fans and compressors in the chemical industry and refineries are affected.

We calculated the limitation factor (L1) according to the following formula:

L1= 100% - %lack of stop

This results in the following limitation factor (L1) for compressors, fans and pumps per sector.

Table 3-19: limitation factor due to lack of maintenance stops (L1) for compressors, fans and pumps per sector

Sectors	lack of stops	$L1_{compressor}$	$L1_{fan}$	$L1_{pump}$
Steam-crackers, industrial gasses, N-fertilizer, refineries	50%	50%	50%	100%
Wider chemical industry	20%	80%	80%	100%
Steel, paper, food	0%	100%	100%	100%

Limitation 2: limited runtime (5500-4000 hours per year).
A runtime of 4000-5500 hours increases the payback period.
As described in 3.2.6 there are two reasons to have a low runtime: redundancy and seasonal influences. In general pumps are redundant, fans operation exhibits mainly seasonal effects (and redundancy to much less extent). Therefore, we use the following formulas to calculate factor L2, see table 3-19 for resulting factors:

$$L2_{compressor} = \sim 100\% \text{ (assumed)}$$

$L2_{fan}$ = % of fans that remain cost effective at 5500 hours compared to 8000 hours =100%
$L2_{pump}$ = % of pumps that remain cost effective at 4000-5500 compared to 8000 hours

Table 3-20: limitation factor due to limited run time hours (L2) for compressors, fans and pumps per sector

Sectors	$L2_{compressor}$	$L2_{fan}$	$L2_{pump}$
Chemical industries, refineries	100%	100%	69%
steel	100%	100%	66%
food	100%	100%	59%
paper	100%	100%	80%

Limitation 3: ATEX
In the chemical industry, refineries and part of the food sector explosion safety is an issue, requiring special adaptations on equipment to prevent an explosion. Such measures may be required in chemical industry and refineries. We estimate that approximately 75% of electrical equipment should be ATEX compatible in steam crackers and refining, 50% of industrial gasses, 50% in N-fertilizer and 20% in Wider chemical industry and 10% in food industry.

ATEX compatibility adds 50% to the price of optimising these systems and therefore makes payback time significantly longer. For chemical industry sectors, refinery sector and steel sector this means that VSDs controlling electromotors driving pumps are feasible from 55 kW motors upward and for food and paper from 30 kW upward, and VSDs controlling electromotors driving fans are already feasible from 15 kW upward This means that in case of pumps approximately 90% and for fans practically all of the VSDs that were economically feasible remain economically feasible. The economy potential of VSD control on compressors was deemed infeasible prior to further ATEX limitations.

This means that in case of pumps approximately 90% (see $P_{ATEX\%,p}$ in table 3-19) and for fans approximately 100% of the VSDs that were economically feasible remain economically feasible (see $P_{ATEX\%,f}$ in table 3-19), for compressors 0% are feasible (see $P_{ATEX\%,c}$ in table 3-19).

Using these insights, we calculated L3 using the following formula:

$$L3 = P_{ATEX\%} * \%\ ATEX + 100\% * (100\% - \%\ ATEX)$$

In which L3 stands for the reduction in potential due to additional costs related to make equipment ATEX compatible, $P_{ATEX\%}$ stands for the percentage of measures that remains economically feasible when additional cost have to be made for ATEX, ATEX stands for the % of the equipment that needs to be ATEX compatible. Both variables vary per type of equipment and with the industrial sector.

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Table 3-21: limitation factor due to limited run time hours (L3) for compressors, fans and pumps per sector

Sectors	ATEX	$P_{ATEX\%,c}$	$P_{ATEX\%,f}$	$P_{ATEX\%,p}$	$L3_{comp}$	$L3_{fan}$	$L3_{pump}$
steam-crackers, refineries	75%	0%	100%	77%	25%	100%	86%
industrial gasses, N-fertilizer	50%	0%	100%	77%	50%	100%	90%
Wider chemical industry	20%	0%	100%	77%	80%	100%	96%
food	10%	0%	100%	93%	90%	100%	96%
steel industry, paper	0%	n.a.	n.a.	n.a.	100%	100%	100%

Limitation 4: Economical limitations

We indicated that costs of installation can vary widely depending on the costs related to integrate the VSD with the control system of the factory. We assumed that installation of a VSD costs approximately 5000,- and 6% over the sum of installation costs and CAPEX, but we acknowledge that costs may vary between €1,000 and 6% of installation costs and CAPEX and €10,000 and 6% of installation costs and CAPEX. This limitation has no significant effect on fans, and compressors, because of the larger relative savings per control in case of fans and the negligible theoretical economical potential in case of compressors, but increases the payback period of VSDs, reducing the pump potential for the paper sector to approximately 70%, the food sector to approximately 42%, the chemical industry sectors to 75% and the steel sector to 71% of the theoretical feasible potential

$$So\ L4_{fan} = L4_{compressor} = 100\%$$

$L4_{pump}$ = % of energy use on pumps for which control optimisation is still economically feasible.
This results in the following limitation factor (L4) by variations in costs for **pumps**:

- 75% of the theoretical economical potential of optimising electromotor systems driving pumps in case of chemical industry sectors;
- 71% of the theoretical economical potential of optimising electromotor systems driving pumps of the steel industry;
- 75% of the theoretical economical potential of optimising electromotor systems driving pumps of the refineries;
- 42% of the theoretical economical potential of optimising electromotor systems driving pumps of the food industries;
- 70% of the theoretical economical potential optimising electromotor systems driving pumps of the paper and board industry.

Conclusions

The only technical limitation is the limitation of the turnaround planning, lowering the feasible technical potential compared to the theoretical technical potential. This effect applies to fans and compressors not to pumps since most pumps have a spare or are in a sector with sufficient maintenance stops. The turn-around planning strongly affects the potential of the steam-cracking sector, the industrial gasses sector, the N-fertilizer sector, and the refinery sector, and to a lesser extend the Wider chemical industry sector. In all other sectors we do not expect a significant effect.

Table 3-22: Overview of results: feasible saving potential (technical / economical) in kton/y

Feasible CO_2 reduction potential		Pumps		Fans		Compressors	
Total top 8 industrial sectors		**Technical**	**Economical**	**Technical**	**Economical**	**Technical**	**Economical**
Chemical industry	Industrial gasses	25	7	21	4	6	0
	Steam crackers	55	14	45	15	12	0
	N-Fertilizer	11	3	9	2	2	0
	Wider chemical industry	57	18	70	14	19	0
Refineries		39	10	32	10	9	0
Iron and Steel		40	11	178	36	3	0
Food		44	6	215	43	64	0
Paper and Board		59	20	94	19	5	0
Total 8 sectors		329	89	663	143	120	0

The feasible technical CO_2 reduction potential of the fans is considerable higher than for pumps. The feasible technical potential of which again is considerable higher than in compressors is deemed negligible.
This can be explained as follows. First of all the saving due to replacement of fans by a high efficiency fan has a large effect (an efficiency increase from 40% to 80% causes a saving of 50%) For pumps and compressors this effect is on average much smaller, respectively 7 and 5% due to the much higher efficiencies that are common for pumps and compressors. Secondly the energy saving due to improved control is much larger in fans than it is in pumps or compressors, respectively an average saving of 30% in fans compared to 12-20% in pumps and 3 % in compressors.

The feasible economical CO_2 reduction potential strongly decreases compared to the feasible technical reduction potential. There are 3 factors that decreased the feasible economical potential compared the feasible technical potential: low economical potential, further decreased by the limited runtime of pumps that are redundant and fans that experience seasonal effects.
The main reason for the decrease compared to the feasible technical potential is that even with 8000 hours runtime, outside ATEX regions and an average cost of implementation for all VSD placements a significant part of the potential is not economically feasible. When correcting the payback period for the low run time of redundant pumps and air-cooling fans, 50% additional costs of ATEX on control optimisation and the actual spread in costs of optimisation this results in the presented numbers.

3.3.10 Sensitivity analysis

We performed sensitivity analysis on certain crucial parameters which are expected to influence the outcomes and can be stimulated by policy measures.

Therefore, we analyzed the effect on feasible economic CO_2 saving potential when:

1. A **payback period of 10 years or less** significantly increases the economical potential The most important effect is that the complete feasible technical potential for fan replacement, becomes economically feasible; in addition, a larger part of the VSDs become economically feasible.
2. A **WACC of 4%** is used to:
   - analyze the future cash flow instead of 8% and,
   - calculate savings for technologies with payback period of 5 years or less;

We did not find a significant effect in the part of the optimisations that had a payback time of more than 5 years. We did see a large effect in the returns on investment over the lifetime of the measures, so it does have a significant effect on the financial attractiveness of the measures. Given the fact that payback times were mostly within 5 years at 8000 hours and largely over at limited runtimes of ATEX conditions the effect of WACC we found was negligible.

3.3.11 Overview of all CO_2 reduction potentials

Table 3-23: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	78	23	51	11	22	11
	Steam crackers	170	50	112	29	34	29
	N-Fertilizer	34	10	22	5	9	5
	Wider chemical industry	168	53	146	32	87	32
Refineries		120	36	80	20	24	20
Iron and Steel		221	60	221	47	213	47
Food		322	68	322	49	226	49
Paper and Board		157	55	157	39	131	39
Total		1270	355	1111	232	745	232

3.4 Industrial Lubricants

All motors with gear boxes use lubricants to decrease friction and increase efficiency. The use of nano structures in lubricants has proven to improve physical characteristics of the lubricants without changing the chemical composition.

3.4.1 Working principle of energy saving by industrial nano-lubricants

The nano structures form a smooth layer between the gear components and the lubricants, reducing the friction and thus lowering the peak temperatures in the lubricants. Lifetime expectancy of lubricants increases with decreasing peak temperatures.

3.4.2 TRL level of industrial lubricants

The working of the nano lubricants is demonstrated mainly in diesel motors for ships. Very little information is available on the working of this type of lubricants on other type of motors. Furthermore, one would expect a relation between motor efficiency and lubricant effect. No information on such relation was found.

This means that although the nano-lubricants for ship applications is on TRL level 9. For other applications it seems on TRL 7-8.

3.4.3 Conditions to allow for industrial lubricants

There need to be parts that need lubrication, in electromotor systems that are mainly gear boxes. No known limitations for using nano-lubricants

3.4.4 Costs and benefits of industrial lubricants

Since the nano lubricants significantly improve lubricant life and the costs are limited the costs are not a limiting aspect.

3.4.5 Overview of all CO_2 reduction potentials

Due to lack of data there is no factual basis to calculate the saving potential. To give an indication of what the potential might be, if the nano-lubricant works, we made an estimate on what saving by lubricants could do.

First step is to estimate the part of the electromotors that needs lubrication.
Only motors larger than 10kW can be lubricated. We assumed that all electromotors that drive v-belt driven fans, conveyors, mills, grinders, laminators, extruders, lifts and hoist can use lubrication.
Fans driven by a V-belt is approximately 30% of all fans in the category fans in Table 3-8, the other types of systems driven by electromotors are described by the categories conveyors and other motor applications.
Using this data, the percentage of the electricity consumption on electromotors per industry sector [E1] and the current electricity consumption per industrial sector [CBS, 2020] we can calculate the electricity used by these motors.
As described in the paragraph on electro motors we calculated the efficiency per motor power-class, and we have the energy consumption per motor class per industrial sector. The only variable missing is the saving caused by the lubricants. We assume that the following equation describes the saving (S_{lub}):

$$S_{lub} = X_{lub}(100\% - \eta\_motor\ )^2 = 2(100\% - \eta\_motor\ )^2$$

The equation for S_{lub} is an expert guess by lack of supporting data. It means that for a motor with a 96% efficiency the saving effect of the nano-lubricants would be 0.3%, and for a motor with a 90% efficiency the saving would be 2%. Using this equation, we estimated the following saving potential:

Table 3-24: Theoretical CO_2 reduction potential (kton/y)

		Theoretical potential	
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**
Chemical industry	Industrial gasses (Air Products, Air Liquide, Linde)	2	2
	Steam crackers (Dow, Shell Moerdijk, Sabic Chemelot)	4	4
	N-Fertilizer (YARA, OCI)	1	1
	Wider chemical industry	4	4
Refineries (BP, ExxonMobil, Gunvor, Koch, Shell Pernis, Zeeland Refinery)		3	3
Iron and Steel (TATA)		5	5
Food (large number of factories producing diary, sugar, oils and fats, etc.)		8	8
Paper and Board (21 factories)		1	1

Given this very limited potential there is not further elaboration of the feasible potential.

4 Heat Integration 2.0

4.1 Introduction and overview of results

This chapter describes 5 technologies aiming to maximise heat integration/utilisation. These technologies are:

- Flue gas recuperation until below the condensation point;
- Heat pumps;
- Mechanical vapour recompression;
- Qpinch Heat transformers;
- Heat storage.

In the tables below the main results are summarised.

Table 4-1: Overview of technologies, saving principles and main conditions.

Flue gas recuperation until below the condensation point	
Technology	The HeatMatrix technology uses a corrosion resistant polymer heat exchanger to recover heat from acidic components containing stack gasses by cooling down below the acid dewpoint (140°C). This is normally not possible with conventional metal heat exchangers, because of corrosion issues.
Savings principle	The typical benefit of using an air preheater is that by preheating the combustion (or drying) air with waste heat from flue gasses (or exhaust gasses) directly results in a saving on fuel for the burner because the air inlet temperature has increased.
Main conditions and sectors	Flue gas heat recuperation with the HeatMatrix technology can in principle be used in every industrial sector where burning or drying processes takes place (furnaces, boilers, ovens, kilns, dryers, incinerators). The maximum flue gas temperature for using a HeatMatrix APH exchanger is limited to 200°C.
Heat pumps	
Technology	A heat pump transfers heat from a lower temperature to a higher temperature, thus making it possible to use low value heat (often waste heat, that is normally discarded) to a more useful level.
Savings principle	Heat pump transfer heat from a temperature where there is a surplus of heat to a temperature where there is a shortage of heat. The transfer of heat costs less than producing heat.
Main conditions and sectors	Heat pumps can be applied cross industry where a surplus of heat at lower temperature is available and a heat demand at temperature levels at temperature levels up to about 185 oC with most potential in the food and paper industries.
Mechanical vapour recompression	
Technology	Mechanical vapour recompression (MVR) is an open compression heat pump. It transfers heat from a lower temperature to a higher temperature by means of direct compression of process streams.
Savings principle	The evaporated water is compressed and can be use as steam for evaporation of the water, as it now has a higher condensation temperature than the evaporated water and thus heat transfer is possible
Main conditions and sectors	The technology is in principle applicable to any process that has a vapour stream that requires cooling at a temperature that is in excess of heat (under the and a need for heat at a higher temperature where there is a shortage of heat (above the pinch temperature). In most cases this would be applicable to LP steam to MP or HP steam, but in many cases also for evaporation of water in drying process. It is expected that MVR can be applied in all sectors except the N-fertiliser and the steel production sectors.

Heat transformers	
Technology	The heat transformer makes use of a reversible chemical reaction in a closed loop between two reactors. In the ‘cold’ (LT) reactor an endothermic oligomerization takes place by means of waste heat at a temperature level > 80°C. On the other side, in the ‘hot’ (HT) reactor, an exothermic reverse reaction takes place at elevated pressure, releasing heat at a (much) higher temperature level.
Savings principle	The liberated heat at higher temperature level can be used to generate useful process heat (steam, thermal oil, water, heating-up of process streams) for industrial processes and thereby replacing other energy sources.
Main conditions and sectors	The main parameters determining the magnitude of the energy savings potential for the heat transformer technology are the available waste heat sources (capacity, temperature level). The working principle of the high temperature heat transformer version is independent of the industrial sector.
Heat storage	
Technology	Thermal storage (heat storage, thermal battery, thermal accumulator) allows heat integration of processes where the heating and cooling doesn’t occur at the same time.
Savings principle	Thermal storage is designed to be capable of responsive heat acceptance/discharge depending on the current availability of the excess heat or the immediate heat demand and hereby avoiding the use of other energy sources
Main conditions and sectors	Heat storage will typically be applied for major cyclic batch operations hot standby back-up boilers for emergency steam generation. Industrial sectors with potential heat storage application are Steel industry, Paper, Chemical and Food industry.

Table 4-2: Overview of results: main economic parameters.

	HeatMatrix flue gas recuperation	HT heat pumps	Mechanical vapour recompression	Heat transformer	Heat storage
Payback period	2	3-1	2-15	3 - 6	5 years or more
TRL	9	7-9	9	7 - 8	8-9

Table 4-3: Feasible economical CO_2- reduction potential given per technology and sector (kton/y)

Total top 8 industrial sectors		Feasible Economical	Feasible Economical	Feasible Economical	Feasible Economical	Feasible Economical
		Heat Transformer	*Flu gas recuperation*	*Heatpumps*	*MVR*	*Heat storage*
Chemical industry	Industrial gasses	0	5	0	0	0
	Steam crackers	29	55	4	15	0
	N-Fertilizer	0	10	1	2	0
	Wider chemical industry	86	59	52	127	0
Refineries		76	85	6	23	0
Iron and Steel		0	49	2	8	0
Food		16	67	165	165	0
Paper and Board		0	20	38	88	0
Total		**207**	**350**	**268**	**428**	**0**

4.2 Flue gas heat recuperation

4.2.1 Working principle of energy saving by application of HeatMatrix flue gas heat recuperation

The HeatMatrix flue gas heat recuperation technology uses a corrosion resistant polymer heat exchanger to recover heat from acidic components containing stack gasses by cooling down below the acid dewpoint (140°C). This is normally not possible with conventional metal heat exchangers, because of corrosion issues.

As heat source flue gasses from burning fuel (e.g. furnaces and boilers) or exhaust gasses (from dryers, ovens and/or incinerators) can be used.
As heat sink for the recovered heat from the stack a preheating of combustion air or drying air can be applied (APH exchanger). Another option is to use the heat for heating water e.g. process water or for district heating (ECO exchanger).

For Project 6-25 the focus will be on air preheating (gas-gas exchange in APH exchanger). The design and performance of the HeatMatrix ECO exchanger (gas-water heat exchange) is much more situation dependent and therefore less straight forward as the APH exchanger.

A simplified process flow diagram (PFD) of the flue gas heat recuperation system with the HeatMatrix APH exchanger is given in Figure 4-1 on the left. The hot flue gasses (red arrow) flow through the inside of the polymer tubes, heating up cold combustion air (blue arrows), as is indicated in Figure 4-1 on the right.

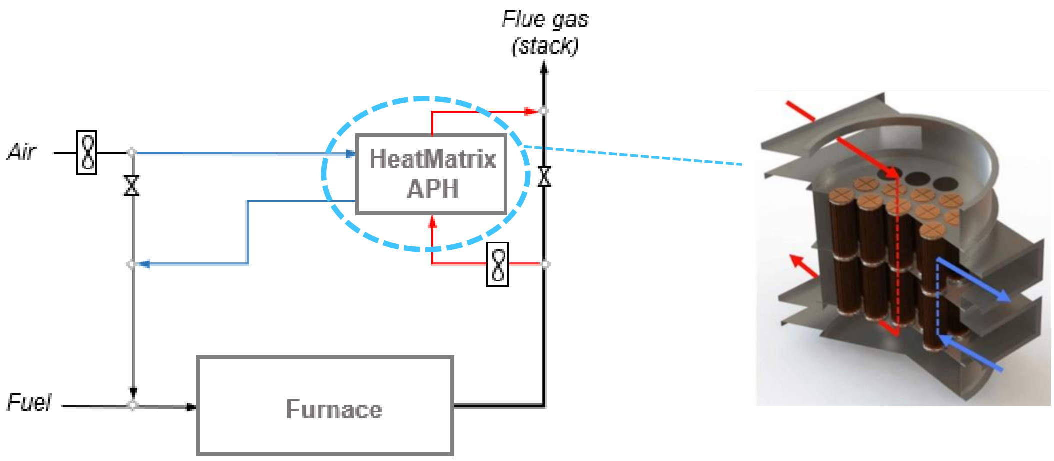

Figure 4-1: Schematic figure of flue gas heat recuperation with HeatMatrix air preheating system

The energy savings potential of this technology is directly related with the used temperature range for the flue gas cooling (cq. air preheating range). A typical example, for instance for a refinery furnace or a SMR application, is cooling down hot flue gasses from 170 → 90°C (ΔT = 80°C) for heating up combustion air from 15 to about 100°C. In utility generation systems, natural gas fired boilers and CHP units normally have somewhat lower stack temperatures (in the range of 120 – 140°C), which means that the heat recovery potential is reduced proportionally (on average ΔT = 60°C).

Besides the heat recovery from acidic flue gasses, also fouling issues might be reduced significantly due to the polymer heat exchanger surface. Retractable tube bundles are used for easy cleaning and maintenance.

4.2.2 TRL level of flue gas heat recuperation

The HeatMatrix technology TRL level is 9. HeatMatrix already has some big scale references. The largest is a project that is currently being designed (2 x 4.4 MW) for a SMR unit in the Netherlands. Other relevant references are:

- SMR unit (5 MW, refinery in Europe);
- RTO incinerator (5.3 MW, utility provider, NL);
- CDU furnace (3 MW, refinery Poland);
- Animal fat fired boiler (1 MW, steam boiler, NL);
- Phosphate additive dryer (0.4 MW, chemical plant, Germany);
- Blood product dryer (0.3 MW, spray dryer, NL);
- Biogas co-fired boiler, (0.3 MW, brewery, Ukraine);
- Biomass fired boiler, (0.2 MW, brewery, Denmark).

4.2.3 Conditions to allow for successful application of flue gas heat recuperation

Flue gas heat recuperation with the HeatMatrix technology can in principle be used in every industrial sector where burning or drying processes takes place (furnaces, boilers, ovens, kilns, dryers, incinerators).

The maximum flue gas temperature for using a HeatMatrix APH exchanger is limited to 200°C. In case of higher flue gas temperatures, it is recommended to place a conventional metal APH exchanger in front of the HeatMatrix APH to cool down the flue gas to a temperature level < 200°C.

4.2.4 Costs and benefits of flue gas heat recuperation

CAPEX costs

The CAPEX cost of a HeatMatrix exchanger lies in the range of 160 – 280 k€/MW, among others depending on the type of heat exchanger. For an APH exchanger the cost is on the lower side of the indicated range (160 – 200 k€/MW).

Figure 4-2 HeatMatrix exchanger equipped with an in-situ cleaning system

A turn-key project (including installation cost) will be in the range of 3 - 5 times the cost of a heat exchanger, and will strongly depend on the local situation (e.g. length of connecting piping, supporting structure needed in case it is preferred to have the exchanger on a certain elevation level).

If the available flue gas temperature is >200°C, an additional metal heat exchanger should be installed in front of the polymer HeatMatrix exchanger for protection which will increase the CAPEX cost, but at the same time the recovered amount of energy will increase.

For cases where it is desired (e.g. when ‘dirty’ exhaust gasses are used), a HeatMatrix exchanger can be equipped with an in-situ cleaning system (Figure 4-2) which might give rise to a (small) increase of CAPEX and OPEX cost.

OPEX costs

The typical benefit of using an air preheater is that by preheating the combustion (or drying) air with waste heat from flue gasses (or exhaust gasses) directly results in a saving on fuel for the burner because the air inlet temperature has increased.
As an example, a simplified calculation of the CAPEX and OPEX cost and the resulting payback time is given in Table 4-4. This indicative calculation is based on an air preheater capacity of 1 MW, which results in a fuel saving of 1 MW, equivalent with a saving of 0.030 PJ/yr (assuming 8300 h/yr on-stream time). The OPEX cost here is only based on utility cost, which means that maintenance and labor cost are not taken into account.

The OPEX cost consist of a substantial saving on fuel (285 k€/yr per MW) and some additional electricity consumption (-18 k€/yr) for a blower to overcome the extra pressure drop, resulting in a total net saving of 267 k€/yr. It is assumed that there are no additional cost/savings for maintenance and management, although fouling issues might be reduced significantly in practice for certain processes.

Table 4-4: Example calculation of the CAPEX and OPEX cost and the simple payback time

natural gas saving	0,030 PJ/yr	CAPEX	180 k€ / MW
electricity blower	50 kWe / MWth	Installation factor	3 *(min 2, max 4)*
operating hours	8300 h/yr		

Savings	Amount	Amount	Price	Saving
Savings on natural gas	1,00 MW	8.300 MWh/yr gas	34,3 €/MWh	285 k€/yr
Extra electricity blower *1)*	0,05 MWe	415 MWh/yr	43,6 €/MWh	-18 k€/yr
Savings on maintenance and management *2)*	0			0 k€/yr
Total savings				**267** k€/yr
Modifications				**Price**
HeatMatrix bare module cost	1 MW			180 k€
Installation cost *3)*				540 k€
Design, Engineering and PM	6% of TIC			43 k€
Total module capital cost				**763** k€
Payback time				**2,9 year**

1) Additional electricity for blower is needed to overcome extra pressure drop
2) Here it is assumed that there are no savings on maintenance. In practice however fouling issues migh be reduced significantly
3) May vary widely (between 2 and 4), depending on local situation. Preliminary installation cost is based on the average value

For the CAPEX cost of an APH exchanger an average price of 180 k€ / MW is assumed, while for the installation factor based on expert judgement an average factor of 3 is taken, resulting in a total module capital cost of 763 k€ (including 6% additional cost for design, engineering and PM). The resulting simple payback time is about 3 years.

4.2.5 Feasible saving potential

Starting point in determining the feasible saving potential was updating the Task 1 theoretical and economical heat savings potential of the HeatMatrix technology (as agreed with the Steering Group experts after Task 1). Following adjustments in the calculation procedure were implemented:

- Wider chemical industry (as additional sub-sector of the chemical industry) was included. A split factor of 50% was used for the division over the defined higher and lower limit case (same split factor as used for the steamcracker, N-fertilizer and industrial gasses sector);
- For the lower limit case the temperature range for flue gas cooling was changed from 130 → 90°C into 130 → 70°C (i.e. ΔT = 60°C). This resulted in an increase of the '% reduction stack losses' of 1.82 → 2.73% and a corresponding increase in the weighted average theoretical savings potential.

With respect to the energy savings potential by applying the HeatMatrix exchanger technology, the following limitations were found to be applicable:

Limitation 1: In some plants air-preheaters are already used.
Some conventional air-preheaters are already installed in certain processes (e.g. paper drying, particular incinerators and (hot-oil) furnaces in refinery and chemical industry, certain dryers in food industry). Next to that, already some HeatMatrix exchangers are installed or planned to be installed shortly in Dutch industry. Based on our experience weestimated that due to this limitation the theoretical CO_2 savings potential is reduced with about 10%.

Limitation 2: Validation interviews of end-users.
As part of Task 2, various people from the assessed industrial sectors were interviewed to validate the used method, assumptions and potential limitations of the proposed technologies within their own plant and/or sector. Based on the confidential information retrieved from these interviews (e.g. feedback on the assumed temperature range dependent heat demand as presented in Table 1-4 of §1.3), following reductions on the remaining theoretical (and economical) potential are introduced:

- 50% reduction for the Steamcracker and N-fertilizer sector
- 10% reduction for the Refinery and Food sector
- No reduction for the remaining sectors

Limitation 3: Turnaround planning
Steamcrackers, Industrial gasses, N-Fertilizer and Refineries have very few stops, typically 1 in 5 to 6 years. For the Wider chemical industry, the picture is less clear, part of the companies also have a planned turnaround (TAR) once per 5 years, some once per 4 years and some more often. The Steel industry stops only 1 in 10 years the blast furnaces, but all other processes are stopped for maintenance on a regular basis. In Food and Paper stops for (preventive) maintenance, hygienic and/or commercial reasons are more common and therefore not directly a limiting factor for the technology implementation.

Based on the above, following reductions on the theoretical (and economical) potential are introduced:

- 50% reduction for the Steamcracker, N-fertilizer, Industrial gasses and Refinery sector;
- 20% reduction for the Wider chemical sector;
- No reduction for the other sectors (Steel, Food, Paper & Board).

Conclusions
It can be concluded from the theoretical savings potential for the 8 assessed industrial sectors (**751 kta** CO_2 in total), about **350 kta** CO_2 savings potential remains after implementing above mentioned limiting factors for the various sectors, which means a reduction of a little more than 50%.
The majority of this reduction in potential can be subscribed to the limitations due to TAR planning for Steamcracker and Refinery sector and limitation 2 (interview end-users) for the Steamcracker sector.

4.2.6 Sensitivity analysis

We performed sensitivity analysis on certain crucial parameters which are expected to influence the outcomes and can be stimulated by policy measures.
Therefore, we analyzed the effect on feasible economic CO_2 saving potential when:

1. A **payback period of 10 years or less** is considered financially attractive;
2. A **WACC of 4%** is used to:

- analyze the future cash flow instead of 8% and,
- calculate savings for technologies with payback period of 5 years or less.

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4.2.7 The results of this sensitivity analysis are presented in the last two columns of the overview given in Overview of all CO_2 reduction potentials

Table 4-5. It can be concluded that for the HeatMatrix technology the effect for both parameters is nihil, i.e. no change in feasible potential can be noticed. This is due to the fact that the payback time for the HeatMatrix technology in all of the assessed cases remains lower than 5 years.

4.2.8 Overview of all CO_2 reduction potentials

Table 4-5: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	10	10	5	5	5	5
	Steam crackers	246	246	55	55	55	55
	N-Fertilizer	43	43	10	10	10	10
	Wider chemical industry	82	82	59	59	59	59
Refineries		210	210	85	85	85	85
Iron and Steel		55	55	49	49	49	49
Food		83	83	67	67	67	67
Paper and Board		23	23	20	20	20	20
Total		751	751	350	350	350	350

4.3 Heat pumps

A heat pump transfers heat from a lower temperature to a higher temperature, thus making it possible to use low value heat (often waste heat, that is normally discarded) to a more useful level.
This can be done in a variety of ways.
Here we indicate with heat pumps the closed mechanical heat pump. A mechanical heat pump uses compression to transfer heat. A closed system heat pump is called a closed system since it does not alter the process streams but uses a working fluid to transfer heat from a heat source to a heat sink. The working principle of such a heat pump is as follows:

The working fluid adsorbs heat at a low temperature from a heat source (‘for example a process stream that needs to be cooled or a waste heat stream’) by means of a heat exchanger. This heat exchanger is indicated as the evaporator. By absorbing the heat, the working fluid changes from the fluid phase to the vapour phase. This vapour is sent to a compressor that compresses the vapour to the required pressure level. By elevating the pressure of the vapour, the condensation temperature of the working fluid is raised. When the working fluid is lead through a condenser (a heat exchanger allowing for condensation of a vapour stream), the condensation takes place at a higher temperature than the temperature at which the heat was absorbed. Thus, allowing the working fluid to transfer the absorbed heat to the process at a higher temperature than the heat originally was absorbed. After condensation and subcooling (if applied) the working fluid is depressurised over a valve and is ready to be send to the evaporator to absorb heat.

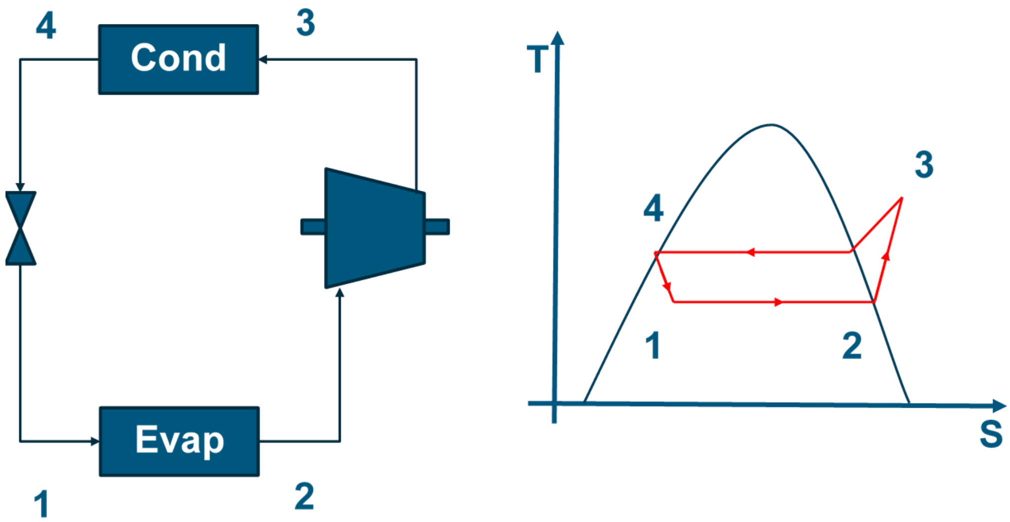

Figure 4-3: Principle of heat pumps.

The main types of closed mechanical heat pumps are the compression type and the absorption type:

- Compression type – using a pure fluid as a working fluid, such as ammonia, propane, butane, etc. This means that the working fluid evaporates and condenses at a fixed temperature;
- Absorption type – using a set of mixture as working fluid (e.g. LiBr & water, ammonia water solution) and evaporating the volatile component (taking up heat in case of LiBr) and absorption of the volatile component (releasing the heat). This means that the working fluid evaporates and condenses over a temperature range.

Both types of heat pumps need electrical power for the compressor.

4.3.1 Working principle of energy saving by application of heat pumps

Heat pump transfer heat from a temperature where there is a surplus of heat to a temperature where there is a shortage of heat. The transfer of heat costs less than producing heat.

The parameter that defines the efficiency of a heat pump is the Coefficient of Performance (CoP) which is the heat delivered at the higher temperature divided by the work that is being done (compressor mainly):

$$CoP = \frac{Qcondensor}{W}$$

Therefore, the compressors efficiency has an effect on the energy saving potential of the heat pump. As has the temperature lift ($Thot - Tcold$) which determines the degree to which the working fluid needs to be compressed. This is reflected by the theoretical maximum CoP is defined by the difference in temperature (cold / hot):

$$CoP = \frac{Thot}{Thot - Tcold}$$

The temperature lift ($Thot - Tcold$) is to a large extend determined by the integration of the heat pump with the process. By a smart choice of working fluid, number of compression steps, determining the actual required temperature in the condenser instead of the current steam temperature are all factors that can strongly influence the saving potential and thus the business case of a heat pump.

The actual CoP is also influenced by the temperature drop over the heat exchangers in the evaporator and the condenser. The smaller these temperature drops the higher the efficiency

Other aspects that influence the saving potential are the emissions caused by the current heat source and the emissions related to the electricity production required for the compressor.
As a first estimate we assumed a COP of 4.5.

4.3.2 TRL level of heat pumps

The article 'High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials' [H20], discusses several commercially available heat pumps that are able to produce steam up to 120 °C and incidentally above that temperature. However, both Siemens and Bronswerk currently work on heat pumps that realise temperatures up to respectively 160 ^{o}C and 185 ^{o}C. The Siemens and the Bronswerk heat pumps are currently tested and expected to enter the market in the next two years. So TRL for Heat pumps up to 120 °C is TRL 9, higher temperatures are TRL 7-8.

4.3.3 Conditions to allow for successful application of heat pumps

Using a compressor implies:

- A sufficiently strong connection to the electricity grid to power the compressor. In some cases, mostly smaller factories outside large industrial clusters, this may be a limiting factor;
- A relatively stable mode of operation, but naturally – depending on type of compressor – some flexibility in operation is possible.

In addition, in more complex factories a pinch analysis is required to assure that the installation of the heat pump leads to a net decrease in energy use. Only heat pumps that transfer heat from under to above the pinch point actually decrease energy use on the level of the total plant.

Heat pumps can be applied cross industry where a surplus of heat at lower temperature is available and a heat demand at temperature levels up to about 185 ^{o}C with most potential in the food and paper industries.

4.3.4 Costs and benefits of heat pumps

Typical costs numbers vary strongly between 250 and 800 €/kW [H20, H21, H22], depending on temperature lift, process integration, scale of operation, and working fluid. Especially the temperature lift has a large impact.
In general, the compressor is the piece of equipment driving the CAPEX and to a lesser extent by the type and amount of working fluid and the type of heat exchangers required.
A high temperature lift demands a very powerful compressor or two compressor steps, both increasing the cost per unit of heat delivered. The scale of the operation tends to increase the investment cost, but due to economies of scale the price per unit of heat delivered decreases with increasing scale

Since the heat pump transfers heat from the temperature range in which an excess of heat exists, the main energy input cost is the electrical power for driving the compressor.

However, costs could be limited to 150-250 €/kW if production of heat pumps was rationalised [H21].

In addition to the CAPEX come the installation costs. Installation costs may vary widely depending on the local situation. The installation of the heat pump as such does not add more than 50% tot the CAPEX but depending on the situation the installation costs can increase to 300% of the CAPEX. Therefore, the costs of installation are very important to the payback time of the heat pump.

4.3.5 Feasible saving potential

In Task 1 we made a first estimate of the saving potential assuming for all sectors that 25% of the heat demand below 250 °C could be supplied by means of heat pumps.
This is a rather crude estimate therefore we make a more detailed estimate in this section for this percentage. Based on this better estimated percentage the saving of energy by applying heat pumps is calculated in the same way as in task 1 as the sum of the saving in CO_2 emission due to reduction in natural gas consumption and the increase in CO_2 emission due to the increase in electricity consumption.
The limitations that we found for saving energy by applying heat pumps are the following:

Limitation 1: In some plants most "waste" heat is already in use.
This is not the case for the very energy intensive plants like steam crackers, refineries etc, but is relevant for some companies in the Wider chemical industry, food and in paper and board industry.
In the latter all heat sources, steam condensate from the dryer cans, hot air from the dryer hoot and fuel gasses from boilers are required to make a reduction of approximately 10% (instead of the 25% assumed in task 1) [expert judgement based on heat integration study at paper mills, verified for other mills during interviews]. This implies that flue gas recuperation and a heat pump are required to bring the heat from the temperature where it is released to the temperature where it can be used. We estimate that his situation is valid for the food, paper and a quarter of the Wider chemical industry sector.
Therefore, we applied a factor 40% to paper and food and 80% to Wider chemical industry [expert judgement].

Limitation 2: Distance between heat source and heat application
On some sites there is a significant distance between the place where the heat is released and the place where the upgraded heat is required, especially in case of spacious streams like flue gasses that can be cooled and air that needs pre-heating, this can be a game changer further reducing the economic saving potential with 25% [expert judgement based on heat integration study at paper mills, verified for other mills during interviews]. Therefore, we applied a factor 75% to paper, food, Wider chemical industry, and steel [interviews].

Limitation 3: Division of sites in sub-sites
For optimal energy saving maximal integration of al heat demanding and heat providing streams is required. However, from a practical point of view this is not always possible. For example, if you have a large plant, not all operations can be in turnaround at the same time since that would require too many contractors on the plant at the same time. Since operations in one subsite cannot be disturbed by a turnaround in another subsite this limits heat integration to sub-site level. In general, this aspect diminishes the saving potential of a large plant. Based on several studies we assume this reduction is 25% [H_27, H_28, H_29].
This reduction of 25% applies to very large plants. Therefore, we applied a factor of 75% to the potential of steam-crackers and refineries.

Limitation 4: some potential in the lower temperature range is already realised
Some heat pump potential is already realised especially under 100°C. We assume that 5% of the heat demand under 250 °C in food industry is already realised, especially in relation with freezer capacity [expert judgement]. Therefore, we applied a factor of 95% to the potential of the food sector.

Limitation 5: Turn around planning

Heat pumps can only be integrated with the processes/steam system during a major stop also called a turn around. When looking at the different industrial sectors we see that the sectors: steam-crackers, industrial gasses, N-fertilizer and refineries only have very few stops, typically 1 in 5 or 6 years.
For the Wider chemical industry the picture is less clear, part of the companies also only have a turn around 1 in 5 years, some 1 in 4 years and some more often [interviews, expert judgement].
The steel industry stops only 1 in 10 years the blast furnaces, but all other processes are stopped for maintenance on a regular basis [interviews].
In food and per stops for maintenance, hygienic and /or commercial reasons are common and therefore not a limiting factor [interviews].
Based on the above we assume that the potential for the food, steel, and paper and board sectors is not affected by the planning of maintenance stops.
The potential of the Wider chemical industry reduces with 20% and the potential of the steam crackers, industrial gasses, N-fertiliser and refineries is halved by the turn around planning.

Limitation 6: limitations in use of heat from a CHP

The application of heat pump reduces the amount of heat that has to be produced by the fossil fired utilities. However, if this utility used CHP production, it also decreases the amount of heat through the turbine and thus reduces the amount of electricity and the income related to electricity production. Currently this is not very cost-effective. Therefore, we assume that on a sector level the heat produced by CHP production cannot be provided by heat pumps. If after 2030 renewable electricity becomes more abundant the position of CHP production may be reconsidered. At that moment the heat supply to the plant has to be redesigned probably increasing the potential for heat pumps.
To estimate the part of the heat under 250 ºC that is not supplied by CHP we used the data in table 1-@@table on heat per temperature in chapter 1@@.
We assumed that the CHP only produces heat up to 500 degrees.
We calculated the part of the CHP that provided heat at temperatures below 250 ºC:
$Q_{CHP<250} = Q_{CHP} * Q_{<250} / Q_{<500}$,
$Q_{CHP<250}$ is the amount of heat provided by CHP below 250 ºC, $Q_{<250}$ is the demand for heat below 250 ºC, and $Q_{<500}$ is the demand for heat below 500 ºC.
The limitation factor for the CHP (L_{CHP}) is calculated according:

$$L_{CHP} = (Q_{<250} - Q_{CHP<250}) / Q_{<250}$$

This results in the following factors per industry:

Industrial gasses	58%
Steam crackers industry	58%
Ammonia and N-fertiliser	58%
Wider chemical industry	58%
Steel	71%
Refineries	81%
Food industry	80%
Paper Industry	57%

Limitation 7: Total cost of installation can vary widely (probability of costs)

As mentioned in task 1 the CAPEX of the heat pump as such normally average between 250 and 800 €/kW, depending on temperature lift, process integration, scale of operation, and working fluid [H20, H21, H22]. Especially the temperature lift has a large impact. We expect that in 2021 heat pumps enter the market that allow for a high temperature lift of approximately 80-90 ºC at a cost below 500 €/kW [H30, expert judgement].

In addition to CAPEX cost come the cost of installation. In task 1 we assumed CAPEX = 400 €/kW and added 150% CAPEX costs for installation yielding a total cost of installed capacity of 1000 €/kW.

Table 4-6: Overview of different combinations that have a payback period of 5 years

COP	CAPEX [€/kW]	Installation costs	Production hours [hours/year]	Payback period [years]
4,5	400	3* CAPEX	8000	11
4,5	400	3* CAPEX	8760	10
4,5	250	3* CAPEX	8760	6
4,5	350	1* CAPEX	8000	5
4,5	400	1* CAPEX	8760	5
4,5	500	0.5* CAPEX	8000	5
4,5	400	0.5* CAPEX	7000	5
5	400	3* CAPEX	8000	10
5	400	1* CAPEX	8000	5
5	550	0.5* CAPEX	8000	5
5	450	0.5* CAPEX	7000	5

However, costs of installation vary widely between sectors. Costs of installation are high in chemical industries and refineries, especially if process integration is the case and much lower in paper and food sectors.
Therefore, we differentiated the installation cost to 3*CAPEX in chemical industry and refinery (total cost of installation = 4*CAPEX) for heat pumps requiring process integration and 1* CAPEX for projects that can be integrated with utilities (total cost of installation 2*CAPEX). We assume that 50% of the cases require process integration.
In food and paper sector we assume 0.5*CAPEX (total cost of installation = 1.5*CAPEX).

Payback period is a function of saving by the heat pump (expressed in COP), CAPEX, installation costs and production hours per year. In table 4-7 we made an overview of different combinations to give a feeling of the sensitivity of the payback period to any of these variables.

Sometimes the cost of installations are higher than the factor 0.5-3 we assumed above.
To correct for that we calculate the % economical feasible heat pumps using the COST division in figure 4-4. In this graph 50% of the heat pumps has a CAPEX of 400 €/kW or less, 88% has a CAPEX of 800 €/kW or less the remainder has larger CAPEX upto 1250 €/kW. That is to compensate for the situations where the COST of installation is larger than used in our estimates.

Resulting in the following division:

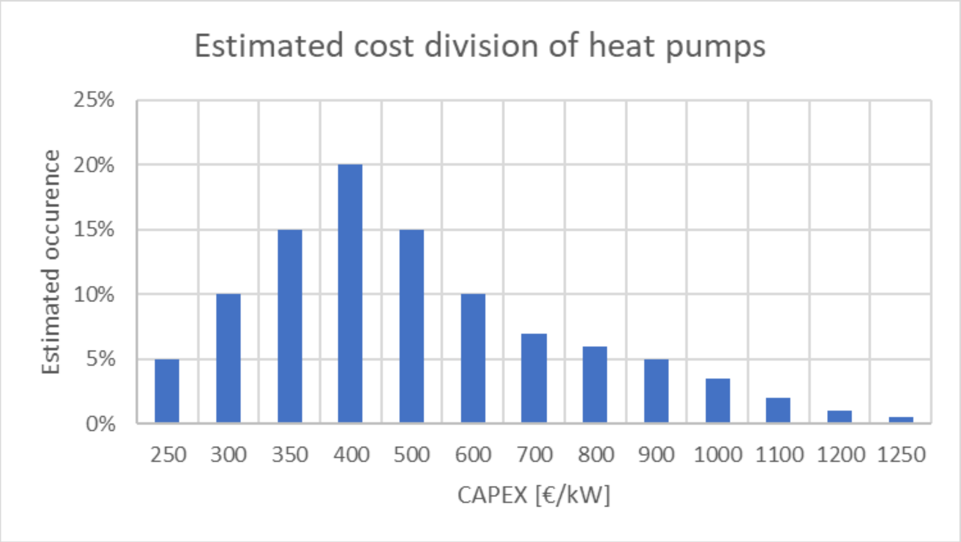

Figure 4-4: Estimated cost division of heat pumps (expert judgement based on cost numbers suppliers

When assuming **COP of 4,5** and taking the above into account this has the following effect on the feasible economic potential per sector:
For chemical industries, refineries and steel applies:

- Half of the potential has installation costs of 3*CAPEX, implying that this potential is not economically feasible;
- Half of the potential has installation costs of 1*CAPEX, implying that of this potential approximately 50% is economically feasible;
- Overall 25% feasible economic potential.

For food and paper sectors with 8000 production hours and installation costs of 0.5*CAPEX, 65% of the potential is economically feasible
For food sector with 7000 production hours and installation costs of 0.5*CAPEX, 50% of the potential is economically feasible.
Overall in the food sector 50-65% ~58% of the saving potential is economically feasible.

Conclusions
In task 1 we assumed that 25% of the heat demand was technical feasible to be replaced by heat pumps. In addition, we assumed that 50% of the technical potential was cost effective.

In Task 2 we looked in more detail and we came with 6 more or less technical limitations and 1 purely economical limitation. Resulting in the following factors per industry sector.

Table 4-7: Estimate of feasible percentages of heat demand below 250ºC that can be provided by heat pumps (Technical) and the factor correcting the feasible technical potential to become a feasible economical potential (economical)

	Technical*	Economical**
Industrial gasses	29%	25%
Steam crackers industry	22%	25%
Ammonia and N-fertiliser	29%	25%
Wider chemical industry	28%	25%
Steel	54%	25%
Refineries	61%	25%
Food industry	23%	58%
Paper Industry	17%	65%

**In task 1 we assumed 25% for all sectors*
*** In task 1 we assumed 50% for all sectors*

When using the technical feasible % to calculate the CO_2 reduction potential as described in task 1 this yields the feasible technical reduction potential as listed in 4.3.7. When applying the economical % from table 4-8 to the feasible technical reduction potential this yields the economical feasible CO_2 reduction potential. The difference between the numbers in table 4-8 and the assumptions made in task 1 explain the difference between theoretical and the feasible numbers in paragraph 4.3.7.

The much higher potential for the sectors; food, Wider chemical industry and paper is explained as follows.
The energy intensive industries use high amounts of energy, however the final energy demand that is used primary to produce heat in the temperature range of heat pumps is rather low, see chapter 1. This makes that the food industry has by far the highest heat demand below 250 ºC, the Wider chemical industry is second and the paper industry is third. The demand in the other industrial sectors is very limited.

The factors determining whether this demand can be met are described in the previous paragraph and result in the factors technical and economic feasibility factors for heat pumps. The limitations that have the most effect on these sectors are: limitations 1 and 2 (limiting amount of heat available for upgrading, limitation 5 (turn around planning) but only on the sector remaining chemical industries and limitation 6 heat produced by CHP. These are all technical limitations.
In addition, there is the rather large limitation of the economic feasibility. Especially in those sectors with high installation costs. For food and paper this factor is much less limiting.

4.3.6 Sensitivity analysis

We performed sensitivity analysis on certain crucial parameters which are expected to influence the outcomes and can be stimulated by policy measures.

Therefore, we analyzed the effect on feasible economic CO_2 saving potential when:

1 A payback period of 10 years or less

When increasing the definition of economically feasible to a payback period of 10 year, this has a strong effect on the economical feasible potential. The economical feasible reduction potential increases from 267 kton CO_2 per year to 500 kton per year. This increase is caused by the following effects:

At continuous production at >8700 hours per year:

- The payback period of measures with a total cost of implementation of 4*CAPEX become economical feasible for CAPEX of 400 €/kW and less (50% of the potential)
- The payback period of measures with a total cost of implementation of 2*CAPEX become economical feasible for CAPEX of 800 €/kW and less (88% of the potential)

At continuous production at 8000 hours per year:

- The payback period of measures with a total cost of implementation of 1,5*CAPEX become economical feasible for CAPEX of 1000 €/kW and less (96,5% of the potential)

At continuous production at 7000 hours per year:

- The payback period of measures with a total cost of implementation of 1,5*CAPEX become economical feasible for CAPEX of 800 €/kW and less (88% of the potential)

How this works out is summarized in table 4-10 in paragraph 4.3.7.

2 A WACC of 4% is used to:

- analyze the future cash flow instead of 8% and,
- calculate savings for technologies with payback period of 5 years or less.

The decrease of a WACC of 8% to a WACC of 4% increases the feasible economical potential with 12% from 267 kton CO_2 per year to 305 kton per year. This increase is caused by the effect it has on the parameters of the calculation of limitation 7 described in the previous paragraph. This limitation evaluates the effect of the range in CAPEX. The decrease in CAPEX allows for an increase of the economical feasible CAPEX with ca 50 €/kW. This increase is not enough to make the measures with a total cost of implementation of 4*CAPEX economically feasible.

Therefore, the factor of the feasible economical potential as calculated under limitation 7 increases from WACC =8% to WACC is 4%, see table 4-9.

Table 4-8: Estimate of the factor correcting the feasible technical potential to become a feasible economical potential at respectively 8% and 4% WACC

	8% WACC	4% WACC
Chemical industry (4 sectors)	25%	30%
Steel	25%	30%
Refineries	25%	30%
Food industry	58%	65%
Paper Industry	65%	70%

4.3.7 Overview of all CO_2 reduction potentials

Table 4-9: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		Theoretical Technical	Theoretical Economical	Feasible Technical	Feasible Economical	Sensitivity analysis	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	0	0	0	0	0	0
	Steam crackers	18	9	16	4	11	5
	N-Fertilizer	2	1	3	1	2	1
	Wider chemical industry	186	93	208	52	144	62
Refineries		10	5	25	6	17	8
Iron and Steel		4	2	8	2	6	2
Food		315	158	287	165	265	186
Paper and Board		85	43	58	38	56	41
Total		620	311	605	268	501	305

4.4 Mechanical vapour recompression (MVR)

Mechanical vapour recompression (MVR) is an open compression heat pump. It means it transfers heat from a lower temperature to a higher temperature by means of compression. But contrary to the heat pumps described in the previous section it does not apply working fluids but directly compresses process streams.

An example for the use of an MVR system is water evaporation from brine. In this case steam is condensed to evaporate water from brine. The evaporated water is then compressed and can be use as steam for evaporation of the water, as it now has a higher condensation temperature than the evaporated water (and thus heat transfer is possible).

Another example is the compression of low-pressure steam (3.5 bara) to medium-pressure steam 12 bara).

In most cases MVR is used in water / steam systems (often dryer / water evaporation applications), but the system could also be applied for other processes where vapours are present.

Also, a hybrid form of is possible in which a vapour stream is compressed but not lead back into the process but instead transferring its heat by means of a heat exchanger to the process. For example, at a distillation unit the top stream can be cooled directly to the air, but it can also be compressed and condensed in a heat exchanger thus transferring its heat to the reboiler of the distillation unit.

4.4.1 Working principle of energy saving by application of MVR

The parameter that defines the efficiency of MVR is the Coefficient of Performance (CoP) which is the heat delivered at the higher temperature divided by the work that is being done (compressor mainly):

$$CoP = \frac{Qcondensor}{W}$$

Therefore, the compressors efficiency has an effect on the energy saving potential of the heat pump. As has the temperature lift ($Thot - Tcold$) which determines the degree to which the working fluid needs to be compressed. This is reflected by the theoretical maximum CoP is defined by the difference in temperature (cold / hot):

$$CoP = \frac{Thot}{Thot - Tcold}$$

Other aspects that influence the saving potential are the emissions caused by the current heat source and the emissions related to the electricity production required for the compressor.

4.4.2 TRL level of MVR

Mechanical vapour recompression is commercially available at any relevant scale. Pressures up to 12 bar (approximately 185 ^{o}C) are widely applied in industry. Higher pressures up to 21 bar (215 ^{o}C) are reported for industrial applications [H$_2$4].
In principle recompression to 70 bar with regular steam compressor equipment is possible [H$_2$5].

4.4.3 Conditions to allow for successful application of MVR

Using a compressor implies:

1 A sufficiently strong connection to the electricity grid to power the compressor. In some cases, mostly smaller factories outside large industrial clusters, this may be a limiting factor;

2 A relatively stable mode of operation, but naturally – depending on type of compressor – some flexibility in operation is possible.

In addition, in more complex factories a pinch analysis is required to assure that the installation of the heat pump leads to a net decrease in energy use. Only if the MVR transfers heat from under to above the pinch temperature energy use decreases on the level of the total plant.

The technology is in principle applicable to any process that has a vapour stream that requires cooling at a temperature that is in excess of heat (under the pinch temperature) and a need for heat at a higher temperature where there is a shortage of heat (above the pinch temperature). In most cases this would be applicable to LP steam to MP or HP steam, but in many cases also for evaporation of water in drying process.

It is expected that MVR can be applied in all sectors except the N-fertiliser and the steel production sectors.

A limitation of the use of MVR on vapour streams is the composition of those streams. If the streams are corrosive or can react under the pressure in the compressor into corrosive substances it may be advisable to choose for a heat pump configuration in which only the heat pump in the evaporator is exposed to these corrosive influences.

4.4.4 Costs and benefits of MVR

Typical costs numbers vary strongly between 100 and 600 €/kW [H$_2$3, H$_2$6], depending on temperature lift and scale of operation. But also the pressure of the vapour stream. Very low pressures of the incoming vapour stream can also significantly increase the compressor costs.

Since the MVR transfers heat from the temperature range in which an excess of heat exists, the main energy input cost is the electrical power for driving the compressor.

A high temperature lift demands a very powerful compressor or two compressor steps, both increasing the cost per unit of heat delivered. The scale of the operation tends to increase the investment cost, but due to economies of scale the price per unit of heat delivered decreases with increasing scale.

In addition to the CAPEX come the installation costs. Installation costs may vary widely depending on the local situation. The installation of the MVR as such does not add more than 50% tot the CAPEX but depending on the situation the installation costs can increase to 300% of the CAPEX. Therefore, the costs of installation are very important to the payback time of the MVR.
Since single step MVR compressor systems typically have a bay back time well below 5 years we assume that 25% of the MVR may have a payback time over 5 years (expert judgement).

4.4.5 Feasible saving potential

In Task 1 we made a first estimate of the saving potential assuming for all sectors that 25% of the heat demand below 250 ^{o}C could be supplied by means of heat pumps.
This is a rather crude estimate therefore we make a more detailed estimate in this section for this percentage. Based on this improved percentage the saving of energy by applying heat pumps is calculated in the same way as in task 1 as the sum of the saving in CO_2 emission due to reduction in natural gas consumption and the increase in CO_2 emission due to the increase in electricity consumption.

The limitations that we found for saving energy by applying MVR are the following:

Limitation 1: In some plants most “waste” heat is already in use.
This is not the case for the very energy intensive plants like steam crackers, refineries etc, but is relevant for some companies in the Wider chemical industry, food and in paper and board industry.
In the latter all heat sources, steam condensate from the dryer cans, hot air from the dryer hoot and fuel gasses from boilers are required to make a reduction of approximately 10% (instead of the 25% assumed in task 1) [expert judgement based on heat integration study at paper mills, verified for other mills during interviews]. This implies that flue gas recuperation and an MVR are required to bring the heat from the temperature where it is released to the temperature where it can be used. We estimate that his situation is valid for the food, paper and a quarter of the Wider chemical industry sector.
Limitation 2: Distance between heat source and heat application
On some sites there is a significant distance between the place where the heat is released and the place where the upgraded heat is required, especially in case of spacious streams like flue gasses that can be cooled and air that needs pre-heating this can be a game changer further reducing the economic saving potential with 25% [expert judgement based on heat integration study at paper mills, verified for other sites during interviews]. Therefore, we applied a factor 75% to paper, food, Wider chemical industry, and steel [interviews].

Limitation 3: Division of sites in sub-sites
For optimal energy saving, maximal integration of all heat demanding and heat providing streams is required. However, from a practical point of view this is not always possible. For example, if you have a large plant, not all operations can be in turn-around at the same time since that would require too many contractors on the plant at the same time. Since operations in one subsite cannot be disturbed by a turnaround in another subsite this limits heat integration to sub-site level. In general, this aspect diminishes the saving potential of a large plant. Based on several studies we assume this reduction is 25% [$H_2$7, $H_2$8, $H_2$9].
This reduction of 25% applies to very large plants. Therefore, we applied a factor of 75% to the potential of steam-crackers and refineries.

Limitation 4: some potential in the lower temperature range is already realised
Some MVR potential is already realised especially in the food sector. We assume that 25% of the heat demand under 250 °C in food industry is already realised, in chemical sectors and refineries the occurrence of MVR is mostly limited to unit operations like reboilers, we assume that the installed capacity is approximately 10% of the potential. Therefore, we applied a factor of 75% to the potential of the food sector and 90% to all four chemical industry sectors and refineries.

Limitation 5: Turn around planning
MVR can only be integrated with the processes/steam system during a major stop also called a turn around. When looking at the different industrial sectors we see that the sectors: Steamcrackers, Industrial gasses, N-Fertilizer and Refineries only have very few stops, typically 1 in 5 or 6 years.
For the Wider chemical industry the picture is less clear, part of the companies also only have a turn around 1 in 5 years, some 1 in 4 years and some more often.
The Steel industry stops only 1 in 10 years the blast furnaces, but all other processes are stopped for maintenance on a regular basis.
In food and per stops for maintenance, hygienic and /or commercial reasons are common and therefore not a limiting factor.
Based on the above we assume that the potential for the food, steel, and paper and board sectors is not affected by the planning of maintenance stops.
The potential of the Wider chemical industry reduces with 20% and the potential of the steam crackers, industrial gasses, N-fertiliser and refineries is halved by the turn around planning

Limitation 6: limitations in use of heat from a CHP
The application of MVR reduces the amount of heat that has to be produced by the fossil fired utilities. However, if this utility used CHP production, it also decreases the amount of heat through the turbine and thus reduces the amount of electricity and the income related to electricity production. Currently this is not very cost-effective. Therefore, we assume that on a sector level the heat produced by CHP production cannot be provided by heat pumps. If after 2030 renewable electricity becomes more abundant the position of CHP production may be reconsidered. At that moment the heat supply to the plant has to be redesigned probably increasing the potential for heat pumps.
To estimate the part of the heat under 250 °C that is not supplied by CHP we used the data in *Table 1-1* on heat per temperature in chapter 1.

We assumed that the CHP only produces heat up to 500 degrees.
We calculated the part of the CHP that provided heat at temperatures below 250 °C:

$$Q_{CHP<250} = Q_{CHP} * Q_{<250}/Q_{<500}$$

$Q_{CHP<250}$ is the amount of heat provided by CHP below 250 °C,
$Q_{<250}$ is the demand for heat below 250 °C, and
$Q_{<500}$ is the demand for heat below 500 °C.

The limitation factor for the CHP (L_{CHP}) is calculated according:

$$L_{CHP} = (Q_{<250} - Q_{CHP<250}) / Q_{<250}$$

This results in the following factors per industry:

Industrial gasses	58%
Steam crackers industry	58%
Ammonia and N-fertiliser	58%

Wider chemical industry	58%
Steel	71%
Refineries	81%
Food industry	80%
Paper Industry	57%

Limitation 7: Total cost of installation can vary widely (probability of costs)
As mentioned in task 1 the CAPEX of the heat pump as such normally average between 100 and 600 €/kW, depending on temperature lift, process integration, scale of operation. Especially the temperature lift has a large impact.
Therefore, we assume that CAPEX costs range between 100-900 €/kW with the average around 300 €/kW for 5 MW heat pumps, about 40% between 300 and 600 €/kW and 10% more than 600 €/kW.

Resulting in the following division:

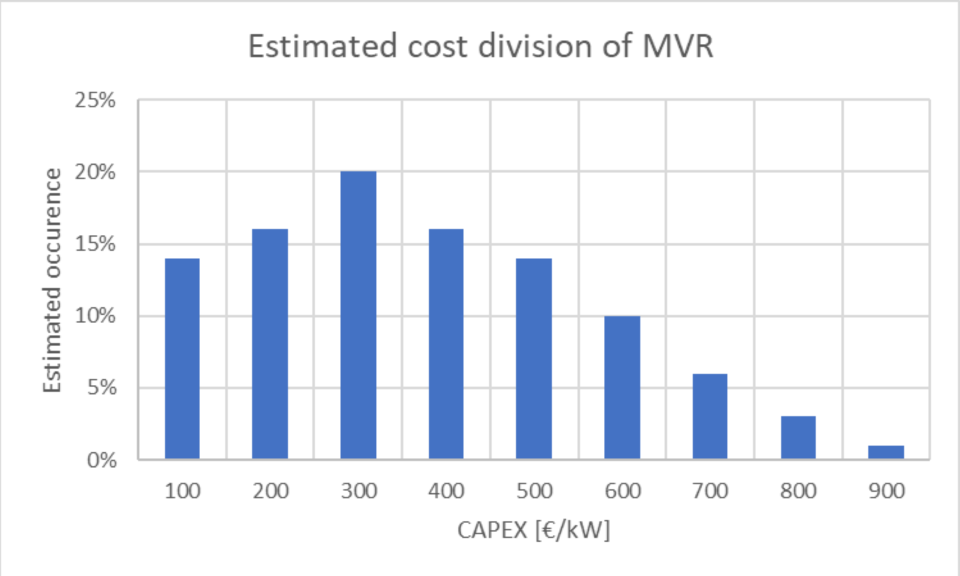

Figure 4-5: Estimated cost division of MVR (expert judgement based on data suppliers)

In addition to CAPEX cost come the cost of installation. In task 1 we assumed a COP of 7,5, CAPEX = 300 €/kW and added 100% CAPEX costs for installation yielding a total cost of installed capacity of 600 €/kW.
We only consider the heat demand between 100 and 250^{oC}

However, costs of installation vary widely between sectors. Costs of installation are high in Chemical industries and refineries, especially if process integration is the case and much lower in paper and food sectors.
Therefore, we suggest to differentiate the installation cost to 3*CAPEX in chemical industry and refinery (total cost of installation = 4*CAPEX) for MVR requiring process integration and 1* CAPEX for projects that can be integrated with utilities (total cost of installation 2*CAPEX) and 0.5*CAPEX in food and paper sector (total cost of installation = 1.5*CAPEX). We assume that 50% of the cases require process integration (expert judgement).

Payback period is a function of saving by the heat pump (expressed in COP), CAPEX, installation costs and production hours per year.

Below we made an overview of different combinations that have a payback period of 5 years to give a feeling of the sensitivity of the payback period to any of these variables.

Table 4-10: Overview of different combinations that have a payback period of 5 years

COP	CAPEX [€/kW]	installation costs	production hours [hours/year]
7,5	250	3* CAPEX	8760
7,5	500	1* CAPEX	8760
7,5	600	0.5* CAPEX	8000
7,5	550	0.5* CAPEX	7000
9	250	3* CAPEX	8760
9	550	1* CAPEX	8760
9	650	0.5* CAPEX	8000
9	550	0.5* CAPEX	7000

When assuming **COP of 7,5** and taking the above into account this has the following effect on the feasible economic potential per sector:
For chemical industries, refineries and steel applies:

- Half of the potential has installation costs of 3*CAPEX, implying that of this potential approximately 40% is economically feasible;
- Half of the potential has installation costs of 1*CAPEX, implying that of this potential approximately 80% is economically feasible;
- Overall 60% feasible economic potential.

For food and paper sectors with 8000 production hours and installation costs of 0.5*CAPEX, 90% of the potential is economically feasible
For food sector with 7000 production hours and installation costs of 0.5*CAPEX, 85% of the potential is economically feasible. Overall in the food sector 85-90% ~88% of the saving potential is economically feasible.

Conclusions
In task 1 we assumed that 25% of the heat demand was technical feasible to be replaced by MVR. In addition, we assumed that 75% of the technical potential was cost effective.
In Task 2 we looked in more detail and we came with 6 more or less technical limitations and 1 purely economical limitation. Resulting in the following factors per industry sector.

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Table 4-11: Estimate of feasible percentages of heat demand below 250ºC that can be provided by heat pumps (Technical) and the factor correcting the feasible technical potential to become a feasible economical potential (economical)

	Technical*	Economical**
Industrial gasses	26%	60%
Steam crackers industry	20%	60%
Ammonia and N-fertiliser	26%	60%
Wider chemical industry	25%	60%
Steel	71%	60%
Refineries	55%	60%
Food industry	18%	88%
Paper Industry	17%	90%

**In task 1 we assumed 25% for all sectors*
*** In task 1 we assumed 75% for all sectors*

When using the technical feasible % to calculate the CO_2 reduction potential as described in task 1 this yields the feasible technical reduction potential as listed in 4.4.7. When applying the economical % from table 4-12 to the feasible technical reduction potential this yields the economical feasible CO_2 reduction potential. The difference between the numbers in table 4-12 and the assumptions made in task 1 explain the difference between theoretical and the feasible numbers in paragraph 4.4.7.

The explanation for the much higher potential for the sectors; food, Wider chemical industry and paper is similar to the explanation for heat pumps. The difference in potentials between MVR and heat pumps is due to the higher savings that are feasible with an MVR than with a heat pump due to the significantly higher COP and the lower cost of the equipment.
Furthermore, the heat demand below 100ºC is not likely to be yielded by an MVR. This reduces the potential compared to a heat pump.

4.4.6 Sensitivity analysis

We performed sensitivity analysis on certain crucial parameters which are expected to influence the outcomes and can be stimulated by policy measures.

Therefore, we analyzed the effect on feasible economic CO_2 saving potential when:

1 A payback period of 10 years or less

When increasing the definition of economically feasible to a payback period of 10 year, the feasible economical reduction potential increases with 28% from 428 kton CO_2 per year to 549 kton per year. This increase is caused by the following effects:

At continuous production at >8700 hours per year:

- The payback period of measures with a total cost of implementation of 4*CAPEX become economical feasible for CAPEX of 500 €/kW and less (80% of the potential)
- For all other situations the total range of CAPEX as depicted in figure 4-5, becomes economically feasible

How this works out is summarized in table 4-13 in paragraph 4.4.7.

2 A **WACC of 4%** is used to:

- analyze the future cash flow instead of 8% and,
- calculate savings for technologies with payback period of 5 years or less;

The decrease of a WACC of 8% to a WACC of 4% increases the feasible economical potential with 7% from 428 kton CO_2 per year to 459 kton per year. This increase is caused by the effect it has on the parameters of the calculation of limitation 7 described in the previous paragraph. This limitation evaluates the effect of the range in CAPEX. The decrease in CAPEX allows for an increase of the economical feasible CAPEX with ca 50 €/kW. Except for the installation cost of 3*CAPEX there the maximal CAPEX remains the same.

Therefore, the factor of the feasible economical potential as calculated under limitation 7 increases from WACC =8% to WACC is 4%, see table 4-9.

Table 4-12: Estimate of the factor correcting the feasible technical potential to become a feasible economical potential at respectively 8% and 4% WACC

	8% WACC	4% WACC
Chemical industry (4 sectors)	60%	63%
Steel	60%	63%
Refineries	60%	63%
Food industry	88%	96%
Paper Industry	90%	98%

4.4.7 Overview of all CO_2 reduction potentials

Table 4-13: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	0	0	0	0	0	0
	Steam crackers	31	23	24	15	22	15
	N-Fertilizer	4	3	4	2	4	2
	Wider chemical industry	210	158	212	127	190	132
Refineries		18	13	38	23	35	24
Iron and Steel		6	5	13	8	12	8
Food		263	197	189	165	189	181
Paper and Board		145	108	98	88	98	96
Total		677	507	578	428	550	458

4.5 Heat transformer

4.5.1 Working principle of energy saving by application of heat transformer

The heat transformer is an absorption heat pump that uses a fully reversible chemical reaction with phosphoric acid (PA) to capture waste heat energy to transform it into process heat. Its main components are two reactors which are interconnected through a closed loop containing a phosphoric acid and water mix. On the cold side (in black), this phosphoric acid is exposed indirectly to the waste heat. The ensuing endothermic reaction causes the PA to oligomerize (from monomer to dimer) and to de-hydrate.
In the hot reactor (in red), the re-hydration of the PA forces it to return to its monomer state, which causes an exothermic reaction at high temperatures. The generated heat is used to produce process heat which can be steam or other forms of process heat such as thermal oil, water or heating up product streams. The PA-water mix is transferred back to the cold reactor and the cycle repeats.

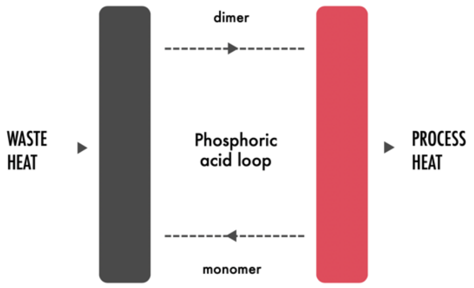


Figure 4-6: General principle of the heat transformer

The general performance of the high-temperature version of the heat transformer returns approx. 50% of the input (i.e. the waste heat now discharged to the environment) as valuable process heat. The other half is cooled away. This means that the heat transformer generates the equivalent amount of its output duty in savings on cooling utilities (e.g. a unit converting 2 MW waste heat into 1 MW process heat, also saves 1 MW in cooling capacity).

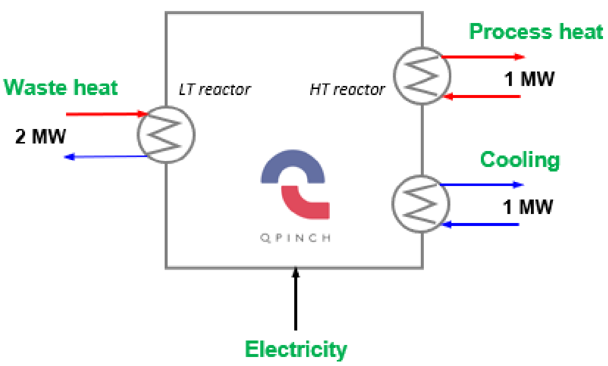


Figure 4-7: Schematic principle of heat transformer

Various types of waste heat can be used as input, i.e., organic vapors (column overheads), process effluents (e.g. product rundowns), exothermic reactor cooling, excess steam, condensate, vapors (e.g. in the food and paper industry) and liquids (waste water streams, geothermal water, cooling loops).

The heat transformer can deal with fluctuations in duty and temperature in the supply of waste heat. This means that a unit, without modifications can be used in processes that have varying conditions. The turndown ratio is 10, which means that a unit designed for an output of e.g. 10 MW can be operated at as low as 1 MW.

The process is thermally driven – i.e. it does not require mechanical compression – and therefore only requires a marginal input of electrical energy, typically 3-4% on thermal output duty.

The operating window of the high temperature version of the heat transformers is indicated in Figure 4-8, with on the x-axis the temperature of the available waste heat and on the y-axis the output temperature of the process heat. The temperature lifts that can be established depends on the state and temperature level of the available waste heat source (for example: with a waste heat source of 130°C, process heat at 200°C can be generated quite easily, as is represented by point 2 in the figure). The limitations set to the current generation of heat transformers is that the waste heat temperature should be >80°C, while on the hot output side the temperature is limited to 230°C (due to material constraints).

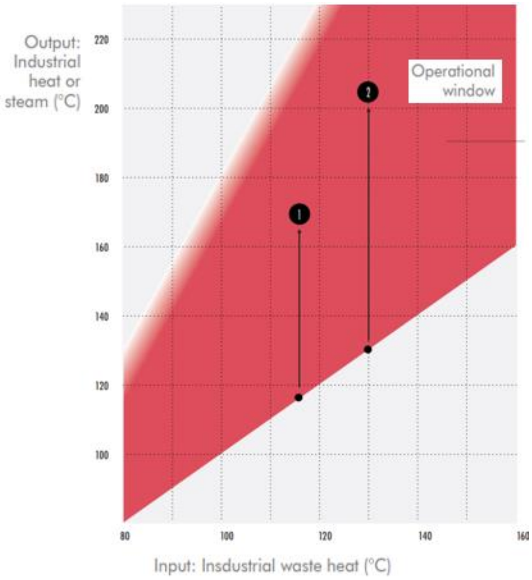


Figure 4-8: Operating window heat transformer

The main parameters determining the magnitude of the energy savings potential for the heat transformer technology are the available waste heat sources (capacity, temperature level). The working principle of the technology is independent of the industrial sector.

4.5.2 TRL level of heat transformers

The currently TRL level of the heat transformer is 7. This will however become TRL 8 as soon as the Qpinch 'flag ship' plant for Borealis (Antwerp) will come onstream. This installation, with a capacity of 1.5 MW (thermal output), is currently in the EPC stage and is expected to be put into operation during the year 2020. Other relevant references for the technology are:

- Kuraray, Antwerp (1.5 MW installation, in EPC phase);
- Recently it was decided to build for SABIC a 2 MW (heat output) pilot installation at the premises of Qpinch in the harbor of Antwerp (currently in EPC stage). If experiments with the pilot installation have a positive outcome, an order for a much larger installation is expected for one of SABIC's production facilities in Saudi Arabia.

For Project 6-25 the focus will be on a heat transformer that uses waste heat of moderate temperatures (> 80°C). Qpinch is also developing another type of heat transformer that can utilize low temperature waste heat of a lower temperature (< 90°C), but this development is at a TRL level (about 5-6) which is not suited for Project 6-25.

4.5.3 Conditions to allow for successful application of heat transformers

For a proper implementation of heat transformers (and heat pumps in general), it is recommended to make a site wide inventory of all the potential waste heat sources with the focus on extracting waste heat from process plants at a temperature level as high as possible. A total site heat pinch analysis is preferred, because this gives a good overview of where the most interesting waste heat sources are located. At the same time also relevant information on potential heat sinks are made available, which makes the targeting of suitable matches easier.

The location of the waste heat sources and targeted heat sinks within a process plant (and/or site) are not only important with respect to the determination of the heat savings potential and the sizing of the heat transformer, but also with respect to the complexity and cost of the connecting piping

A heat transformer, consisting of several heat exchangers and pumps, may be regarded as a (small) chemical plant on its own and therefore the plot space availability is of importance, especially for brown field scenarios. Due to its vertical design, the plot space is limited, typically from 6 x 6 to 9 x 9 meters, for duties from 1 to 10 MW.)

The heat transformer technology has a very good scalability which makes that the heat transformers can be applied also for large scale processes (1 – 100 MW). From an economical point of view, larger scale installations are preferred because of economy of scale. Larger implementations also allow to integrate smaller waste heat streams which, because of their limited potential or too low temperature, could otherwise not have been exploited.

An on-stream time of 8300 hours per year is expected to be feasible. The technology is very flexible with respect to fluctuating availability of waste heat sources which makes operation possible even at very large turn down ratios.

The heat transformer makes use of a strong, but food grade, acid, which is of importance with respect to certain material and safety issues. The heat transformers can be built to ATEX standards.

4.5.4 Costs and benefits of heat transformers

CAPEX and OPEX costs

The CAPEX cost of a small to medium sized heat transformer lies in the range of 1 – 1.5 M€/MW. The installation cost may vary widely, depending on the local situation. Preliminary installation cost will be estimated by PDC.

The OPEX cost here is only based on utility cost, which means that maintenance and labor cost are not taken into account. The heat transformer is driven by waste heat which is assumed to be available for free. The OPEX cost is therefore limited to the electricity consumption for the heat transformer and for cooling. The electricity consumption of the heat transformer is 3-4% (of the output heat). The cooling duty can be converted to electricity consumption (for fans and pumps) for which Table 4-14 might be used [H5.1].

Table 4-14:Global comparison of energy use of several cooling systems (H5.1)

Koelsysteem (fans en pompen)	Energie verbruik kW/MW$_{th}$		
	Pompen	Ventilatoren	Totaal
Doorstroomkoeling met (oppervlakte)water	26		26
Koeling met koeltoren (fans en waterpomp)	20	14	34
Luchtkoeler direct (product door luchtkoeler)		26	26
Luchtkoeler indirect (met tussenmedium)	16	26	42

The waste heat source taken from the process normally needs to be cooled within the process by cooling water or air cooling. Because the heat transformer takes over (a part of) the cooling duty, this will lead to a saving on electricity (for the waste heat cooling).

The heat transformer generates process heat (normally steam) at higher temperature levels. It is assumed that this will lead to a saving on fuel, because less steam has to be generated with the on-site steam generation system.

4.5.5 Feasible saving potential

Starting point in determining the feasible saving potential was updating the Task 1 theoretical and economical heat savings potential of the technology, based on additional information that came available during the execution of task 2.

Following adjustments in the theoretical savings potential for the technology were implemented:

- The theoretical potential of the Refinery sector is increased to 408 kta CO_2 in the bottom-up approach. This amount is equivalent with a savings potential of 35 MW / 200 kbpd according the top-down approach that is used more frequent in the refinery world and by clients;
- I theoretical potential of the Food industry is reduced substantially (to 73 kta CO_2), while also the Wider chemical industry has been reduced a little (to 241 kta CO_2).

With respect to the energy savings potential by applying the heat transformer technology, the following limitations were found to be applicable:

Limitation 1: Piping cost
Piping cost (for connecting the waste heat source(s) with the installation and for connecting the generated process heat with the envisaged heat sink) were not included in the Task 1 CAPEX cost. However, if they will be included, a part of the installations in the lower capacity region (i.e. part of the 2 MW installations) will become not economic anymore, because the resulting payback time will become larger than the threshold value of 5 years. Here it is assumed that 50% of the 2 MW installation will become not feasible when piping cost is included.

Limitation 2: Plot space requirements
The heat transformer needs a plot space of 6x6 to 9x9m depending on the output capacity of the plant (for 1 to 10 MW capacity). For certain industrial plants and/or sites, this plot space requirement might be problematic, especially for compactly build plants for instance on certain refinery and steamcracker sites. Following reductions on the theoretical potential are introduced to account for this limiting factor (expert judgement):

- 25% reduction for the Steamcracker, Refinery and N-fertilizer sector;
- 10% reduction for the Wider chemical industry and for the Food sector.

Limitation 3: Validation interviews of end-users.
As part of Task 2, various people from the assessed industrial sectors were interviewed to validate the used method, assumptions and potential limitations of the proposed technologies within their own plant and/or sector. Based on the information retrieved from these interviews (e.g. more detailed feedback on the assumed temperature range dependent heat demand as presented in Table 1-4 of §1.3), following reductions on the remaining theoretical (and economical) potential are introduced for the technology:

- 100% reduction for the N-fertilizer sector;
- 50% reduction for the Refinery and Food sector;
- 33% reduction for the Steamcrackers;
- 10% reduction for the Wider chemical industry.

Limitation 4: Turnaround planning
Steamcrackers, Industrial gasses, N-Fertilizer and Refineries have very few stops, typically 1 in 5 to 6 years. For the Wider chemical industry, the picture is less clear, part of the companies also have a planned turnaround (TAR) once per 5 years, some once per 4 years and some more often. The Steel industry stops only 1 in 10 years the blast furnaces, but all other processes are stopped for maintenance on a regular basis. In Food and Paper stops for (preventive) maintenance, hygienic and/or commercial reasons are more common and therefore not directly a limiting factor for the technology implementation.

Based on the above, following reductions on the theoretical (and economical) potential are introduced:

- 50% reduction for the Steamcracker, N-fertilizer, Industrial gasses and Refinery sector;
- 20% reduction for the Remaining chemical sector;
- No reduction for the other sectors (Steel, Food, Paper & Board).

Conclusions
From Table 4-15 in §4.5.7 it can be concluded that from the theoretical savings potential for the 8 assessed industrial sectors (**846 kta** CO_2 in total), about **207 kta** CO_2 feasible savings potential remains after implementing above mentioned limiting factors for the various sectors (and **136 kta** CO_2 economic feasible potential).
The majority of this reduction in potential can be attributed to the limitations due to TAR planning, plot space limitations and the interview results for especially the Steamcracker and Refinery sector.

4.5.6 Sensitivity analysis

We performed sensitivity analysis on certain crucial parameters which are expected to influence the outcomes and can be stimulated by policy measures.

Therefore, we analyzed the effect on feasible economic CO_2 saving potential when:

1. A **payback period of 10 years or less** is considered financially attractive;
2. A **WACC of 4%** is used to:

- analyze the future cash flow instead of 8% and,
- calculate savings for technologies with payback period of 5 years or less;

The results of this sensitivity analysis are presented in Table 4-15, in the last two columns. For most sectors, the potential for the two sensitivity analysis leads to the same result as for the feasible technical potential. Compared to the feasible economical potential, the potential for both sensitivities has increased because of the relaxation on the constraints of payback time respectively WACC percentage.

4.5.7 Overview of all CO_2 reduction potentials

Table 4-15: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses						
	Steam crackers	113	113	29	29	29	29
	N-Fertilizer	11	11				
	Wider chemical industry	241	197	130	86	86	86
Refineries		408	408	76	76	76	76
Iron and Steel							
Food		73	51	27	16	16	16
Paper and Board							
Total		846	780	262	207	207	207

4.6 Heat storage

4.6.1 Working principle and energy saving by application of heat storage

Thermal storage (heat storage, thermal battery, thermal accumulator) allows heat integration of processes where the heating and cooling doesn't occur at the same time. This may be the case for intermittent, fluctuating or cyclic batch processes. Thermal storage is designed to be capable of responsive heat acceptance/discharge depending on the current availability of the excess heat or the immediate heat demand.
There are three types of the thermal storage technologies, depending on which principle of the energy is utilized [H41]:

- Latent heat of phase change (PCM);
- Heat of reversible reaction;
- Sensible heat (temperature shift).

Thermal storage utilizing latent heat (PCM materials) of change are able to operate close to isothermal conditions at a designed temperature, which corresponds to phase shift of the selected heat-storing material. PCM heat storage materials include organic compounds (e.g. fatty acids), inorganic compounds (e.g. salt hydrates) and eutectic mixtures. Sensible heat storage can be done by liquid materials (water for low temperature applications, molten salts for high temperature application), or solid materials as e.g. concrete. A special kind of storage is steam accumulators in grid to stabilize the disturbances in the steam grid and saturate occasional peak steam demands. These are hot water tanks for generating flash steam when needed by pressure reduction in tank.

Energy savings potential achievable by various heat storage technologies is governed by occurrence of the batch/cyclic/fluctuating/internment processes, that may exhibit fluctuations in immediate heat balances of plants. In that case, thermal storage may be needed to integrate the heat of such operations. Most large-scale operations in major industrial sectors (with notable exception of the steel industry) is however continuous and operating in (queasy) steady state. This eliminates the fluctuating/intermittent operation in the first place to achieve better operation efficiency. In case that operation is batch/fluctuating, best way how to improve the energy efficiency is to make the operation continuous if possible. For minor fluctuating processes with the excess heat used for steam production, steam grid may be supported by e.g. large steam boiler and a thermal storage is not needed. This is a likely case of larger well integrated industrial sites. Addition of thermal storage remains as a solution if other options are not technically feasible or economic.

4.6.2 TRL level of the heat storage

Heat storage is a mature, well established TRL 9 technology with numerous low and large-scale applications in industrial heat recovery, power generation sector and district and building heating [H42]. Novel heat storage materials and technologies are in development.

4.6.3 Conditions to allow for successful application of heat storage

- Operations where heat storage may be advantageous for:
  - Batch / Fluctuating processes;
  - Processes with large intermittent heat supply or demand.

- Infrastructure & additional equipment is needed to deliver heat between heat source and heat sink. Heat transfer fluid cycle is needed for the heat transfer.
  - For solid thermal storage technologies, secondary heat transfer fluid cycle is needed, with additional heat exchangers to recover waste heat and deliver it to other process sink;
  - Thermal storage can be integrated with steam grid with steam/boiler feed water used directly without additional heat transfer fluid needed in some applications;
  - For liquid thermal storage technologies (e.g. water or molten salts as capacity medium) the storage media can be directly the heat transfer fluid.

- Following industrial sectors were identified for potential heat storage application:
  - Steel industry – major cyclic batch operations which are heat intensive;
  - Paper, chemical and food industry – hot standby back-up boilers for emergency steam generation.

4.6.3.1 Steel industry

Steel industry in the Netherlands is represented by TATA steel in IJmuiden. Several large operations of steel manufacturing (coke production, blast furnace, BOF) are cyclic batch operations, with large energy duties, therefore heat storage technologies are generally applicable.

Based on the information available in the Midden report [H43], energy consumption of TATA Steel in IJmuiden plant was summarized, recalculated in GJ/t of produced steel and presented in Table 4-16. This information was in Table 4-16 compared to published figures of energy intensity of steel industry [H44] in general. Following the information in [4], the implementation of best practices for steel industry leads to a minimum specific energy consumption of 18-19 GJ/t of steel (net primary fuel for the process, see Table 4-16. This was also confirmed by optimization using rigorous pinch analysis of a steel plant presented in [H42]. Tata Steel plant in IJmuiden is close to this minimum energy consumption interval, Table 4-16.

Energy savings achievable by heat integration that were calculated by pinch analysis in [H42] assumed thermal storage technologies (or other means of heat duty averaging) already implemented in a plant. Appropriate measures to deal with fluctuating heat generation/demand are essential to achieve low energy consumption corresponding to best practice reference of 18-19 GJ/t. Hence, heat integration techniques to overcome fluctuating heat generation/demand are likely already implemented in the TATA steel plant to some extent. An example are the Cowper stove heat regenerators used to preheat air for BOF by hot flue gas outflow [H42].

From the information from TATA steel, it was indicated that there is residual waste heat potential of several streams. The useful heat potential between 600°C and 120°C is about 1.4 GJ per ton of produced steel (~10 PJ/a) [H45]. This residual heat is present in the solid or gaseous streams of the main steel making operations. This heat can be recovered in the steam which can be distributed via the plant grid. As expressed, the company was actively looking in the heat storage technologies to recover and utilize this heat. The recovery of this waste heat is challenging due to:

- Corrosive/fouling gasses requiring special heat exchangers or solid streams requiring additional operations of dry heat quench.
- Large intermittent waste heat peaks requiring thermal storage to smoothen the heat recovery
- Potential problems with integration due to space/connectivity restrictions of the on-site equipment

Table 4-16: Comparison of the TATA steel energy consumption (expressed as GJ/T of steel produced) with a typical not-integrated steel plant [H42].

	TATA Steel	Steel industry in general
Coal, GJ/t	17.8	22.2
Fuel gas, GJ/t	5.0	4.0
Electric energy, GJj/t *(as primary fuel gas)	1.3 (3.9)	2.2 (6.6)
Fuel gas to power, GJ/t	-7.5	-9.2
NET PRIMARY FUEL	**19.2**	**23.6**

** expressed as primary fuel using conversion factor of fuel to power equal to 0.33 as in [H42]*

4.6.3.2 Other industry sectors

Thermal batteries in other industries for integration of cyclic batch or fluctuating processes may be applicable for specific on-site circumstances, which cannot be evaluated on a general basis. These applications are however expected to be minor, since the with the exception of the Steelmaking, the other major processes are mainly continuous.

Processes in production of industrial gases and fertilizers are generally continuous and large part of the heating is supplied from process heat. Refineries have generally steam grid build around central CHP unit and further supplying of steam from secondary fired process heating sources with all processes continuous. These sectors have very limited application potential for heat storage.

Steam in paper, food and Steam crackers + chemicals clusters can be generated by on-purpose fired boilers or waste process heat recovery boilers. Steam system may benefit from additional optimization by heat storage if fluctuations of the steam grid are frequent and are problematic to be corrected for by boilers in a responsive way. This can be assessed only by further detailed research taking specific parameters of individual plants into account. The boilers have to be supported by sufficient reserve capacity of steam generation as back-up. This steam generation back-up capacity needs to be readily available immediately in case of trips of a process heat steam generator or a boiler.

In larger sites, this can be achieved by integrated grid containing several boilers (or HRSGs of CHP), which operate well below rated capacity and can be ramped to maximum steam production in case one of the parallel steam source's trips or one of the supplied processes needs large steam loads during non-standard situations.

Other approach relies on back-up boilers, which need to be continuously heated for hot-standby to be able to generate steam immediately when needed. Hot-standby mode is coupled with parasitic fuel consumption to keep the boiler heated. Alternative to this approach is using a permanently charged thermal storage, which has expected lower thermal losses. The thermal storage would provide steam generation for 2 - 3h, during which a back-up boiler can be heated-up from a cold-standby. Cold stand-by has no parasitic consumption of fuel. This measure can bring potential saving of energy, if the heat-loss of the charged thermal heat storage is less than fuel consumption of hot-standby boilers.

Based on the available information, parasitic load of hot-standby boilers can be up to 5% [H46] of rated power output. This in good correspondence with estimated heat losses from operating boilers, which is 1 to 4% of the consumed heat or 1 to 5% of the heat of the generated steam during normal operation [H47, H48]. 4% is further assumed as the parasitic load fraction of the fuel consumption for rated fired duty of boilers, which is consumed to keep boiler in a hot-standby backup state.

Based on information from technology provider, loss fraction of a charged thermal heat storage is 1-3% of the charged energy amount [H49] per day. 2% thermal energy loss per day is taken in further considerations, which yields 0.1% loss of charged thermal energy per hour.

It is assumed that battery capacity needs to suffice for 3h of steam generation, before cold standby-backup boiler can be ramped up to production of steam. By comparing the numbers, the estimated heat loss for existing hot-backup boilers is 4% of their nominal capacity, while the thermal loss of a charged battery as a replacement of hot-standby backup boilers is 0.3% of the backup boiler capacity.

To estimate the savings potential, 10% of the heat consumption of the Paper, Food and 5% of steam crackers (with coupled chemical clusters) is further assumed as being available to be immediately replaced by hot-backup steam boilers. It is also estimated, that highly superheated or larger pressure steam (e.g. from CHP) is available in the facility to charge the battery at higher temperature as compared to saturation temperature of the steam which needs to be generated in case back-up capacity needs to be activated.

4.6.4 Costs and benefits of heat storage

Since various materials are used, and a range of specific applications, there is an interval of the waste heat capture efficiency of 50-90% for sensible heat and 75-90% for PCM reported in public domain information (PCM) [H41]. There is a wide range of CAPEX of the technology for a multitude of reasons.

- Range of complexity of the thermal storage technologies using different techniques and different heat storage materials;
- For sensible heat storage (e.g. concrete blocks), the size of the battery depends on the temperature operation window depending on the temperature of the heat supplying stream and the heat discharge stream. The size of the battery is proportional to $1/\Delta T_{TS}$, where ΔT_{TS} is the temperature operating window of the battery. Increasing ΔT_{TS} decreases the temperature, at which the captured heat can be re-used;
  - Example: Sensible heat storage with temperature operation range (temperature difference between charged and discharged state) of 50°C will need to have double the size as compared to temperature operation range of 100°C for the same ammount of energy captured in both cases.
- Storage capacity needed for certain throughput depending on time duration of a charging – discharging cycle. The longer the cycle time, the larger the battery size needed for the same energy throughput;
  - Example: Thermal storage for 1h charging (1 MW) and 2h discharge (0.5MW) needs capacity 1MWh. Thermal storage for 2h charging (1 MW) and 4h discharge (0.5MW) needs capacity 2MWh. The heat throughput (energy saving/time) is in both cases the same (0.5 MW);
  - Assuming energy savings in form of additional on-site steam (12 EUR/t of steam) and negligible maintenance, minimum of 50 charge-recharge cycles are needed for each 1 EUR/kWh of CAPEX for thermal storage.

The CAPEX starts at (from) 20 EUR per kWh of stored energy, for the whole project it is (from) 30 EUR/kWh bases on the information from one of the heat storage technology providers. This economic figure is applicable for the presented economy figures [H49]:

- Maximum temperature of the heat transfer fluid: 393°C;
- Temperature of heat transfer fluid from the thermal storage of 260°C;
- 8h charging and 8h discharging time in one cycle.

A document mapping introduction of the heat storage technology [H42] presents several existing (large scale applied) and developed examples of the heat storage techniques. Water tank storage technologies, Cowper stove regenerators in the steel sectors and glass furnace regenerators are known and well-established applications.

Several guideline examples of industrial and power applications of heat storage were selected in the document [B] for additional indicative CAPEX estimation for heat storage in general.

▪ Steel plant Cowper stove regenerator (solid - sensible heat storage).	
▪ Direct heat exchange (BOF flue gas -> heat storage -> fresh air to BOF):	15 - 40 EUR/kWh
▪ Hot standby backup boiler replacement, PCM storage material:	85 EUR/kWh
▪ Water and oil tanks:	15 - 53 EUR/kWh
▪ Steam accumulators:	70 - 300 EUR/kWh
▪ Molten salt as heat transfer fluid & storage material for solar powerplants with steam cycle power generation:	20 EUR/kWh

The economic benefits of thermal storage are in the form of fuel savings and avoided penalties for CO_2 emissions, that wouldn't be possible if thermal storage wouldn't be used to enable heat integration.

For utilization of the steam storage as a back-up heating capacity, parasitic consumption of boilers kept in hot-standby is reduced (thermal storage has also minor energy losses). In case of installation of the thermal storage to cover occasional peak demands of heat, the size for the marginal heating utility source (boiler) can be decreased to suffice for steady average steam demand.

4.6.5 Feasible saving potential

4.6.5.1 Steel Industry – Technical Potential

Theoretical technical potential of waste heat recovery in the steel industry was obtained using in the phase 1 report following assumptions:

- 50% of this heat is in streams, where heat capture is technically feasible (PDC assumption)
- 40% of the waste heat can be captured to a thermal storage (corresponding temperature interval of utilized waste heat between 600 and 400°C, PDC assumption)
- Therefore 2 PJ/a of heat are estimated as potential for waste heat savings
- Fuel gas consumption in boilers reduced by 2.2 PJ/a (90% efficiency of on-purpose boilers assumed by PDC)
- Saved fuel gas used in on-site GTCC for power production with assumed efficiency of 40%, i.e. saving ~0.9 PJ/a of electric power

This potential was further refined to feasible technical potential based on additional more specific information about utilization of this waste heat on site in Steel Industry. Steam is generated mainly in central heat and power unit from the fuel gases produced on-site with only a minor on-purpose NG fired boilers without power production. There is only very limited additional fuel (NG) fired for steam generation that can be replaced by waste heat of the processes. Majority of the recovered waste heat can be theoretically transformed in additional power generation, e.g. by using condensation turbine or ORC. This is certainly not economical due to large additional CAPEX of the power generation equipment for minimum power gain (for example, heat to power conversion factor for LP steam is only ~10%). Therefore, while there is a large waste heat available to be recovered, there is almost no practical sink for it presenting energy savings.
Future project creating sink for low potential heat are expected, presenting additional potential for heat storage in the future. These projects will not be realized before 2025.

- Therefore, theoretical potential of 2PJ/a of waste heat recovered from Phase 1 report is reduced to 0.25 PJ/a replacing the steam produced by NG;
- The saving is now evaluated as saved fuel (NG) not as additional power generation in theoretical potential.

4.6.5.2 Steel Industry – Economic Potential

In Phase 1 report, following assumptions were taken into account in the evaluation of the CAPEX and energy savings of the heat storage project in the industry.

- 24h length of thermal storage charge /discharge cycle;
- 260°C operation temperature window 9charged-discharged temperature);
- Final CAPEX of 50 to 100EUR/kWh of storage, depending on the additional costs related to integration of the heat storage of 0 to 100% of the energy storage costs;
- Saving of GTCC power generated by saved fuel gas;
- Leading to payback period of 5 to 13 years.

These numbers of the theoretical potential were corrected based on additional information from TATA Steel:

- 84h thermal storage charge /discharge cycle for the considered waste heat source due to the location (24h is applicable to other waste heat sources in other parts of the company);
- Final CAPEX approximately 3 times CAPEX for thermal storage only;
- 10 to 15 years payback period.

4.6.5.3 Other Industries – Technical and Economic Potential

For other industries, the potential estimate in the Phase 1 report (Task 1) is kept without further changes. The estimate is based on estimation of the potential of hot backup boilers replacement as a representative for potential savings that can be achieved by any optimizations of steam systems. Following assumptions were taken into account in this estimate. The main difference is that the estimate was extended remaining industries, using the same approach as for Steam crackers

- Rated capacity of the boilers which are as back-up on hot standby accounts for 10% of the total heat consumption in food and paper sectors and 5% in Steam cracker and Remaining industries (PDC estimates). This corresponds to steam generation capacity of ~16 PJ/y;
  - The estimated parasitic energy consumption of the boilers of hot stand-by is 4% of the rated capacity, while the parasitic consumption of the thermal storage to replace the hot-standby mode is 0.3% of the rated capacity.
- CAPEX estimation;
  - Thermal storage to provide steam generation for 3h when needed;
  - Thermal storage operation at temperature 80°C larger than the required steam;
  - CAPEX ESTIMATE 33 EUR/kWh to 66 EUR /kWh, assuming additional factor for estimated of storage to account for other potential site-specific costs of integration of 0 to 100% of thermal storage technology price.
- OPEX estimation: OPEX is estimated as 1% of CAPEX (PDC assumption);
- Following assumptions lead for minimum of 8 years payback period (for 33EUR/kWh CAPEX).

4.6.6 Sensitivity analysis

Main variables that affect the economy potential are expressed in the section 4.6.4 and on the assumptions/known inputs for estimation of the potential of Heat storage technology in 4.6.5. There is a significant variability of the CAPEX depending on several parameters, including:

- Process waste heat temperature;
- Time length of one cycle for fluctuating processes;
- Process waste heat stream state (gas/liquid/solid);
- Additional costs of integration (piping, special HEX);
- Competition with other waste heat sources on site (actual waste heat demand).

The CAPEX, which depends on specific circumstances of each application and site has major impact on each project viability. The feasible technical potential and economic figures presented in this report estimates based on several global assumptions. A detailed research on case to case basis (done internally by companies or via tailored energy audits) is needed to reveal the potential in individual industrial facilities, where economic viability of projects is expected to vary significantly.

4.6.7 Overview of all CO_2 reduction potentials

Table 4-17: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	-	-	-	0	0	0
	Steam crackers	18	0*	*18	0	0	0
	N-Fertilizer	-	-	-	0	0	0
	Wider chemical industry	6	6	*6	0	0	0
Refineries		-	-	-	0	0	0
Iron and Steel		180	180	*18	0	0	0
Food		14	0*	*14	0	0	0
Paper and Board		4	0*	*4	0	0	0
Total		222	186	0	0	0	0

**The estimated technically feasible potential is ~60kta. Additional research of more detailed inside production plants level is needed to asses all relevant parameters to estimate the potential cases, possibly revealing additional specific opportunities of savings.*
The Economical feasible potential is low for under the assumptions of this estimation. The technology CAPEX is strongly influenced by parameters of each application and varies significantly even for cases of similar energy saving. Detailed assessment of individual cases internally by production plants may reveal successful business cases.

5 ICT

5.1 Introduction and overview of results

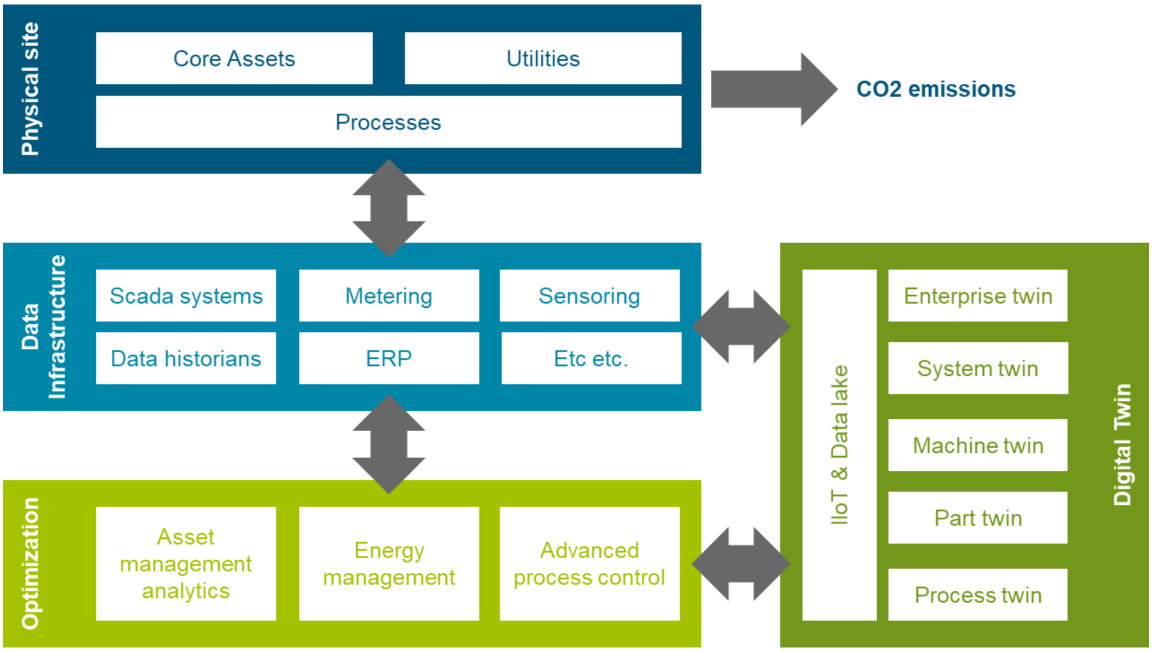
This chapter describes five technologies aiming to optimize energy usage using ICT. These technologies are:

- Data infrastructure;
- Asset Management Analytics;
- Energy Management Analytics;
- Advanced Process Control;
- Digital Twin.

These technologies are related to each other and thus cannot be assessed individually:

- **Data infrastructure** is the starting point and a precondition for all savings and reductions which may be facilitated by ICT. Data infrastructure embraces current data sources within Industries which can be Scada systems, Data historians, ERP systems, installed sensors and (sub)metering, etc. Data infrastructure also includes new to be installed sensors or (sub)meters to collect additional data to enable use cases to work correctly;
- **Asset management analytics** is defined as optimizing assets which are part of processes;
- **Energy management analytics** focusses on all energy flows on industrial sites with the objective to an optimized and balanced generation and use of energy. This also includes equipment performance analysis, so there is some overlap with asset management analytics. Advanced energy management systems are also able to generate energy saving setpoint that can be applied by operations, so there also is overlap with advanced process control systems;
- **Advanced process control** systems are applicable to optimize specific processes related to assets on an industrial site and is defined as closed loop optimization;
- **Digital twin** can be defined on different levels; enterprise twin, system twin, machine twin, process twin (simulations) and part twin. As in the project definition process simulation is mentioned, the scope for project 6-25 is limited to process twinning.

Figure 5-1: The coherence between these five technologies is displayed in below diagram



A short explanation to this diagram: the physical site (ISA 95 level 0) can be divided in three main parts, core assets of the concerning production process, utilities around the core assets and production processes. There are both systems for Operational Technology (OT) and Information Technology (IT) in place which form the current data infrastructure and can be used for future optimization. Typical OT related systems are sensors and actuators (level 1), Scada systems (level 2), Data historians and MES (level 3) and ERP systems (level 4).

Optimization knows three levels:

- Advanced process control is about production processes at the physical site. A combination of core assets and enabling utilities is optimized as a process;
- Energy management analytics is about optimizing enabling utilities like power, gas, heat, etc;
- Asset management analytics is about optimizing core assets like boilers, burners and other equipment.

This section starts with explaining which information is used as a starting point; factsheets from suppliers. After this each technology is analysed in following way:

- Short description of each technology: explaining working principle of the saving potential, TRL level, CAPEX & OPEX estimation of the technology. And, industrial relevant conditions which need to be met before the technology can be applied in a cost-effective manner;
- Technology-Industry matrix with Theoretical Technical and Theoretical Economical Saving potential per technology;
- Indicative description of which factors could probably limit their respective potential and which factors may increase the potential;
- Technology-Industry matrix with Feasible Technical and Feasible Economical Saving potential per technology.

The section concludes with both the theoretical and feasible saving potential matrix.

Important remark: Data infrastructure is not assessed separately as data infrastructure independently cannot provide energy or CO_2 savings. Savings can only be made in optimization processes. Digital twin also is not assessed as only a simulation factsheet is in scope; simulation independently will not lead to CO_2 savings, but can support in finding potential. Digital twin is much more than simulation and included next generation technologies advanced data analytics like machine learning and artificial intelligence. These technologies have potential for additional savings by combining data in other ways that is done before. The other side is that industrial references are limited.

Main results

In the tables below the main results are summarised.

Table 5-1: Overview of technologies, saving principles and main conditions.

Advanced process control	
Technology	Based on data infrastructure, predictive models are used to optimize control actions to achieve a desired higher performance of the (part of) plants and utilities; combinations of assets.
Savings principle	Advanced process control (APC) tools create more synergy between dynamic models of processes, data storage for past performance and predictive analysis algorithms. This leads to optimization of amongst others, energy usage based on costs, recovery of residual heat, fuel savings and emission reduction.
Main conditions and sectors	APC technologies are operational in several energy intensive industries incorporating complex processes like refineries, iron and steel manufacturers, crackers, etc.
Energy management analytics	
Technology	Energy management analytics focusses on all energy flows on industrial sites with the objective to an optimized and balanced generation and use of energy. This also includes equipment performance analysis, so there is some overlap with asset management analytics.
Savings principle	Energy management analytics systems are self-learning systems covering multiple commodities of energy. Analysed are systems from several suppliers. Some systems have a specific focus like steam, other systems include energy trading or balancing aspects. These systems can influence business cases in a positive way by using trading and imbalance functionality. This specific functionality does not add direct value from an energy saving perspective.
Main conditions and sectors	Applicable for all sectors. Savings differ per sector. Starting point is available energy data, process data and weather data. Additionally, submetering will add value.
Asset management analytics	
Technology	Asset management analytics is defined as optimizing assets which are part of processes.
Savings principle	In general asset management analytics are software applications that use and gather information out of all kinds of existing or new sensors which are part of assets. These can get information out of existing SCADA systems, fields devices, system controls and combine it with other sensors at the site or other data sources outside the site like weather data. By analysing historical data and the outcome of these settings, new optimised settings can be calculated and advised often with a better result and potential saving on energy or fuel consumption. An asset by itself can never be more efficient than the original specs of this asset. Savings, that are achieved by better alignment in the process are part of the advanced process control savings.
Main conditions and sectors	Essential to the application of these solutions, is the connectivity of each device that is to be provide data. Most PLCs are connected to a Scada system by conventional cabling and installations like BACnet, Lon or other protocols. If the Scada system is open to send information to the analytics software there is no need to change the existing cabling.

Royal HaskoningDHV

PDC Process Design Center

Table 5-2 Overview of results: main economic parameters.

	Advanced Process Control	Energy management analytics	Asset management analytics
Payback period	<2 years	<2 years	<2 years
TRL	9	9	9
% energy savings	1-3%	0-2%	0-2%

Table 5-3 Overview of results: theoretical saving potential (economical) in kton/y.

Total top 8 industrial sectors		Feasible Economical	Feasible Economical	Feasible Economical
		APC	*EM*	*AM*
Chemical industry	Industrial gasses	26	14	16
	Steam crackers	74	36	39
	N-Fertilizer	49	21	19
	Wider chemical industry	58	25	57
Refineries		65	31	29
Iron and Steel		46	23	17
Food		106	63	62
Paper and Board		23	14	14
Total		**447**	**227**	**253**

5.2 Principles and starting points

In this section, it is described what is used as input (supplier factsheets) and how the assessment has been done including the interpretation of numbers.

5.2.1 Supplier factsheets

Starting point for this project are supplier factsheets. Factsheets which are used are summarized and mapped in the table below.

Table 5-4: Overview of factsheets

Technology	Factsheets
Advanced process control	• Combustion One: Duiker/ Yokogawa Furnace Control & Mechanical Improvements ** • Emerson Utility Area Optimization ** • Emerson Process Unit Energy Optimization (Distillation Column, Reactors, Compressors, etc) / Emerson Furnace & Fired Heater Optimization ** • Emerson Boiler Optimization ** • Emerson Steam Header Optimization **
Energy management analytics	• Emerson Energy Management Information Systems (EMIS) ** • EnerGQ AI Based Energy & Equipment performance Analytics ** • Energy21 Utility Area Optimization
Asset management analytics	• Heat exchangers & Cooling Towers Equipment Performance Optimization • Emerson Equipment performance & optimization ** • Compressed Air Monitoring: 1. Sorama high-resolution acoustic camera 2. RVO compressed air (related to Sorama technology) 3. Emerson Compressed air monitoring

Technology	Factsheets
	• Emerson Steam trap Monitoring ** • Emerson Flare System Monitoring ** • Rotating Equipment Performance Optimization: 1. Factsheet SEMIOTIC LAB rotating equipment analytics 2. Factsheet ABB Ability™ Condition Monitoring for Powertrains

*Factsheets marked with ** were also discussed and further clarified during interviews with suppliers.*
Note to the Energy Management Analytics category: parts of mentioned solutions are also applicable to Asset Management Analytics. To avoid double counting the choice is made in the project to report numbers under energy management analytics.

5.2.2 Assessment and calculation principles

The challenge assessing the ICT part was the incompleteness of numbers, e.g. Capex and Opex numbers which are often confidential and where numbers about additional costs (installation, implementation, additional infrastructure, etc) are not available or very specific per situation. Following approach was used to come to a validation in the best way by comparing numbers from different perspectives. A visualisation of this approach is displayed in below figure.

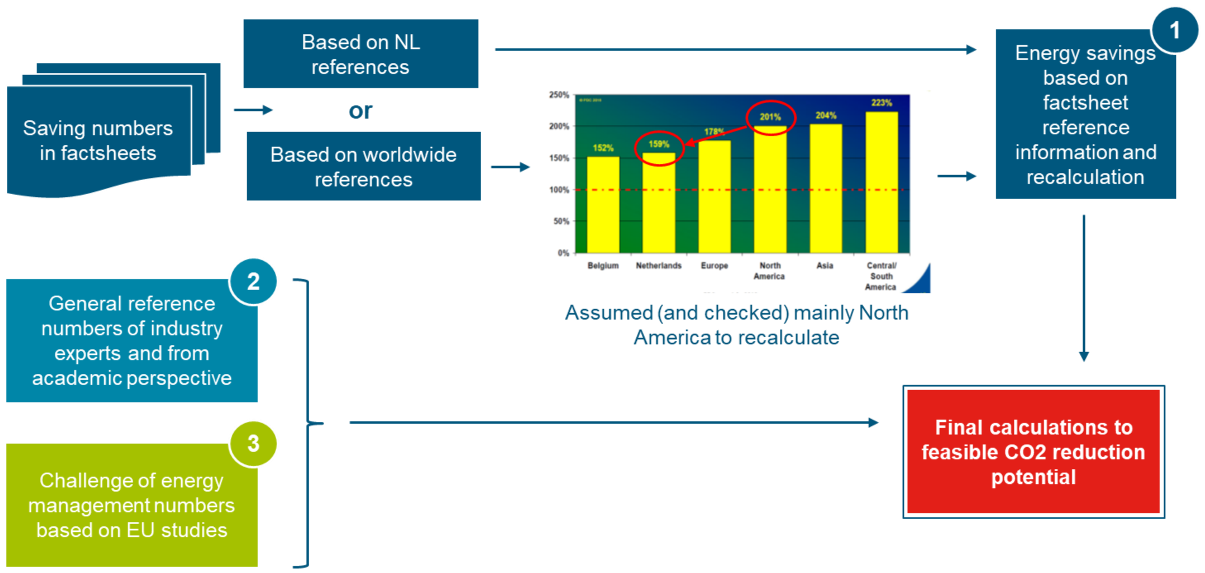


Figure 5-2: ICT assessment approach and calculations

Some reference cases and examples are Netherlands based and/or specific to the 8 industries that are being assessed. These numbers were analysed based on information in factsheets. Several interviews have been conducted and desk research was performed to gain more insight into these numbers to be able to compare numbers from different dimensions.

Interpretation of energy savings from other regions
In some cases, more general numbers were provided in factsheets, or numbers from Dutch reference cases were not available due to confidentiality, or these references in the Netherlands were not in place. In these cases, the numbers provided were noticed by us to be numbers from Northern American cases. For re-calculating North American numbers to the Dutch situation “Energy Benchmarking results - comparison countries & regions” of PDC is used, see also below Figure. This is based on an aggregated survey based on ~50 international energy efficiency benchmark data from PDC, see also https://www.process-design-center.com/energy-benchmarks.html.

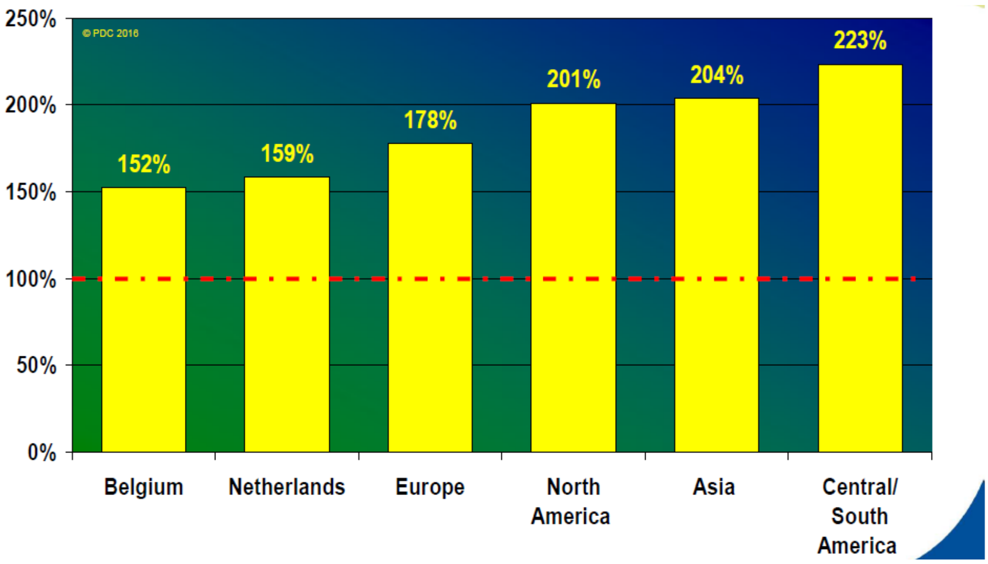


Figure 5-3: Interpretation of energy savings from other regions (I3)

The 100% line represents all the best plants in the world, the mentioned numbers per region tell how much more energy on average per region is currently consumed to produce the same products. This means that North American plants consume (on average) substantially more energy to produce the same products than their counterparts in Netherlands and that the saving potential implementing best practices for that reason is also higher. Knowing this, it is realistic to translate saving numbers from reference cases in North America to the Netherlands with a maximum factor of 50%.

The 50% is calculated according to our expert judgement as following:

- *North America operates on average at 201%, savings of **50.2%** are needed to go to the 100% baseline;*
- *The Netherlands operates on average at 159%, savings of **37.1%** are needed to go to the 100% baseline;*
- *So from a saving perspective The Netherlands is at **73.8%** compared to North America. This number is lowered to 50% because the additional saving will diminish towards the 'tail end of saving potential';*
- *Remark: this may verify from sector to sector.*

Methodology
Different suppliers have provided numbers on energy savings, investments and ROI times. It is hard to assess and validate all these numbers. Therefore, a three-dimension approach was used to do this effectively.

Dimension 1 was done by analysing factsheets, assessing these from an industry expert point of view, and interviewing suppliers to challenge numbers and understand application principles. This can be characterised as a bottom-up approach.

Dimension 2 aimed at challenging energy savings by benchmarking the bottom-up numbers from factsheets to top-down numbers from industry experts and academical studies including breakdowns of the 8 industries. Basis for this were confidential interviews performed by PDC with industry experts and professors (see Appendix A.5).

Dimension 3 is an add on to energy management analytics where different opinions may be there from a traditional energy management perspective versus a new generation technology perspective using advanced data analytics solutions in combination with submetering. For this dimension several academic and EU studies were assessed on high-level, specific report “151201 DG ENER Industrial EE study - final report_clean_stc” (reference I24). Recalculations were needed to come to a number fitting in the scope for project 6-25. According to our expert judgement supported by confidential industry interviews we arrived at1.15% for all industries except food and paper where numbers from dimension are used.

5.3 Data infrastructure

Data infrastructure is starting point, a precondition for all savings and reductions. Data infrastructure embraces current data sources within Industries which can be SCADA systems, Data historians, ERP systems, installed sensors and (sub)metering, etc. Data infrastructure also includes new to be installed sensors or (sub)meters to collect additional data to enable use cases to work correctly. The sensors and products addressed in this chapter do not work stand alone and are part of an ecosystem/ installation. A sensor by itself is not reducing CO_2, the complete solution might do this. As data infrastructure on itself will not provide energy or CO_2 reductions, this is not analysed separately.

5.4 Advanced process control

5.4.1 Working principle of energy saving by application of advanced process control

In general, Advanced process control (APC) tools create more synergy between dynamic models of processes, data storage for past performance and predictive analysis algorithms. Usually, predictive models with AI, are used to optimize control actions to achieve the desired higher performance. This leads to optimization of amongst others, energy usage based on costs, recovery of residual heat, fuel savings and emission reduction.

The working principles varies based on the end unit of application. In summary, working principle of APC for major units are mentioned below.

Furnaces & fired heaters optimization
Industrial furnaces can gain savings on operational cost by optimization of fuel consumption, operations and efficiency with control logic units and mechanical improvements. The working principle is based on optimizing oxygen content in the furnace and required fuel consumption. A high oxygen content will lead to suboptimal performance. Oxygen level can be measured by installing a probe in the furnace. By using APC, the level will be reduced to a safe minimum which will subsequently provide reduction in fuel consumption and CO_2 emission.

Utility optimization
This principle can also be applied to **multifuel boilers** where biggest concerns amongst others are:

- Varied availability of alternate fuels;
- Differences in energy content per unit of alternate fuels;
- Limitation in operation (fluctuation of steam demand) and CO_2 emission.

The efficiency of such boilers can be improved by integrating an automatic control unit which embeds combustion control technique. It can also be integrated with data historian systems like Osisoft. Such measures could possibly lead to operating boiler in automatic control over 95% of the time. The working principle is same for all the sectors.

This technology is economically attractive for large installations >10 MW producing high temperature heat. The boilers must be connected to a Programmable Logic Controller (PLC) which can host Model Productive Control (MPC) which is provided by technology supplier (I5). The saving potential depends essentially on possible reduction of air or O_2 consumption. This varies largely for each installation units. The potential for each unit will differ based on its past performance efficiency, lifetime, fuel consumption and steam production profiles.

Furthermore, the topic utility area optimization provides solutions for steam system & Cogen systems to reduce their energy consumption. It works essentially on an open loop real-time optimization system. The solution provides operational recommendations on optimal setpoints, constraints and equipment changes.

Industrial processes optimization
APC technologies are operational in several energy intensive industries incorporating complex processes like refineries, iron and steel manufacturers, crackers, etc.

On top of existing APC, further enhancement of energy recovery could be possible. Thereby, field devices are studied at the beginning. Following the study, asset performance data is analysed, and improvements are recommended. Such improvement entails, installation of additional wireless sensors for unit mass and energy balances. Often, replacement of existing control system in process units and mechanical adjustments on existing processes are essential. Further, new Standard Operating Procedures are created, and crew shall be trained to hone the needed skills. For example solutions are available for refinery and cracker industries.

5.4.2 TRL level of advanced process control

The purpose of APC is to optimize the set points of single- loop controls to maintain key operational variables close to targets and achieve the best operational target by optimizing several variables. APC has been evolving since more than 40 years.[16]

APC is available and being implemented for industrial processes (like distillation columns), furnaces, boilers, etc. They are applicable across all the sectors in the industries. Thereby, it is recognised at TRL 9.

5.4.3 Conditions to allow for successful application of advanced process control

Furnaces & fired heaters optimization
Furnace optimization requires mechanical installations of probes apart from control unit. Thereby, space for the laser spectrometers inside through the heater and, at the outside of the heater will be needed. Further, past operational data of the furnaces including fuel consumption profiles, efficiency performance, O_2 level, etcetera are essential to determine technical and economic feasibility of such solution on plant level.

[16] https://www.controleng.com/articles/five-advanced-process-control-data-analytics-connections/

Industrial processes optimization

Following data integration and/or data infrastructure is needed:

- Based on existing operational data and energy data e.g. data historians like Osisoft Pi and or integration with site control, Scada and enterprise systems;
- Installation of wireless sensors for unit mass and energy balances in process units;
- Adjustments of closed loop based on utility pricing models to achieve optimization of processes.

5.4.4 Costs and benefits of advanced process control

Furnaces & fired heaters optimization

Typical total installation cost of such system incorporating bare equipment and installation costs is € 500,000. There are no lifetime fees applicable and yearly maintenance is not mandatory. If an industry prefers to avail yearly review of operations, control logic and other adjustment by the supplier then an additional cost of € 10,000 per annum shall be borne.

The ROI is dominated by achievable savings on fuel and CO_2 costs. Lower fuel cost (ex: Natural gas) will not have a positive impact on ROI. The impact of such an installation on consumption of fossil fuel is directly related to decrease in O_2 consumption. For example, a decrease of 1% in O_2 level could subsequent provide a reduction of approximately 4% in fuel consumption whereas no reduction in O_2 level will provide no reduction in fuel consumption. ROI on this specific case of 1% decrease in O_2 level is 1 year.

Such solutions can be installed in furnaces where demand of high temperature heat is significant. Thereby, saving potential in sectors like refineries, steam crackers, industrial gasses, ammonia & fertilizers and steel are possible.

Utility optimization

The analysis on utility optimization was done based on the available information from factsheets and interviews. No information on cost related to equipment, instalment and operation have been shared or provided.

- Utility Area Optimization: Most of the available references in supplier factsheets are outside Benelux region where possible energy (electricity and fuel) savings in the range of 2-5% have been demonstrated. If these figures are interpolated, assuming from Northern America to the Netherlands based on Figure 5-3, possible energy savings of 1-2.5% can be achieved;
- Boiler Optimization: Similarly, the available references for this technology is very limited in Benelux region. After interpolation from North America to NL, the possible savings on boiler fuel can be 0.5-1.5% (from 1-3%);
- Steam Header Optimization: Likewise, owing to limited references in the Benelux region, the savings following interpolation can be 2.5-10% (from 5-20%).

Return of investment

- Turbines & Compressors: ROI <1 year –Refineries, Steam crackers, Steel, Ammonia & N-fertilizer, and Industrial gasses;
- Steam Boilers & Headers: ROI 1-2 years – Applicable for all 8 sectors;
- Complex steam/Cogen systems: Steel <2 year.

Industrial processes optimization
It would provide more evidence if we would have received more information about costs from other suppliers in the field, but the analysis was done based on information available in the timeframe of this study. For example, following ROI information is available:

- Process Unit Energy Optimization: Most of the available references are outside Benelux region where possible energy savings in the range of 3-10% have been demonstrated for process units. If these figures are interpolated, assuming from Northern America to the Netherlands based on Figure 5-3, possible energy savings of 1.5-5% can be achieved.

Return of investment

- Steam cracker Systems: ROI <1year –Refineries and steam crackers;
- Vapour & Vacuum Systems: ROI <2 years –Refineries, steam crackers and food.

5.4.5 Feasible saving potential

To implement an APC project, planning, controlling and monitoring are crucial aspects amongst others like safety inductions and regulations.

Often, control systems changeover is required to implement APC:

- This entails, limited scope stops;
- The outages could be required during production continuity. Therefore, it is important to liaise with production team to ensure that it does not coincide with high production demand periods.

Outage durations depend on installation time, statutory inspections and production requirements:

- Installation of submetering, cables and other hardware (a more detailed explanation on impact in section 5.6);
- Mechanical adjustment of instruments if needed (ex: furnace optimization, to install probes);
- Comprehensive testing;
- Update control logics/ install new control systems
- Verify control solutions to ensure that there is no operational or basic design issue;

Monitor & realize:

- Process start-ups and controls' fine tuning to achieve the performance benchmark;
- Required trainings and hand over procedures to plant operators.

Furnace optimisation
This solution entails mechanical adjustment of burners and optimisation of existing control logic systems. The installation time can vary from few hours to 2 weeks, which depends on the site. The system can usually be installed during yearly maintenance of burners. No additional shut down is expected for installation and the implementation could be done outside a turnaround.

Boiler optimisation
Boiler optimisation require installation of mechanical improvements to multi-fuel boilers. This could include fuel train changes, burner modifications, fan modifications, air system upgrades or damper improvements.

Industrial processes optimization
The solution delivers optimum process control. Additional wireless sensors for unit mass and energy balances are usually installed and advanced controls are implemented to optimize energy based on cost.

ICT knowledge infrastructure and competences
Implementation of ICT technologies requires the availability of an ICT knowledge infrastructure and competences at the industry. This is crucial for a fast and effective implementation of advanced process control analytics. In case an ICT knowledge infrastructure and competences is lacking this results in a limiting factor.

Our assessment bases on expert judgement supported by confidential interviews with industry experts is:

- Large international oriented companies have access to the international markets and resources whether in house or externally. So no limitation due to implementation time;
- In Food and Paper & Board we see a mixed picture. The large international companies have some access but for the smaller, local companies this is a serious constraint;
- The Wider chemical industry is positioned in between.

Therefor our assessment results in the following % of the economical feasible potential that can be realized before 2025. The full potential can be realized before 2030.

Table 5-5: Economical feasible potential given per industry sector in percentage

Industry sector	% Potential that can be implemented in or before 2025
Industrial gasses	100%
Steam crackers	100%
Ammonia & N- fertilizer	100%
Wider chemical industry	75%
Refineries	100%
Iron and Steel	100%
Food	50%
Paper & Board	50%

Other limiting factors described above have a minor influence on the feasible saving potential and are not taken into account further

5.4.6 Sensitivity analysis

Not applicable for ICT.

5.4.7 Overview of all CO_2 reduction potentials

Table 5-6: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		Theoretical Technical	Theoretical Economical	Feasible Technical	Feasible Economical	Sensitivity analysis	
						Pay back ≤ 10 yrs	WACC 4%
Chemical industry	Industrial gasses	26	26	26	26	26	26
	Steam crackers	74	74	74	74	74	74
	N-Fertilizer	49	49	49	49	49	49
	Wider chemical industry	78	78	78	58	58	58
Refineries		65	65	65	65	65	65
Iron and Steel		46	46	46	46	46	46
Food		213	213	213	106	106	106
Paper and Board		45	45	45	23	23	23
Total		596	596	596	447	447	447

5.5 Energy management analytics

5.5.1 Working principle of energy saving by application of energy management analytics

Energy management analytics systems are self-learning systems covering multiple commodities of energy. Analysed are different solutions as mentioned in section 5.2.1. Some systems have a specific focus like the steam, other systems include energy trading or balancing aspects. These solutions can influence business cases in a positive way by using trading and imbalance functionality. This specific functionality does not add direct value from an energy saving perspective.

Energy management systems contain functionalities around asset optimization and anomaly detection which can be both positive (keep) or negative (prevent) anomalies.

In general, these systems have the following characteristics:

- Energy is monitored in an integral way, so for different commodities like gas, electrical power and steam;
- All is based on near real time analysis based on existing data from e.g. data historians like Osisoft Pi. Additionally, submetering can be added to get more precise and detailed data. Without submetering the payback period is 1-2 years in most cases, for some solutions even within 1 year. Some solutions are provided as Software as a Service (SaaS) so that CAPEX costs are not applicable, there are just OPEX costs. When adding submetering in a structured way additional energy savings can be realized, but the payback period will increase as submetering impacts costs;
- Energy management systems function one way from measure to conclude. No setpoints are set, this is up to the user to arrange this in advanced process control systems;
- Machine learning algorithms are based on a number of variables. There are advanced solutions which are based on 15 variables which is above average.
- The working principle of energy management analytics is generic for the various industrial sectors.

5.5.2 TRL level of energy management analytics

The TRL level is at 9 as these kinds of solutions are proven in operational situations.

5.5.3 Conditions to allow for successful application of energy management analytics

The following data integration and/or data infrastructure is needed for energy management analytics solutions:

- Based on existing operational data and energy data e.g. data historians like Osisoft Pi and or integration with site control, Scada and enterprise systems;
- Weather data;
- Submetering energy usage and power quality.

5.5.4 Costs and benefits of energy management analytics

It is hard to get insight in detailed costs as costs cover more than just an energy management solution. Depending on the way a solution must be integrated on the site, costs for installation and implementation will increase. For example, there are solutions which basically can work just based on data historians like Osisoft Pi. As most of the industries have these kinds of solutions in place the mentioned return on investment (ROI) times of 1-2 years seems to be realistic; some solutions lower (<1 year), some higher (1-3 years). When submetering has to be added ROI times may increase with 1 year.

We conclude that if solutions that are based on existing data historians, they can be implemented easily, and ROI times are within the required ROI of 5 years. Adding submetering can be done in a very focussed manner by analysing where submetering is needed, so then this can be added based on upfront developed business cases. So, this can be done in a controlled way.

Elements to consider when implementing energy management solutions:

- Basic costs are for software licenses, hosting, application maintenance & support, or SaaS approaches including everything. Choices can be made to run software as SaaS / cloud solution or run it on premise;
- Optional costs for submetering (hardware), temperature transmitters and costs for installation of submetering on site;
- Workshops with clients are needed to assess processes and domain knowledge;
- Additional wins to reduce ROI: when also taking predictive maintenance benefits into account ROI can be reduced to a few months;
- Quick scans are often offered to do an assessment on potential wins and to assess the additional value of sub metering. Via this kind of approach energy management projects can be started in a controlled and safe way.

Implementation time is between 3-12 months.

5.5.5 Feasible saving potential

As energy management analytics systems basically function based on existing data there are not much limitations. Adding submetering could be a limitation as this means that ROI times will increase. As mentioned in section 5.5.4 this will impact ROI with ~1 year by which the ROI still stays within the limit of 5 years.

A more detailed explanation on impact of submetering can be found in section 5.6.

ICT knowledge infrastructure and competences
Implementation of ICT technologies requires the availability of an ICT knowledge infrastructure and competences at the industry. This is crucial for a fast and effective implementation of energy management analytics. Same approach and reduction % is applied as described in section 5.4.5.

5.5.6 Sensitivity analysis

Not applicable for ICT.

5.5.7 Overview of all CO_2 reduction potentials

The theoretical saving potential is based on numbers of suppliers and the validation process as described in section 5.2.2:

- In energy intensive industries 2% should be realistic using next generation solutions including artificial intelligence;
- For Food and Paper/board 5-10% energy savings should be possible based on same assumptions as mentioned for energy intensive industry (so including artificial intelligence);
- 2-7% savings are based on references not in Benelux where is assumed that most of these references are from North America where saving potentials are much higher. Recalculating these to the Netherlands (as explained in section 5.2.2) means to halve these, so 1-3.5% which is in line with other numbers;
- When these numbers are assessed against numbers from industry experts (see 5.2.2) numbers seems to be realistic for the energy intensive industry, but mostly this kind solutions are in place yet. For food and paper/board 2% is realistic which is in line with the recalculated non Benelux references. When a solution is based on next generation data analytics better savings can be made potentially, but industrial references are not yet sufficiently available to assess this in all industrial sectors. So numbers in below table are conform references, but may be higher in future by next generation data analytic technologies.

Table 5-7: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	14	14	14	14	14	14
	Steam crackers	36	36	36	36	36	36
	N-Fertilizer	21	21	21	21	21	21
	Wider chemical industry	33	33	33	25	25	25
Refineries		31	31	31	31	31	31
Iron and Steel		23	23	23	23	23	23

	Theoretical potential		Feasible potential			
Total top 8 industrial sectors	**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
Food	125	125	125	63	63	63
Paper and Board	28	28	28	14	14	14
Total	311	311	311	227	227	227

5.6 Asset management analytics

5.6.1 Working principle of energy saving by application of asset management analytics

Asset management analytics is defined as optimizing assets which are part of processes. Advanced process control and energy management analytics were focussing on optimizing processes, asset management analytics is about optimizing ‘isolated’ assets. The aim is to optimize assets to their optimum. This also includes optimizing maintenance and repair by using ICT which is faster, more effective and addresses the problem better than the traditional way of working.

In general asset management analytics are software applications that use and gather information out of all kinds of existing or new sensors which are part of assets. These can get information out of existing SCADA systems, fields devices, system controls and combine it with other sensors at the site or other data sources outside the site like weather data. By analysing historical data and the outcome of these settings, new optimised settings can be calculated and advised often with a better result and potential saving on energy or fuel consumption.

Most of the asset management analytics optimise machine lifetime or prevent downtime. These effects are relevant to the business case but do not cause direct energy savings and therefore do not result in scope one or two CO_2 savings. Only those measures are taken into account that directly relate to energy savings like leak detection in compressed air systems.

For rotating equipment no specific CO_2 savings are assessed as equipment performance optimization already includes energy savings figures for rotating equipment like pumps, coolers, conveyors, etc. Condition based monitoring has no direct saving on it selves. By looking at the energy use of rotating equipment, problems can be identified in an early stage and before it fails. This really has value, but does not give primary CO_2 savings.

For this phase of the project we analysed factsheets of multiple vendors as mentioned in 5.2.1.

5.6.2 TRL level of asset management analytics

The maturity of these software programmes is on level 8 or 9. For example all factsheets spoke about real life customers achieving the results mentioned on the factsheets.

5.6.3 Conditions to allow for successful application of asset management analytics

Essential to the application of these solutions, is the connectivity of each device that is to be provided with data. Most PLCs are connected to a Scada system by conventional cabling and installations like BACnet, Lon or other protocols. If the Scada system is open to send information to the analytics software there is no need to change the existing cabling.

When additional sensors need to be placed in the current surrounding, these need to be connected to a device to collect the data and transfer this to the analytics software. These devices are often referred to as “edge” devices (working on the edge to gather the data and send requested data to the analytics software). An example of a function of an edge device is the following: a sensor measures every millisecond, but just an average of every ten minutes is needed unless a certain boundary is crossed. In these cases measurements every minute are needed.

In case existing systems are not “open” enough to interface with the requested data, it can be a more attractive solution to place additional sensors in the factory instead of trying to integrate with old legacy equipment or old software.

5.6.4 Costs and benefits of asset management analytics

Unfortunately, there is not a typical cost number for these kinds of installations since every industry and every customer is on a different level of integration and maturity in digitisation. This can result on very high and big wins with only a very small investment versus a very large investment with lower results. As a result of this, not all suppliers were able to give us a bandwidth of costs versus a bandwidth of profits on CO_2 reduction.

The analysis was done as expert judgement based on available information from several suppliers. Following ROI times are available:

- Turbines & Compressors: <1 year (all sectors, except food and paper/board);
- Static Heat Transfer Systems: <1.5 year (refineries, energy intensive, ammonia);
- Compressed air Systems: <1.5 year (all sectors, except food and paper/board);
- Steam trap Systems: <0.5 year (all sectors);
- Pressure Relief Valve System: <0.5 year (refineries).

5.6.5 Feasible saving potential

Besides using historical data, in some cases additional sensoring and/or submetering is needed to gather more detailed data or to solve issues around not open systems that contain data which is needed for asset management analytics. When adding sensoring and/or submetering additional installations are needed which will e.g. measure energy consumption of the factory so that this can be combined with available historical data. The more submetering is in place the more accurate the outcome will be. Therefore, it is recommended having submetering in line with the large energy consumption units in the industry.

The use of wireless solutions will make the CAPEX cost of the installations more effective. For a temporally solution in energy consumption there are ‘clamp-on’ products available in the market. These will provide direct insight in energy usage and do not need a stop during installation. A permanent solution, which requires a stop, can be installed later, e.g. during a planned stop.
Wireless solutions are available with a 10 year battery lifetime. The battery lifetime is related to the amount of data and the frequency that is transported. Therefore, the permanent solution is often based on wired situations. Transmitting the data can stay wireless in a permanent solution, as long as the sensor/ submeter is wired and powered to grant enough power for a high frequency and large amount of data to be send.

Some sensors use Energy harvesting to power itself. Unfortunately, the reliability of sending enough data on a high and regular frequency is not enough at this time.

Energy harvesting is rapidly evolving. Harvesting energy out of the air, or by converting vibrations into energy. At this moment the TRL level of energy harvesting is not on TRL level 8 on this field.

Submetering, especially in energy consumption has been underestimated and not frequently placed Due to software solutions working with artificial intelligence and machine learning to analyse the performance of machines submetering is getting necessary for condition-based maintenance.

Conclusion on sensoring and submetering is that it adds value to all asset management solutions analytics, but also to energy management and some APC cases. It can be installed without stops where clamp-on and/or wireless solutions are implemented. Later on, during a planned stop, a final solution can be added. Submetering does not change the ROI times dramatically, ROI times will increase at most with 1 year.

Compressed air

For compressed air, potential is calculated with 20% savings overall based on supplier factsheets and general information about compressed air such as the factsheet from RVO (reference I6). This is high for the whole industry on average. For industries which have large compressors in place which have a big share on electricity usage this makes senses, but for other industries 20% is too high. From our expert judgement supported by confidential interviews of industry experts this is assessed as following:

Table 5-8: Feasible savings of compressed air given per industry secort in %.

Industry sector	% Feasible savings
Industrial gasses	5%
Steam crackers	5%
Ammonia & N- fertilizer	10%
Wider chemical industry	10%
Refineries	5%
Iron and Steel	20%
Food	20%
Paper & Board	20%

ICT knowledge infrastructure and competences

Implementation of ICT technologies requires the availability of an ICT knowledge infrastructure and competences at the industry. This is crucial for a fast and effective implementation of asset management analytics. Same approach and reduction % is applied as described in section 5.4.5.

5.6.6 Sensitivity analysis

Not applicable for ICT.

5.6.7 Overview of all CO_2 reduction potentials

Table 5-9: Theoretical and feasible CO_2 reduction potential (kton/y)

	Theoretical potential		Feasible potential			
Total top 8 industrial sectors	**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
					Pay back≤10 yrs	*WACC 4%*

Chemical industry	Industrial gasses	45	45	16	16	16	16
	Steam crackers	103	103	39	39	39	39
	N-Fertilizer	28	28	19	19	19	19
	Wider chemical industry	117	117	76	57	57	57
Refineries		73	73	29	29	29	29
Iron and Steel		17	17	17	17	17	17
Food		123	123	123	62	62	62
Paper and Board		28	28	28	14	14	14
Total		534	534	347	253	253	253

5.7 Digital twinning

Digital twinning is not assessed from a factsheet point of view and formally not in scope. Our vision on how digital twinning may be of value in the journey of CO_2 savings, on the longer term, is the following:

Digital twins can help in reach CO_2 emissions. By creating a virtual replica of the physical asset, process or systems we can run and investigate multiple scenarios to optimize CO_2 impact versus other performance indicators. Adding models about the behaviours of the physical world and new digital technologies like machine learning to it, we can create self-learning systems that further optimize performance. In case we develop these digital twins based on a uniform set of principles and frameworks that ensure the possibility of exchanging data, they can together create an eco-system of twins optimize a whole value chain or regions in their CO_2 performance.

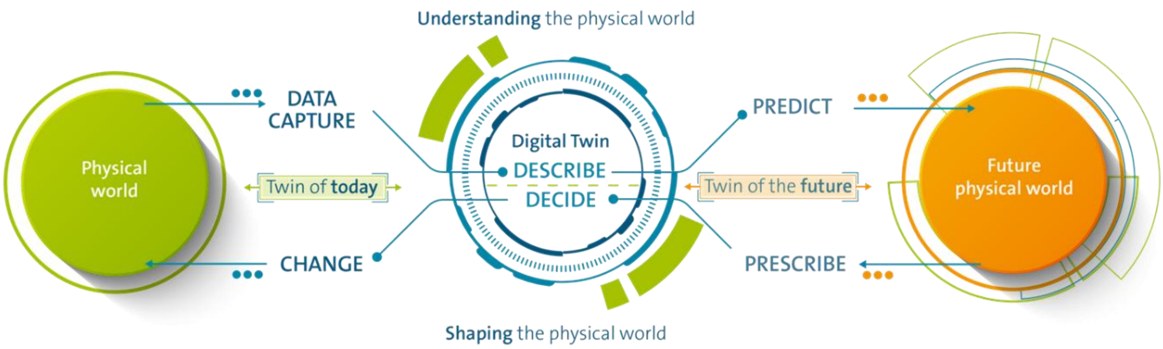


Figure 5-4: Representation of Digital Twin.

5.8 Overall saving potential & conclusions

This section compares dimension 1 (bottom-up approach) with dimension 2 (top down approach) and also included dimension 3 which is a challenge on energy management analytics, as depicted in our methodology (5.2.2). This entails comparing these numbers and making a conclusion on the ICT part.

Theoretical savings

Dimension 1, our bottom-up analysis based on supplier factsheets and references concluded with following:

- Overall savings over a 4-year period (2021-2025) of **7%** for natural gas and electricity is possible across the 8 sectors;
- The cumulative savings on natural gas and electricity, can provide net CO_2 savings of up to **1310 kton**.

Dimension 2, our top down analysis concluded with following:

- Overall savings over a 4-year period (2021-2025) of **4%** for natural gas and electricity is possible across the 8 sectors;
- The cumulative savings on natural gas and electricity, can provide net CO_2 savings of up to **947kton**.

Dimension 3 makes an nuance on energy management analytics for all industries, except remaining chemicals, food and paper. After adding this change to dimension 2, the cumulative savings on natural gas and electricity, can **increase** net CO_2 savings with **125 kton**.

Detailed tables with all numbers for the three dimensions can be found in Appendix A5. And are visualized in below diagram.

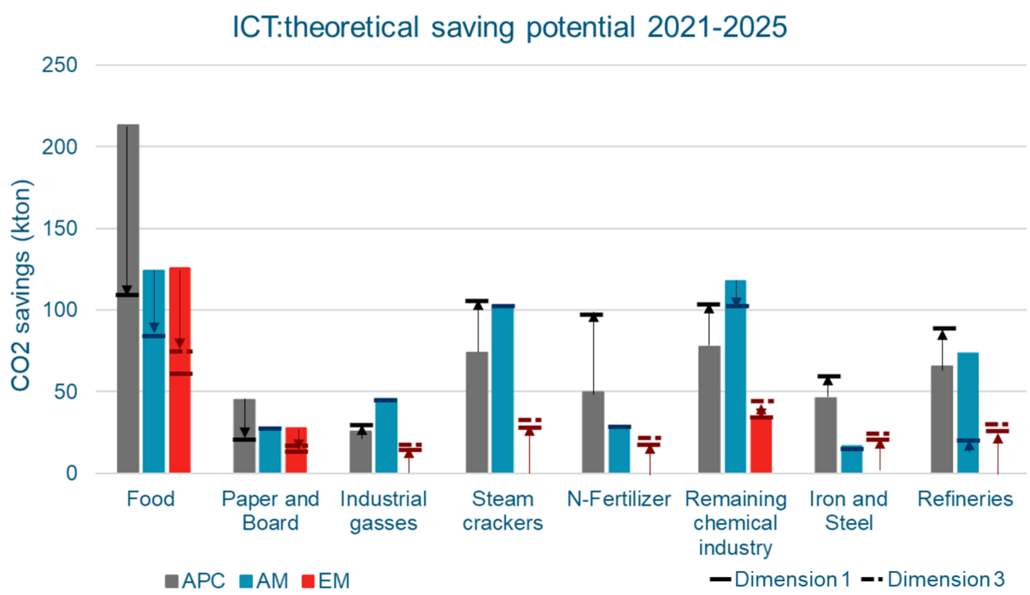


Figure 5-5: Overview of ICT- Theoretical economic saving potential. The base figures are taken from Dimension 2. These are compared with Dimensions 1 & 3.

This brings to the conclusion of theoretical savings with ICT solutions. Numbers of dimension 1 and 2 are compared and are in-line with each other, except compressed air where we assessed quite higher numbers. There are also differences on specific technology / industry combinations. Specific on energy management there is a difference which is assumed to be caused by traditional energy management vs energy management with advanced data analytics. For this part we base our conclusions on an EU study on this topic (reference I24) as described in section 5.2.2.
Finally the numbers from the three dimensions are reported as following for the theoretical potential:

- The numbers from dimension 2 are used as baseline (see Appendix A4 and Appendix A5);
- To the asset management analytics part assessed numbers on compressed air are added to these;
- For energy management analytics numbers from the EU study (see reference I24) are used for Wider chemical industry, Food, Paper and Board;
- The cumulative savings on natural gas and electricity, can provide net CO_2 savings of up to **1440 kton**.

Feasible potential
As described in section 5.4.5 implementation of ICT technologies requires the availability of an ICT knowledge infrastructure and competences at the industry. This is crucial for a fast and effective implementation of all three ICT technologies. In case an ICT knowledge infrastructure and competences is lacking this results in a limiting factor.

Our assessment is:

- Large international oriented companies have access to the international markets and resources whether in house or externally. So no limitation due to implementation time;
- In Food and Paper & Board we see a mixed picture. The large international companies have some access but for the smaller, local companies this is a serious constraint;
- The Wider chemical industry is positioned in between.

Therefor our assessment results in limitations for Wider chemical industry, food and paper & board. Herewith feasible economical potential for ICT will be as displayed in below table.

Table 5-10: ICT- Final numbers feasible economical saving potential

Total top 8 industrial sectors		Advanced Process Control [savings (kton)]	Asset Management [savings (kton)]	Energy Management [savings (kton)]
Total		**447**	**252**	**226**
Chemical industry	Industrial gasses (Air Products, Air Liquide, Linde)	26	16	14
	Steam crackers (Dow, Shell Moerdijk, Sabic Chemelot)	74	39	36
	N-Fertilizer (YARA, OCI)	49	19	21
	Wider chemical industry	58	57	25
Refineries (BP, ExxonMobil, Gunvor, Koch, Shell Pernis, Zeeland Refinery)		65	29	31
Iron and Steel (TATA)		46	17	23
Food (large number of factories producing diary, sugar, oils and fats, etc.)		106	62	63
Paper and Board (21 factories)		23	14	14

The cumulative savings on natural gas and electricity, can provide net CO_2 savings of up to **925 kton**.

6 Separation technology

6.1 Introduction and overview of results

Four main different gas separation technologies are in use in industry. These four are adsorption, chemical/physical absorption, cryogenic distillation and membranes. Adsorption (temperature/pressure swing adsorption) is the physical process in which a certain kind of gas molecules will adhere to the surface of the adsorbing material (e.g. silica gel, colloids, metals and so on). This process can be done in cyclic batch or continuous counter-current mode. Absorption (scrubbing) is the process in which a certain kind of gas mixture is contacted with a liquid in which one or more components from the gas stream will preferentially dissolve. The absorption process can be physical or chemical depending whether any chemical reaction happens between solute and solvent. Cryogenic distillation consists of distillation between different components of the gas mixture at cryogenic temperatures (generally below -150 °C or -180 °C). This process is very energy intensive and with high associated CAPEX and OPEX. In membrane gas separation processes, separation occurs due to size exclusion (e.g. for H_2 and CH_4) or preferential dissolution and diffusion of a specific gas molecule through the membrane layer (for high soluble molecules such as CO_2 and water). In this process, the quality of separation depends on selectivity and permeability of the membrane towards the desired component. In this section we describe how energy can be saved by the application of membranes to realize the desired separation for the following separation processes:

1 Membrane separation of H_2 from hydrocarbons

2 Membrane separation of N_2 /O_2 from Air

3 Pervaporation-based ethanol drying

In the tables below the main results are summarised.

Table 6-1: Overview of technologies, saving principles and main conditions.

Membrane separation of H_2 from hydrocarbons	
Technology	Polymeric membranes can remove impurities from gas streams and save money by recycling valuable products from a gas mixture. The separation principle is based on selective permeation of gas molecules across the membrane layer.
Savings principle	Hydrogen recovery has large impact on greenhouse gas reduction by reduction of CO_2 emission in H_2 production. The recovered hydrogen can be recycled back to the front end of the process or, sold to a third party
Main conditions and sectors	Membrane separation systems are designed in modules and can be used for small to medium size operations. These systems are typically used in ammonia synthesis purge gas recovery, oil refinery applications, Hydrogen to carbon monoxide ratio adjustment of synthesis gas, methanol purge gas recovery and other petrochemical applications. Hydrogen recovery from refinery fuel streams and purge gas streams is already a common practice in industry.
Membrane separation of / from air	
Technology	A nitrogen membrane separator uses asymmetric hollow fibre membrane technology to separate and recover nitrogen from compressed air. The membrane uses the principle of selective permeation to produce high-purity N_2 /O_2.
Savings principle	Generally, membrane technology requires less energy compared to the cryogenic distillation and Pressure Swing Adsorption (PSA), in which the separation can be performed at milder operating conditions. By replacing the conventional technologies by membranes, substantial amount of energy could be saved.

Main conditions and sectors	Main conditions are the required production capacity, the purity specs of the Nitrogen, and selectivity and the recovery of the membrane. In potential applicable at the sectors Steel, Ammonia and N-fertiliser and industrial gasses. If the above conditions are met which is at present not the case (e.g. not TRL 8-9 for required specifications of these applications).
Pervaporation-based ethanol drying	
Technology	A liquid mixture is in direct contact with a membrane, where one component will selectively diffuse through the membrane and will be evaporated in the permeate side of the membrane
Savings principle	A much more energy efficient separation process can be performed in comparison with distillation where all the components need to be evaporated
Main conditions and sectors	Compact zeolite membrane plants are typically in use for processing of about 3800-11350 litres per day of ethanol. This technology is applicable in the (bio)ethanol production plants while its widespread application in industry is limited due to technical limitations.

Table 6-2: Overview of results: main economic parameters.

	Membrane separation of H_2 from hydrocarbons (PRISM®)	**Membrane separation of N_2 / O_2 from air**	**Pervaporation-based ethanol drying (HybSi®)**
Payback period	1	NA	3
TRL	9	NA	5

Table 6-3: Feasible economical CO_2- reduction potential given per technology and sector (kton/y)

Total top 8 industrial sectors		**Feasible Economical**	**Feasible Economical**
		Membrane separation of H_2 from hydrocarbons	*Pervaporation-based ethanol drying*
Chemical industry	Industrial gasses	-	-
	Steam crackers	-	-
	N-Fertilizer	3	-
	Wider chemical industry	-	-
Refineries		73	-
Iron and Steel		-	-
Food		-	-
Paper and Board		-	-
Total		77	0

6.2 Membrane separation of H_2 from hydrocarbons

As demand for industrial-grade hydrogen increases, its recovery from industrial off-gases becomes more interesting. Hydrogen containing off gases can be found in processes like ethane steam cracking, propane and butane dehydrogenation, chlor-alkali processing, and catalytic reforming. Hydrogen can be combusted to recover its fuel value, but in some cases, it is more profitable and more efficient to recover hydrogen from off gases. Hydrogen price is 3-4 times more than natural gas (on a volumetric basis), LHV of hydrogen is roughly 3 times of natural gas. So, the true cost of hydrogen used as fuel is 11-15 times higher than natural gas used for the same purpose [S1]. In addition, due to growing market (e.g. in glass,

electronics, chemicals, annealing atmospheres for metals processing), interest in more profitable hydrogen sources has been increased [S1].
Different recovery technologies have been applied at industrial scale. Each technique has its own benefits and limitations. As summarized in Table 6-4, different recovering methods can be applied for different purity of hydrogen and quantity of off gases. The recovered hydrogen can be recycled back to the front end of the process or sold to a third party. In general, significant cost saving and productivity improvement can be achieved by a hydrogen recovery system.

Table 6-4 Hydrogen purification techniques and their performance criteria [S1]

Parameter	Membrane separation	Pressure-Swing Adsorption	Cryogenic Distillation
H_2 purity	90%-98%	99.999%	95%-99%
H_2 recovery	85%-95%	75%-92%	90%-98%
H_2 Product Pressure	<Feed pressure	Feed pressure	Feed/Low pressure
Feed Pressure	21-159 bar	10-41 bar	>5-76 bar
H_2 feed content	>25-50%	>40%	>10%
Byproduct Capability	Poor	Poor	Excellent
H_2 Capacity	1178-58880+ Sm3/h*	1178-235520 Sm3/h	11776-88320+ Sm3/h
Pretreatment Requirement	Minimum	None	CO_2, H_2O removal
Capital Cost	Low	Medium	Higher
Scale economics	Modular	Moderate	Good
Start-up Time	Minutes	Minutes	Hours

**(Sm3: 1.01325 bar a, 15 °C)*

6.2.1 Working principle of energy saving by application of membrane separation of H_2 from hydrocarbons

Polymeric membranes can remove impurities from gas streams and save money by recycling valuable products from a gas mixture. The separation principle is based on selective permeation of gas molecules across the membrane layer. The mechanism is based on size exclusion for H_2 and CH_4 molecules and a combination of dissolution and diffusion for high soluble molecules such as CO_2. Polymer structure and gas composition determine the solubility of different gas components and permeation rate is dependent on partial pressure different of the gas molecule across the membrane thickness. Separation capability is determined by the relative permeation rate of individual gas components. The greater the relative permeability rate, the more effective separation can be obtained.

Membrane separation systems are designed in modules and can be used for small to medium size operations. These systems are typically used in ammonia purge gas recovery, oil refinery applications, Hydrogen to carbon monoxide ratio adjustment of synthesis gas, methanol purge gas recovery and other petrochemical applications [S2]. Hydrogen recovery from waste and purge gas streams is already a common practice in industry [S3]. Table 6-6 summarizes some membrane separations applied for H_2 recovery in different industrial processes.

Table 6-5 Industrial membrane separations for H_2 in different industrial processes [S3]

Separation	Process	Conventional technology	Membrane material	H_2 Permeability at 30 °C (Barrer*)	Supplier
H_2/N_2	Ammonia purge stream	PSA	Polymer (polysulfone)	14	Air Products, Air Liquide, Praxair, Linde
H_2/CO	Syngas ratio adjustment	PSA	Polymer (polyimide)	28.1	Air Products, Air Liquide, Praxair
H_2/hydrocarbons	Hydrogen recovery in refineries	PSA	Polymers (silicon rubber; polyimide)	28.1	Air Products, Air Liquide, Praxair

*Barrer = 10-10 cm3 cm/cm2 s cmHg

However, Hydrogen separation membranes have limitations. Although they can separate hydrogen from a bulk mixture but to reach high hydrogen purities membranes may not be suitable. So, membranes should be used when high purity is not required. Also, their performance is dependent on the feed pressure and major impurities in the feed stream. As it was shown in Table 6-4, hydrogen purities up to 98% can be reached with membranes but, 95% purity is more typical value for hydrogen purity obtained by membranes. Also, highly acidic and corrosive components (e.g. H_2S) can severely damage membrane bundles. So, membranes should not be used for streams containing such components. In addition, the presence of liquids and saturated feed can permanently damage the membranes. Thus, membranes should be used with care for off gases containing such components and impurities must be cleaned before off gases reach to the membranes [S1].

H_2 from Ammonia synthesis purge

Separation of H_2 from N_2 and CH_4 in Ammonia synthesis purge stream gases has been in use industrially and for typical purge flow rates of 10000 Nm^3/h. The purge stream from the ammonia synthesis reactor (110-130 bar) can be passed through a membrane separation system and recovery rates of above 90% can be achieved (Figure 6-1). Typically, the feed gas includes hydrogen (~ 66.5 mol%) and high concentration of methane (8.4 mol%), N_2 (22.2 mol%) and argon (2.9 mol%). Hydrogen molecules will pass faster through membrane selective layer and upgraded stream of hydrogen can be obtained at lower pressures (25-70 barg). This upgraded hydrogen can be recycled back to the Ammonia synthesis loop. The non-permeating stream (retentate side) will remain at high pressures (100-120 bar) and is suitable to be used as fuel [S4 & S5].

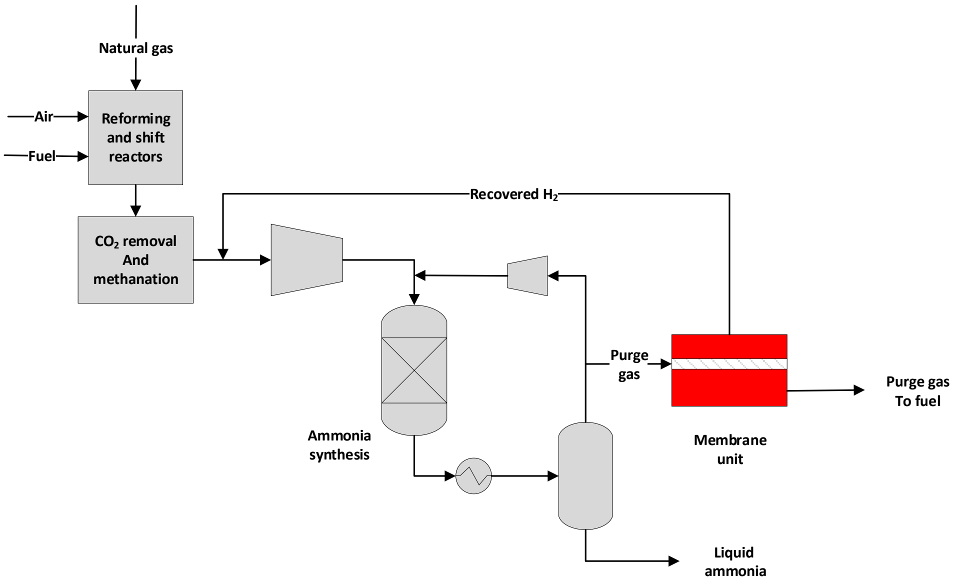


Figure 6-1: Hydrogen recovery system from ammonia synthesis purge stream

Hydrogen recovery has tremendous impact on greenhouse gas reduction by reduction of CO_2 emission in H_2 production for example, in ammonia industry, hydrogen recovery saves 8.5 tonnes of CO_2 for each tonne of H_2 recovered [S6].

Theoretical CO_2 saving potential for the Dutch Ammonia and N-fertiliser sector was estimated based on H_2 recovery potential from ammonia synthesis purge stream at OCI Nitrogen B.V. production plants. The ammonia plants at Yara are all of the purifier technology, this means a cold box purifier is installed upstream of the synthesis gas compressor that removes all unconverted methane and approximately 60% of the Ar. Purge from the synthesis loop is hence limited in this case, as purge is only required for Ar and He, not for methane . Purge is for >95% redirected to the inlet of the purifier, which again removes 60% of Ar. Only a few percent are sent to fuel to prevent accumulation of Helium. Potential of H_2 membranes in these plants is for this reason very low. In this case and to have a feasible solution, H_2/He selective membranes are required which can be interesting for further R&D work.

An annual purge stream value was estimated (simulated data) for a former DSM ammonia plant in Geleen. This value was linearly scaled up for OCI's production plants. Applying the separation performance criteria from the technology provider (Air Products), the annual potential for H_2 recovery for the Dutch Ammonia and N-fertiliser sector was calculated. It should be mentioned that, to obtain this saving potential, in a separate simulation done in Aspen plus, the required energy for recovery of H_2 from purge stream using hydrogen membranes was calculated and compared with the energy requirement of the benchmark technology (cryogenic distillation). Furthermore, this value was used to calculate the total amount of natural gas (or CO_2) that can be saved for production of the same amount of H_2 via steam methane reforming process (CH_4:H_2 1:4).

H_2 from cracker gas at steam cracker

Steam cracking plants typically have very high production capacities in the order of 2-5 Mtonnes per plant. In this process the cracked material (e.g. Naphta) is mixed with an inert (e.g. steam) and heated up to 900-1000 °C for a very short time (milliseconds). During this process a mixture of H_2, methane, hydrocarbons and CO_2 will be formed. For separation of such gas mixture, primarily CO_2 is removed and later H_2 (~7 mol%) and methane need to be separated from the rest of hydrocarbons. The separation process is most often complex, and the process steps are optimised based on the capital investment and energy consumption costs where the exact configuration depends on the feedstock and products [S7].

Conventionally the separation method involves mixed gas compression to 34.5 Barg and cooling down to -100 °c (typically done by chilling and adsorption on molecular sieves). During this process C2+ hydrocarbons will be separated from H_2 though some methane will remain with H_2 in the gas phase. Similar streams containing H_2, methane and some number of light hydrocarbons such as ethylene and propylene can be found in number of refinery processes as well (e.g. FCC units). Theoretically, Hydrogen can be separated from such gas mixtures utilising membrane technology with high energy saving potential in comparison with the cryogenic process.[S7-9].

Proposed by Baker et al. in 1998 [S7], this separation can be theoretically done in three steps: condensation, flash evaporation and membrane separation. In this process, H_2 and methane can be efficiently removed from the mixture, offering hydrocarbon distillation steps possible without demethanizer step. Also, similar process can be applied in refineries, where valuable olefins can be extracted as additional product. However, this process has not been yet implemented commercially and no information on available technology with TRL 8-9 could be found. Importantly, no commercial membrane with high flux/selectivity towards Hydrogen was found to provide high purity Hydrogen to be used in hydrogenation units in the steam cracking plants. For above reasons, it was not considered in this investigation.

H_2 from waste gas streams at refineries

In refineries membrane gas separation systems can be applied in many steps. This includes hydrogen upgrading, inert by product rejection, hydrogen recovery, and off gas upgrading. In general, membrane systems can be economically applied for any hydrogen recovering processes within hydro processing applications [S10]. By recovering hydrogen, less manufactured hydrogen is required to maintain the hydrogen balance in the system. The recovered hydrogen can be recycled back to the front end of the process offering significant cost saving and productivity improvement in the plant. Typically the left over unused residue gas, depleted of H_2, but rich in HC's is put into the fuel gas network at refineries.

In refineries, waste gas streams containing 10 mol% up to 60 mol% Hydrogen from hydro-processing units can be further upgraded by membrane separation systems to achieve hydrogen streams of 92-98 mol% and recoveries of 85-95%. For streams with lower hydrogen content (nearly 20-30 mol% hydrogen of off-gas streams from catalytic cracker), membrane separation systems provide hydrogen purities of 70-90 mol% in one single stage and a second stage is required to reach ator 95 mol% of hydrogen. Also, in a conventional hydrogen production plant, hydrogen can be recovered from the feed-gas resulting in higher hydrocarbon conversion in the steam methane reformer, thereby increasing hydrogen production rate [S10].

Membrane technology for hydrogen recovery is a proven technology and number of hydrogen recovery units have been already in use in refineries in the Netherlands to recover hydrogen from waste streams and several membrane suppliers provide membrane technology for hydrogen recovery in refineries when the hydrogen content is at least 25%. In general, recovering hydrogen from waste streams is more energy efficient than hydrogen generation by steam methane reforming. But the energy saving potential, and profitability really depends on the application and differs per each plant. In this respect, the direct energy saving potential for the refining sector depends on the extent this sector produces or obtain hydrogen from third parties. In each refinery, the potential energy saving is of course depending on availability of suitable flows for hydrogen recovery [S11-S13].

For calculation of theoretical CO_2 saving potential of H_2 membranes for the Dutch refineries, H_2 recovery from waste gas streams (with 10 till 60 mol% H_2) was considered. It was our expert judgement that benefits of H_2 recovery from dilute streams is very low, and only concentrate on 80% highly concentrated with nearly

60 mol% H_2. It was our expert judgement that potential additional recovery in case membrane technology is used at certain off-gas streams in a reference Dutch refinery to be about 0,5 T/h of Hydrogen. Applying the separation performance criteria from the PRISM® membrane technology [S10], annual potential for H_2 recovery for the reference refinery was calculated. This value then linearly scaled for other Dutch refineries (with various capacities) and a total value for the entire sector was estimated. This value represents also the associated total amount of natural gas (or CO_2) that can be saved for production of H_2 via steam methane reforming process. It should be noted that, the precision of this estimate can be further improved by considering the calorific loss due to H_2 recovery in the fuel network, while accounting for increase in efficiency of the process due this recovery (no publicly available data could be found in this regard). The probable conclusion is that the estimated potential may be further reduced.

In summary, in short term (<5 years), number of opportunities exist for H_2 membranes in industry. Most importantly in retrofitting in H_2 management in refineries, and ammonia plants to improve efficiency and off-gas management [S14].

6.2.2 TRL level of membrane separation of H_2 from hydrocarbons

Description of information on TRL level

Membranes separation technology is used on commercial scale for specific capacity. Thus, the TRL is 8-9.

Parameters determining whether TRL is 8-9 or lower

- Flow rate of the H_2 containing stream;
- Required H_2 purity for the desired application area;
- Membranes selectivity and recovery values (e.g. polymeric membranes cannot be applied for H_2 recovery coming out from a steam methane reforming process due to their low H_2/CO_2 selectivity).

Does the TRL level vary in various industrial sectors? If so to what extend/in what way?

Among various industrial sectors different hydrogen flow rates with different purity is required. Commercial membrane separation units (TRL 8-9) are available for H_2 recovery from waste streams (up to 95% purity), for higher purity H_2 production or larger capacities the TRL is lower and other conventional separation technologies (e.g. PSA) is used.

6.2.3 Conditions to allow for successful application of membrane separation of H_2 from hydrocarbons

What type of infrastructure is required?

Site preparation is minimal and requires simple concrete pad plus process and utility lines. Membrane separation systems can be deployed within the existing process with minimal infrastructural costs.

What type of equipment is required?

Depends on feed condition and membrane separation operating limits, compressors and heat exchangers might be required for feed temperature, and pressure adjustments. Also, feed pre-treatment might be required in case of any impurity (e.g. water) that can damage the membranes. For example, considering H_2 recovery from ammonia synthesis purge stream, initially the purged gas should be cooled from ammonia synthesis temperature down to a tolerable temperature for membrane unit. Later, the recovered H_2 need to recompress to the reactor pressure.

What type of information should be available?

Feed specifications should be known (feed flow rate, composition, temperature and pressure). In addition, desired gas purity and flow should be known.

Are there conditions that are critical in a specific industrial sector? If so for which sector and to what extend/in what way?

The main challenge membranes face is the cost/performance at large scales in comparison with conventional separation technologies.

6.2.4 Costs and benefits of membrane separation of H_2 from hydrocarbons

What are typical cost numbers?

CAPEX: Approximately €2,5 million for an average size of 25000 Nm^3/h.
OPEX: Approximately 0,5% of CAPEX /year.

What parameters increase cost numbers; what parameters decrease cost numbers?

Feed specification will determine if any feed temperature and/or pressure adjustment(s) is required. Need for pre-treatment step (e.g. removal of contaminants) and required membrane surface area (number of required separators for such separation) are other two main parameters that affect cost numbers. It should be noted that membrane systems can be built in different configurations for any specific recovery, purity and capital cost requirement.

What are typical benefits?

Typically, membranes provide good operating flexibility. This is very important when planned or unexpected process changes occur. Also, multiple take offs can be extracted from the permeate manifold for different purities and flow rates. Membrane systems have compact and modular design and can be mounted on a skid (can be moved).

Membrane separation systems also provide many economic benefits. They are usually compact and efficiencies up to 80-95% can be achieved [S1]. The utility consumption is limited to instrument air and water for temperature control. Purge streams are typically at pressures suitable for an efficient separation and no additional compression step is required. Also, start-up and shutdowns are simple (no cool down and preconditioning is required) and recovery begins immediately after gas feed into the separator.

Since membrane separation systems have no moving parts, no monitor, replace or maintenance is required. If they are installed properly based on design specs, no maintenance is required. Depends on membrane material type, tolerance to small amount of impurities is possible (e.g. water, ammonia, H_2S, CO_2, hydrocarbons and aromatics). Although, for certain membrane material, even ppm level of H_2S in gas feed can be detrimental to membranes. In this case, pre-treatment of the feed-gas is vital. This will determine the lifetime of the membrane as well.

What parameters determine the value of these benefits?

NA

How vary costs and benefits per industrial sector? Are there industrial sectors with strongly differing costs and /or benefits?

Depends on feed flow rate and required hydrogen purity. Also, in some applications application areas feed-gas pre-treatment is required.

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6.2.5 Feasible saving potential

- Technical limitations

No actual technical limitation for implementation of H_2 membranes was found. However, for refinery and Ammonia & N-fertilizer sectors, H_2 membranes are in competition with other CO_2 abatement strategies such as blue H_2 (SMR+CCS), and greenH_2 (electrolysis)technologies.

- Limitations due to planning

Considering an average turn around timing of 6 years for refineries and ammonia and N-fertilizer sectors, theoretical economical saving potential was halved.

- Economical limitations (probability of costs)

NA

- Conclusions:

  As summarized in Table 6.2.7, H_2 membranes show small to moderate feasible CO_2 saving potential in refineries and Ammonia and N-fertiliser sectors. However, this potential might strongly be affected in competition with other CO_2 abatement strategies such as blue and green H_2 production. These technologies are out of scope of the 625 project and are therefore not considered. Sensitivity analysis – TASK 2

6.2.6 Sensitivity analyses

For the sensitivity analysis, the effect of payback period and other competitive CO_2 abatement strategies on feasible CO_2 saving potential of H_2 Membranes were investigated. No change in feasible saving potential due to changes in payback period (being always <5 years) was found. However, H_2 membranes potential was found to be sensitive in competition with other CO_2 abatement strategies specially blue/green H_2 production.

6.2.7 Overview of all CO_2 reduction potentials

Table 6-6: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	-	-	-	-	-	-
	Steam crackers	-	-	-	-	-	-
	N-Fertilizer	6.6	6.6	3.3	3.3	3.3	3.3
	Wider chemical industry	-	-	-	-	-	-
Refineries		147	147	73	73	73	73
Iron and Steel		-	-	-	-	-	-
Food		-	-	-	-	-	-
Paper and Board		-	-	-	-	-	-
Total		153.6	153.6	76.3	76.3	76.3	76.3

Notes to table:
Steam crackers: *This process has not been implemented commercially therefore this technology is not available for this application at TRL 8-9.*
Refineries: -
Steel: In metal working hydrogen is in use for Iron reduction, as blanketing gas, and as forming gas while it is typically supplied in cylinders or tube trailers (so no large on-site hydrogen production). In addition, no membrane technology with TRL 8-9 was found for hydrogen separation in steel industry.
Ammonia and N-fertiliser: -
Industrial gasses: It was not considered in this investigation (due to lack of available data we were not able to determine the potential).
Paper and board: No potential was identified regarding H_2 membranes potential in paper and board industry, also because of lacking data.
Food: About 1% of total hydrogen demand in industry is used in general industry (semiconductor, glass production, hydrogenation of fats, cooling of electrical generators, and propellant fuel). The hydrogen supply for these units is via tube trailers, cylinders, or small on-site hydrogen production (SMR plus PSA). The potential for hydrogen membranes is low and scattered over many applications and therefore was not considered in this study.

All above notes are based on expert judgement and confidential interviews

6.3 Membrane separation of N_2 / O_2 from air

6.3.1 Working principle of energy saving by application of membrane separation of N_2 / O_2 from air

Different technologies can be used to separate N_2 /O_2 from air, such as cryogenic distillation (CD), pressure swing adsorption-(PSA) and membrane technology. Generally, membrane technology requires less energy compared to the CD and PSA, in which the separation can be performed at milder operating conditions. By replacing the conventional technologies by membranes, substantial amount of energy could be saved. The applicability of membrane separation technology depends mainly on the required capacity and purity of N_2 /O_2 in which it was investigated per industrial sector.

Description of working principle

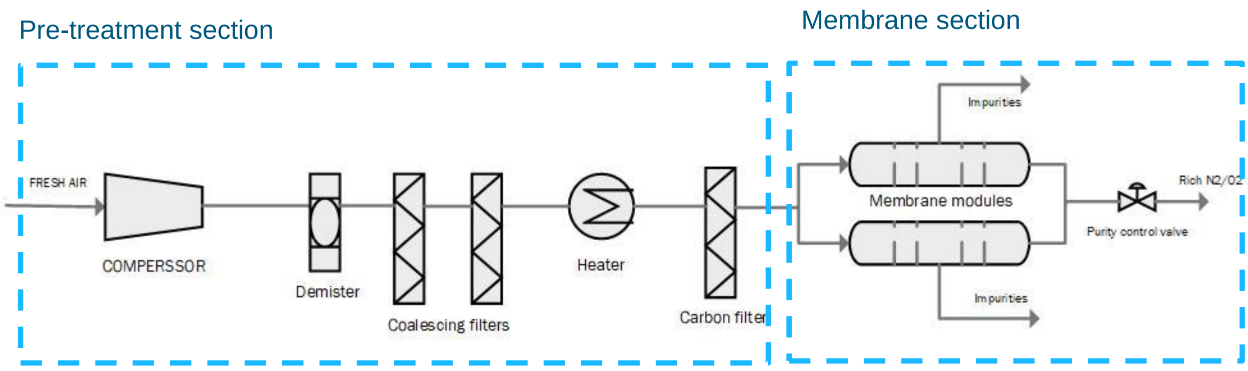


Figure 6-2 Air separation using membrane technology - working principle description

Nitrogen Production Units (NPU) take untreated air and convert it into nitrogen at purities from 95% - 99.9%. As it can be seen in Figure 6-2, the untreated air is compressed and then goes through a selection of filtration methods (coalescing, moisture and carbon) to remove hydrocarbons (oils), moisture and particulates. After this filtration, the air passes through the hollow fibre membranes where the molecules are separated.

A typical nitrogen membrane separator (such as PRISM® PA) uses asymmetric hollow fibre membrane technology to separate and recover nitrogen from compressed air. Atmospheric air contains 78% nitrogen, 21% oxygen, and 1% other gases. The membrane uses the principle of selective permeation to produce high-purity nitrogen. Each gas has a characteristic permeation rate, which is a function of its ability to dissolve and diffuse through a membrane. As it can be seen in Figure 6-3, oxygen is a “fast” gas and is selectively diffused through the membrane wall, while nitrogen can travel along the inside of the fibre, thus creating a nitrogen-rich product stream. The oxygen-enriched gas, or permeate, is vented from the membrane separator at atmospheric pressure. The driving force for the separation is the difference between the partial pressure of the gas on the inside of the hollow fibre and that on the outside.

In the PRISM® PA membrane separator, compressed air flows down the inside of hollow fibres. Fast gases—oxygen, carbon dioxide, and water vapor— and a small amount of slow gases, pass through the membrane wall to the outside of the fibres. They are collected at atmospheric pressure as the permeate. Most of the slow gases and a very small amount of the fast gases continue to travel through the fibre until they reach the end of the membrane separator, where the product nitrogen gas is piped to the application [S15].

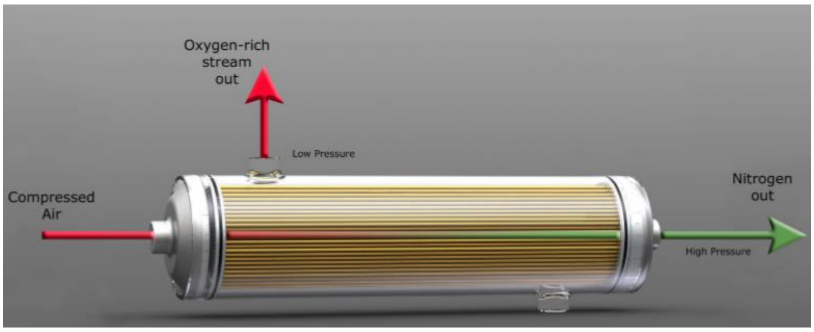


Figure 6-3 Typical membrane modules for nitrogen generation [S15]

A typical membrane separator contains thousands of fibres that are bundled and encased at both ends in epoxy resin. The ends of the bundle are cut, which leaves the fibre pores open on both ends, allowing the gas to travel from one end to the other. The fibre bundle is enclosed in a suitable casing. The casing protects the fibres and routes the gas properly [S15].

Parameters determining a large or a small energy saving potential
The energy saving potential depends on the following:

- Feed conditions: whether the feed requires additional pre-treatment steps such as extra compression, heating/ cooling or specific energy intensive filtration;
- Capacity and purity specs: with higher purity specs, the production capacity decrease;
- Operating conditions.

Does the working principle change in various industrial sectors? If so to what extend/in what way?
No.

6.3.2 TRL level of membrane separation of N_2 / O_2 from air

Description of information on TRL level
Generally, Membranes separation technology is used on commercial scale for specific capacity. Thus, the TRL is 8-9 at that capacity. As it will be seen in details about the application of technology in every sector in the table below, it was concluded that for nitrogen separation at the required capacity and purity it is not at TRL 8-9 , because they are very bulky processes and membranes are not applicable to satisfy the required capacity and it is not a proven technology for that capacity. Therefore, PSA and cryogenic are used for these bulky processes.

Parameters determining whether TRL is 8-9 or lower
The TRL of 8-9 or lower depends on the applicability of membrane which depends on the parameters below:

- The required production capacity;
- The purity specs of the Nitrogen;
- The selectivity and the recovery of the membrane.

Does the TRL level vary in various industrial sectors? If so to what extend/in what way?
TRL dose not directly vary with regarding the industrial sector but rather depends on the purity and the capacity of Nitrogen required in that specific sector. Details about the capacities and purities of nitrogen in the sectors are mentioned in the table below.

6.3.3 Conditions to allow for successful application of membrane separation of N_2 / O_2 from air

What type of infrastructure is required?
No specific infrastructure is required. A utility (electricity and steam). Simple concrete pad plus process and utility lines.

What type of equipment is required?

- Heat exchangers;
- Compressors;
- Various types of filters.

What type of information should be available?

- Product specifications (purity, capacity, temperature and pressure);
- Feed conditions;
- Product recovery.

Are there conditions that are critical in a specific industrial sector? If so for which sector and to what extend/in what way?
No.

6.3.4 Costs and benefits of membrane separation of N_2 / O_2 from air

What are typical cost numbers?
NA; it is irrelevant because membrane separation is not being applied for separation of nitrogen and oxygen from air at the desired capacities and purities.

What parameters increase cost numbers; what parameters decrease cost numbers?

- Production capacity: with higher production capacity, larger membrane area is required, thus, it increases the cost numbers;
- Flux and selectivity;
- Operating conditions of the feed: temperature and pressure determine whether the operation running at the optimum performance.

What are typical benefits?
Energy saving by separation at milder conditions compared to the cryogenic distillation.

What parameters determine the value of these benefits?
Energy consumption of the process, yield, and product quality.

How vary costs and benefits per industrial sector? Are there industrial sectors with strongly differing costs and /or benefits?
NA

6.3.5 Feasible saving potential

The feasible saving potential is not applicable because there is no theorical saving potential for membrane separation of N2 /O2 from air for the industrial sectors and technologies defined within the scope 6-25 project. For more info refer to the section 6.3.7.

6.3.6 Sensitivity analysis

Sensitivity analysis is not applicable because there is no theorical saving potential for membrane separation of N_2 /O_2 from air for the industrial sectors and technologies defined within the scope 6-25 project. For more info refer to the section 6.3.7.

6.3.7 Overview of all CO_2 reduction potentials

Table 6-7: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		Theoretical Technical	Theoretical Economical	Feasible Technical	Feasible Economical	Sensitivity analysis	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	-	-	-	-	-	-
	Steam crackers	-	-	-	-	-	-
	N-Fertilizer	-	-	-	-	-	-
	Wider chemical industry	-	-	-	-	-	-
Refineries		-	-	-	-	-	-
Iron and Steel		-	-	-	-	-	-
Food		-	-	-	-	-	-
Paper and Board		-	-	-	-	-	-
Total		0	0	0	0	0	0

Notes to table above all based on expert judgement and confidential interviews unless specified otherwise

Steam Crackers:

- **Nitrogen** is not directly used in the processes of operating steam cracker plants, simply because it can cause a default on the plant's production specifications. However, nitrogen can be commonly used in the following services: Tank or vessel blanketing, as a seal gas for rotating equipment such as compressors and pumps, various other applications such as dispersion of hydrocarbon releases through vent safety devices; or equipment purging for operation and maintenance services [S16]. The saving potential from these small amount of nitrogen streams is out of the scope of this project;
- **Oxygen** is not used in the current state of art processes of steam cracking**.**

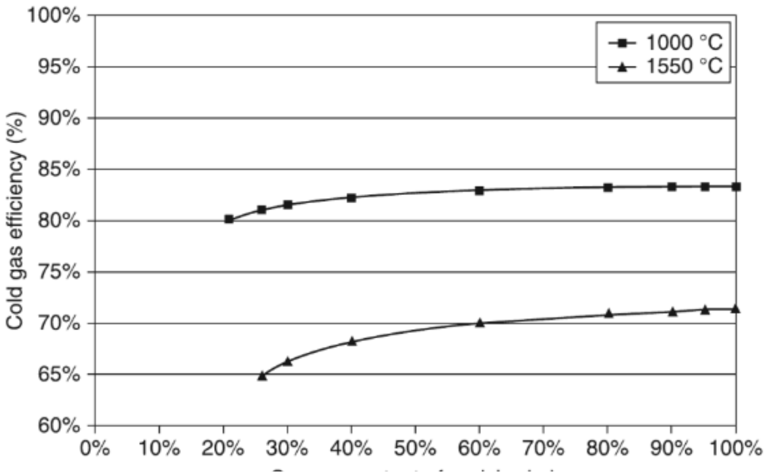
The conclusion is the saving potential is very low thus, it is not considered further.

Refineries:

- **Nitrogen** is not used directly but rather used as industrial gas for services in the plant such as purging and drying to pigging and pressure testing. These are considered as small nitrogen streams. Thus, the saving potential is too small, therefore it was taken into account and it falls out the saving potential scope of this project;
- **Oxygen** is mainly used in refineries as an oxidant for gasification process. Taking shell/Air products gasification process technology as benchmark, the oxygen purity requirements for this technology is 95 – 99.5 % volume [S17]. A membrane system with TRL 8-9 which can deliver the required purity of oxygen does not exist;

- **Oxygen enriched air** could be used as alternative for the high purity oxygen gasification feed. Even though, oxygen air enrichment technology is outside the defined scope of 6-25 project but there are existing membrane systems at TRL 8-9 which can give oxygen enrich air with oxygen purities ranges (25 – 50 %v). However, there are other technical reasons why oxygen is preferred over enriched air, even when the presence of nitrogen is not a fundamental problem. As it can be seen from Fig 6.4, while the cold gas efficiency does not vary very much over the range 85 -90 % oxygen, it falls off ever more rapidly closer it approaches the level of 21 % oxygen found in the atmosphere. Essentially, this represents the penalty of having to heat up the nitrogen to the gasification temperature, which was chosen as 1500 °C in this example. The oxygen demand is increase as the syngas as quantities to be cooled and treated are approximately doubled. These disadvantages are more than enough to offset the capital and operating cost of an air separation plant [S18]. Therefore, it is recommended to conduct furthermore detailed and in-depth investigations to explore this subject.

Figure 6 4: Cold gas efficiency as a function of air enrichment in gasifier oxidant [S18]



Steel:

- **Oxygen:** A membrane system with TRL 8-9 which can deliver the required purity of oxygen needed for steel production which ranges from (95 - 99.5) vol% does not exist [S19]. The existing membrane systems at TRL 8-9 give a maximum purity of (50 vol %) [S20]. Therefore, it is concluded that there is no TRL 8-9 membrane can deliver these purities and no any practical application of this technology for this separation;
- No Nitrogen streams available for the targeted separations.

Ammonia and N-fertiliser:

- Nitrogen: The Haber Process combines nitrogen from the air with hydrogen derived mainly from natural gas (methane) into ammonia. Since, the total production capacity of ammonia for Yara's smallest plant (smallest plant in the sector) was given as 1231 ton/day [S21]. Then, total nitrogen requirement to produce 1231 ton/day was back calculated. The nitrogen capacity required is 19000 Nm3/hr with 99.9 vol % purity. But a membrane system with TRL 8-9 Which can deliver the required capacity and purity of nitrogen needed for ammonia production plant does not exist.

Because the maximum production capacity of membrane system can deliver 1875 Nm3/hr at the required purity [S22]. Therefore, it is concluded that there is no TRL 8-9 membrane can deliver these capacities and no any practical application of this technology for this separation at the required capacity.

- No Oxygen streams available for the targeted separations.

Industrial gasses: data are inaccessible due to confidentiality.

Paper and Board: No Nitrogen/Oxygen streams available for the targeted separations.

Food:
- Liquid nitrogen is used for the following:
  - Freezing agent in food freezers;
  - In mixing applications, liquid nitrogen is used to chill sauces and gravies to stop the cooking process while reducing cool cycle times;
  - In coating applications, the low temperature of liquid nitrogen allows it to enrobe individually quick-frozen (IQF) products in sauces while they freeze, helping produce an even coating. Specialized equipment can be coupled with liquid nitrogen to help optimize IQF and non-IQF food freezing, crust freezing, chilling, coating, mixing, and forming. Gaseous nitrogen can be used in a wide range of packaging processes, including Modified Atmosphere packaging (MAP), to help preserve the quality of food.

Thus, these applications require small amount of nitrogen and the saving potential from these small amounts of nitrogen is out of the scope of the project. As a result, the saving potential is very low and therefore it is out of scope.
- No Oxygen streams available for the targeted separations.

6.4 Pervaporation-based ethanol drying

6.4.1 Working principle of energy saving by pervaporation-based ethanol drying

In pervaporation (PV), a liquid mixture is in direct contact with a membrane, where one component will selectively diffuse through the membrane and will be evaporated in the permeate side of the membrane. Because of this, a much more energy efficient separation process can possibly be performed in comparison with distillation where all the components need to be evaporated. Also, separation of azeotropic mixtures can be done using PV and in one single step. Thus, the partial replacement of distillation (hybrid separation) with PV can to a large extent decrease the energy consumption of the process, yield and product quality [S23].
To determine the energy saving potential, several aspects need to be considered. Temperature drop along the membrane module due to the heat of evaporation of water and the number of modules, required heat exchangers, and piping should be accounted for. When temperature drop is large, flux decreases, and large membrane area is required. For several smaller modules with interstate heating, the temperature drop will be lower resulting in a smaller membrane area, but extra requirements for piping, heat exchangers, etc. In addition, permeate pressure will directly affect the techno-economic feasibility of the process [S24].

For calculation of theoretical CO_2 saving potential of PV ethanol drying, real case, state of art technology for ethanol drying was simulated in Aspen plus to mimic the actual process and to serve as reference case for the conventional technology. The energy consumption of this state of art technology was an output of the process model in Aspen. The plant was simulated for the actual production capacity of ethanol for Cargill plant. By contacting HybSi® membrane technology provider [S25], they provided the energy saving potential when membranes are applied instead of the conventional technology which is 30% less of the base case. The energy consumption of the membrane case was calculated as 30% of the base case. Using the production capacities of another plants, the energy consumptions and savings were scaled up from the Cargill case to the other plants, and the summation of the individual plants determines the saving potential of the sector.

Does the working principle change in various industrial sectors? If so to what extend/in what way?
NA

6.4.2 TRL level of pervaporation-based ethanol drying

Compact zeolite membrane plants are in use for processing of about 3800-11350 litres per day of ethanol [S24]. Membranes separation technology is used on commercial scale for this specific capacity. Thus, the TRL is 8-9. However, based on expert's opinion, for several reasons large scale application of pervaporation for ethanol dehydration is not technically interesting because the process is bulky and sensitive to impurities in the liquid phase. Other methods such as vapor permeation (VP) with polymeric membranes providing feasible energy saving of 10-15 % can be considered instead [S26].

Figure 6-4: Photographs of compact zeolite membrane plants processing 1,000 to 3,000 gallons per day of wet ethanol [S24].

In PV membranes are arranged in series and any potential failure in one module will affect the whole separation while at the same time higher capacities is limited. In VP mode, modules can be arranged in parallel and higher capacities can be realised with lower physical footprint.

Another aspect that needs to be addressed is the membrane material type. Typically for PV technology with ceramic or zeolite membranes, a deep vacuum is required to arrive at high flux and separation factors. This represents additional cooling water (cooling tower and chillers) requirement to be built at the plant. In contrast, for VP technology with polymeric membranes a moderate vacuum is required which typically can be found at the plant site and no extra cooling towers is required.

According to ICE™ technology solution [S26], two configurations for VP are possible:

- First, as a bolt-on solution to an existing ethanol production plant with demonstrated CO_2 saving of 15-20 ktonnes/year (CO_2 eq. for a plant of 18000 tonnes ethanol/year) [S26]. In this case a high energy saving can be realised by removing the recycle streams generated during distillation and Molecular Sieve Units (MSU). This will relief the rectifier load and higher ethanol capacities can be reached at lower energy consumption;
- Second, to replace Molecular Sieve Units with demonstrated CO_2 saving of 30-40 ktonnes/year (nearly 40% energy saving). In molecular sieves and due to many pressure swings cracks will appear in the vessel due to high strain. Replacing the mol-sieves with membranes can solve this issue and bringing high energy saving by removing the recycle stream. This will relief the rectifier load and higher ethanol capacities can be reached at lower energy consumption.

In addition, looking at the ethanol production process and experts opinion (confidential interviews), it was found that mechanical vapor recompression (MVR) technology for energy saving at the distillation tower can also provide an extra feasible CO_2 saving potential in ethanol production plants.

Parameters determining whether TRL is 8-9 or lower:

- The required production capacity;
- The purity specification of the product;
- The selectivity and the recovery of the membrane.

Does the TRL level vary in various industrial sectors? If so to what extend/in what way?
The TRL level of pervaporation depends on the product capacity and application area.

6.4.3 Conditions to allow for successful pervaporation-based ethanol drying

What type of infrastructure is required?
No specific infrastructure is required. A utility (electricity and steam). Simple concrete pad plus process and utility lines.

What type of equipment is required?
Heat exchangers, pumps

What type of information should be available?
Wet ethanol flow rate, operating condition and required purity of dry ethanol

Are there conditions that are critical in a specific industrial sector? If so for which sector and to what extend/in what way?
The main challenge membranes face is the cost/performance at large scales in comparison with conventional separation technologies.

6.4.4 Costs and benefits of pervaporation-based ethanol drying

What are typical cost numbers?
No data was provided by the technology providers [S24-S25].

What parameters increase cost numbers; what parameters decrease cost numbers?
Number of separators installed to meet performance criteria.

What are typical benefits?
Much more energy efficient separation process can be performed in compare with distillation

What parameters determine the value of these benefits?
Energy consumption of the process, yield, and product quality.

How vary costs and benefits per industrial sector? Are there industrial sectors with strongly differing costs and /or benefits?
NA

6.4.5 Feasible saving potential

The feasible saving potential is not applicable because there is no theorical economic saving potential for membrane separation of pervaporation-based ethanol drying for the industrial sectors and technologies defined within the scope 6-25 project. For more info refer to the section 6.4.7.

6.4.6 Sensitivity analysis

Sensitivity analysis is not applicable because there is no theorical economical saving potential for membrane separation of pervaporation-based ethanol drying for the industrial sectors and technologies defined within the scope 6-25 project. For more info refer to the section 6.4.7.

6.4.7 Overview of all CO_2 reduction potentials

Table 6-8: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	-	-	-	-	-	-
	Steam crackers	-	-	-	-	-	-
	N-Fertilizer	-	-	-	-	-	-
	Wider chemical industry	718	-	-	-	-	-
Refineries		-	-	-	-	-	-
Iron and Steel		-	-	-	-	-	-
Food		-	-	-	-	-	-
Paper and Board		-	-	-	-	-	-
Total		718	0	0	0	0	0

Notes to table based on expert judgement and confidential interviews

Steam crackers: Not applicable
Refineries: Not applicable
Steel: Not applicable
Ammonia and N-fertiliser: Not applicable
Industrial gasses: Not applicable
Paper and board: Not applicable
Food: Not applicable

7 Power Flexibility

7.1 Introduction and overview of results

In this chapter we discuss two technologies for power flexibility:

1. Fly wheel technology
2. Hybrid boiler

In the tables below the main results are summarised.

Table 7-1 Overview of technologies, saving principles and main conditions.

Fly wheel	
Technology	Fly wheel technology is a system to store electricity. Electric storage systems store electrical energy when the demand is low and release the energy when the demand is high. Flywheel technology operates on a timescale of (milli)seconds to minutes. This can be used in the industry to absorb peaks in power demand of electric motors, or other electric machines, at start-up for example.
Savings principle	By storing and later releasing surplus renewable energy, curtailment of these renewable energy sources is prevented. In this way the production of electricity by non-renewable, CO_2 emitting sources is reduced.
Main conditions and sectors	Savings are scope 2 and not subject of this study. The technology can be applied by network/electricity companies directly.
Hybrid boiler	
Technology	The hybrid boiler can produce steam up to 50 bar(a) and with a maximum temperature of 500 °C by means of an electrode system. The hybrid boiler concept is aimed at utilization of cheap electricity in electricity systems with high shares of renewable electricity production capacity and frequent oversupplies of renewable power compared with grid demand.
Savings principle	During periods with high supply of cheap renewable electricity the electricity is utilized for steam generation, substituting (part of) the on-site fossil fuel consumption and avoiding associated CO_2-emissions and at the same time providing a use for surplus power that may otherwise have to be 'disposed of'. Because the utilized electricity stems primarily from renewable sources, the associated CO_2-emission is zero to limited.
Main conditions and sectors	Resulting from this study, the main applications concern gas fired CHP plants supplying low pressure to medium pressure steam and are primarily operational in paper industry and food industry. CHP plants outside of both sectors included in the theoretical technical potential include Pergen VOF and YARA Sluiskil BV, centrale 3. The given theoretical technical potential refers to a reduction potential of approximately 35% of total current fuel consumption within the considered sectors and by the specific units mentioned.

As flywheel technology has a limited storage capacity, it was concluded in consultation with the technology supplier that this technology has not enough energy saving potential to justify further analysis.

Table 7-2 Overview of results: main economic parameters.

	Fly wheel	Hybrid Boiler – balancing with CHP
Payback period	n/a	Subsidized
TRL	9	9

Table 7-3: Feasible economical CO_2- reduction potential given per technology and sector (kton/y)

Total top 8 industrial sectors		Feasible Economical
		Hybrid boilers
Chemical industry	Industrial gasses	90
	Steam crackers	0
	N-Fertilizer	10
	Wider chemical industry	90
Refineries		0
Iron and Steel		0
Food		130
Paper and Board		50
Total		**370**

7.1.1 Working principle of energy saving by flywheel technology

Flywheel technology is a system to store electricity. Electric storage systems store electrical energy when the demand is low and release the energy when the demand is high. Flywheel technology stores energy by accelerating or decelerating a rotating mass with a large rotational inertia, using a motor/generator to convert electric energy to and from kinetic energy.

The practical applications of electric storage systems differ per timescale. Flywheel technology operates on a timescale of (milli)seconds to minutes. This can be used in the industry to absorb peaks in power demand of electric motors, or other electric machines, at start-up for example. This reduces the strain on the local power grid. It can also be applied as an uninterrupted power supply (UPS).
When a flywheel is implemented as an UPS, it can also function as a power factor adjustment system through is power electronics [F1, interview S4 Energy].

Note: There are various technologies that store electric energy on longer timescales like batteries (hours) or hydrogen (seasonal). On this scale electric storage can be used to store surplus renewable energy, preventing curtailment of renewable energy sources.
Storage of ‘surplus’ renewable electricity is not restricted to industrial production facilities but is rather an option for any party with access to the grid, varying from large scale power producers, by way of network companies and industrial sites down to end users, e.g. smart charging of electric cars.

As it seems more logical that storage takes place 'higher up' in the power grid - for example, on a high-voltage or medium-voltage grid or near solar PV systems (for example, the neighbourhood battery) - or with electricity users who pay a higher price per unit of electricity, it has been assumed that storage on industrial sites has little potential.

The flywheels can also be combined with battery energy storage to combine their respective advantages, i.e. the ramping rate and high capacity of flywheels with the energy storage volume of batteries [F1, interview S4 Energy].

Note: The specific technology provided by S4 Energy is also able to do power factor adjustments. Power factor adjustment is used to reduce reactive power. Various types of electric equipment introduce reactive power in the system, in turn increasing the amount of current needed to deliver the same amount of real power to the system. This increases electrical losses and congestion in electrical grids.

7.1.2 TRL level of fly wheel technology

Flywheel technology is already operational and can use off-the-shelf components, indicating a TRL of 9. The TRL of the technology is independent of the industry sector it is used in, while the applicability might vary.

There are many different electric storage technologies being developed, most of them consider battery technology. Some of the technologies are at the very start of their development, while other technologies are already commercially deployed and technically proven [F3, https://www.iea.org/reports/tracking-energy-integration/energy-storage]. The TRL of various different energy storage systems cover 1 through 9.

7.1.3 Conditions to allow for fly wheel technology

The required conditions of electric storage systems depend on the intended application of those systems. Fly wheel technology is used for local peak power reduction (to either reduce grid tariffs or local congestion), in this case no special conditions are required.
Batteries are used for the storage of intermittent renewable power. In such a case a grid connection of sufficient capacity is required.

7.1.4 Costs and benefits of fly wheel technology

The report costs for flywheel technology are €0,40 and €0,04 per kWh of stored energy (TCO) [F5, product documentation S4 Energy] or 0,145 M€/MW [F6, Danish Energy Agency – Technology data catalogue for energy storage https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.xlsx].
These kinds of systems can be used to reduce peak electricity demands, reducing grid tariff costs or the need to upgrade the capacity of the grid connection. The economic benefits will vary greatly depending on the specific case (e.g. specific load profile of electric machines, costs for upgrading the grid connection).

Note: Flywheel and other energy storage technologies with larger storage duration, like batteries, can operate on the various energy and imbalance markets of electricity. In the use case of the energy markets a profit can be made by the difference in energy prices of the bought (stored) and sold (released) energy. In case of surplus renewable energy, the prices will generally be low, while in case of less renewable energy the prices are expected to be higher. In the use case for the various capacity markets (FCR, aFRR) revenue is created by offering power flexibility on short time scales.
This last application is not dependent on the industry in which it is deployed, as it is a separate business activity, not linked to specific industries, requiring specialist knowledge of and access to short term electricity markets.

Note: As for the 'ad-on' of the S4 Energy fly wheel technology, improving the power factor of an industrial site can decrease energy losses, networks tariffs and possibly circumvent an upgrade of the grid connection. But when electric storage is only used as a power factor adjustment system, it is not economically viable. So only in specific, combined cases, a viable business case can be created [F1, interview S4 energy].

7.1.5 Saving potential

Using flywheels or similar technologies to reduce the peak power demand on industrial sites can be important to enable other electrification options, that in some cases could otherwise be too expensive to implement. The technology itself however does not provide a direct reduction of CO_2 emissions.

By storing and later releasing surplus renewable energy, curtailment of these renewable energy sources is prevented. In this way the production of electricity by non-renewable, CO_2 emitting sources is reduced. Moreover, this application of electric storage system is not specific to industry, but a business on its own and depends largely on the short term (minutes) imbalance in renewable energy production. In general, it is expected that network companies invest in these activities, as part of their core business of providing a stable and profitable energy supply. As they are 'upstream' from the industry they are in the position to harvest the profits that can be made here, before the industry can. Therefore, we do not expect that the industry is in a position to invest in these types of activities in a durable manner.

Note: Using electric storage to improve the power factor can decrease energy losses and reduce related CO_2 emissions. But as mentioned in the previous chapter, is not a viable business case on its own and requires a specific case. It is therefore not analysed further.

7.2 Hybrid Boiler

7.2.1 Working principle of energy saving by hybrid boilers

Description of working principle of the hybrid boiler concept

The 'hybrid' boiler concept developed by Stork is mentioned in various brochures and presentations to be able to produce steam up to 50 bar(a) and with a maximum temperature of 500 °C. The end temperature implies production of superheated steam.

Figure 7-1: Cross section of a Stork 'hybrid' boiler and example of electrode steam boiler with electric superheater. Sources: several brochures by Stork

An overview of technical details is included in Table 7-4.

Table 7-4: Technical details of Stork hybrid boiler concept, details of electrode boilers for comparison

Boiler type:	**Stork hybrid boiler concept**	**DEA, 2020**	**Berenschot, 2015**
Response time hot stand-by:	<2 sec		
Heat	Up to 500°C	saturated	saturated
Pressure	Up to 50 bara	n.s.	70
Capacity (MWth)	5-50 MWe per unit	0,1 - 60	0,5 - 80
Efficiency	99%	99%	99%
Stand-by power consumption (perc of full load)	2%	<1% - 5%	1%
Hot start-up time (seconds)	30	30	30
Cold start-up time (seconds)	n/a	300	300
Techniques:	Combustion + Electrode	Electrode	Electrode

The current concept features an electrode boiler in parallel with a conventional steam generator.

In general water is heated in electrode boilers by means of an electrode system consisting of (typically) three-phase electrodes, a neutral electrode and a water level & flow control system. When power is fed to the electrodes, the current from the phase electrodes flows directly through the water in the upper chamber, which is heated in the process.
With electrode boilers saturated steam of pressures up to 70 bar can be produced [Parat brochure[17]]. A second option for generating superheated steam is producing saturated steam at higher pressure than required, followed by reducing pressure over a control valve.

Figure 7-2: An example of electrode steam boiler with electric superheater

The example concerns a rapid reaction back up steam supply unit at Chempark Leverkusen including:

- 7 MW/10kV boiler, 32 barg steam
- 1 MW "low voltage" superheater (380 °C – 400 °C)

[17] *Parat is a vendor of large capacity electrode boilers*

Description of working principle of energy savings with the hybrid boiler concept

There are potentially three working principles of energy savings with the hybrid boiler concept:

1 Balancing with existing CHP[18];

2 Substitution of existing boiler as steam generator;

3 Substitution of existing CHP as steam generator;

4 Substitution of standby facilities, reducing standby energy consumption.

The hybrid boiler concept is aimed at utilization of cheap electricity in electricity systems with high shares of renewable electricity production capacity and frequent oversupplies of renewable power compared with grid demand.
During periods with high supply of cheap renewable electricity the electricity is utilized for steam generation, substituting (part of) the on-site fossil fuel consumption and avoiding associated CO_2-emissions and at the same time providing a use for surplus power that may otherwise has to be 'disposed of'. Because the utilized electricity stems primarily from renewable sources, the associated CO_2-emission is zero to limited.

In addition, due to its low turndown ratio it may also save standby energy consumption from approximately 10% of consumed on-site heat to several percent[19].

In the evaluation conducted in this project the first option has primarily been considered. Options 3 and 4 have been ignored based on the considerations mentioned below:

- Complete substitution of a CHP would require frequent start-stop operations, which is demanding for gas turbines and will reduce the technical life of the gas turbine, while increasing O&M costs. Complete substitution of the CHP will also require investment costs in systems, such as heating blankets, to keep the gas turbine in hot standby.

  But even then, start up after hot standby requires a ramp up period of tens of minutes before full load has been reached and requires natural gas consumption for further heating the CHP without steam being generated for on-site processes.
- In short, complete substitution of the CHP seems technically challenging and economically less attractive;

  Substitution of natural gas stand-by steam generation capacity has been assumed to give limited savings. Next to that, there is no clear benefit in this situation compared with alternative energy saving options (e.g. steam injection).

Option 2 has been explored only in a manner of sensitivity analysis.
In case of utilizing an e-boiler for substitution of a steam boiler, the technical and economic feasibility is significantly influenced by

- Sufficient transport capacity on the electricity grid for transmitting surplus power to potential customers;
- Availability of a connection with sufficient capacity (in kVA) at a relevant voltage (6 – 24 kV) or with a transformer station with sufficient capacity;
- In case of large production sites, availability of on-site power transportation capacity may also be a limiting condition.

[18] As stated in DEA, 2020: "electrode boilers constitute a promising option for thermal power plants to integrate the electrical output in minimum load operation situations. Thus, the electrical power can be used for heat generation instead of being fed into the grid in hours of negative spot prices".
[19] An alternative option is keeping a stand-by boiler hot by injecting a very limited amount of steam into the boiler. This concept is e.g. applied at in Ede and at Cuijk BCC utilities centre.

As illustrated by e.g. examples related to AVEBE, Smurfit-Kappa Roermond and Royal FrieslandCampina Veghel and evaluations for confidential business cases[20], investment related to increasing grid connection, transformer station capacity on-site transport capacity or laying a new cable from main grid to production site are often prohibitive. In one example for a chemical plant in Rotterdam, investment costs for the e-boiler amounted to M€3, but investment costs for transformers, switch gear, on-site cabling, PF correction amounted to > M€40, while the site is situated adjacent to a high voltage transmission line.

Next to that, in for example the Rotterdam area and Zeeland industrial cluster electricity grid transport capacity is in many areas limited and capacity for transporting surplus power to potential consumers is limited to practically non-existing.
Congestion has also become a problem in more rural area's (Graafschap, Groene Hart, Kop van Noord-Holland)[21] where potential industrial customers are often absent.

A third aspects concerns competition with potential alternative utilizers of surplus or cheap electricity, such as horticulture, electric car owners and operators of heat distribution systems.

The potential problems mentioned above are not relevant when balancing with CHP as power generation and power consumption occur at the same site and on the same spot. In contrast, balancing with an existing CHP can help solving congestion on the electricity grid by halting supply to the grid and utilizing residual electricity production on-site.

Parameters determining a large or a small energy saving potential

Parameters influencing the amount of on-site energy consumption saved are for example:

- The applied concept (complete substitution or balancing, stand-by reduction);
- The hours per year that electricity is utilized for steam generation;
- The efficiency of the reference installation.

In supplied written information, Stork gives an indication that their concept will have an operational time of approximately 1.100 hours/year[22]. In personal communication, operational time is indicated to be potentially significantly higher than 2.000 hours/year, in particular due to the forthcoming SDE++ regulation which gives a subsidy per MWh therm produced up until 2000 hours.
The operational time per year depends for example on the extent to which trading on the various imbalance markets (passive imbalance market, FCR, aFRR) is possible and to what extent trading results in improving the business case.

For comparison:

- In DEA, 2020 the number of full-load hours (heat) for electric boilers is indicated to be 500 per year;
- In the PBL financial gap analysis an operational period of 2.000 full-load hours/year in 2030 has been assumed.

In present assessment the 2.000 hours/year assumed by PBL has been taken as basic assumption (see paragraph 0 for elaboration)

[20] *See: https://www.berenschot.nl/publish/pages/4219/rapportpowertoproducts_1.pdf*
[21] *See e.g.: https://solarmagazine.nl/nieuws-zonne-energie/i19891/liander-meldt-voor-derde-keer-in-2-weken-congestie-elektriciteitsnet-vol-in-dinxperlo-en-hengelo, https://www.enexis.nl/zakelijk/duurzaam/beperkte-capaciteit/gebieden-met-schaarste, https://www.netbeheernederland.nl/dossiers/netcapaciteit-60, https://www.liander.nl/transportschaarste/beschikbaarheid-capaciteit.*
[22] *Source: Stork Project 6-25 Factsheet, author Bart Bramer*

Analysis of the marginal production units of electricity production in 2030 as estimated in the KEV 2019 shows that for up to 2000 full load hours per year, there is a strong correlation in 2030 between a low wholesale electricity price and the use of renewable energy technologies in the electricity production.

7.2.2 TRL level of hybrid boilers

TRL level: 9
Electrode steam boilers are a mature technology and have a Technical Readiness Level of 9. In general electrode boilers concern off the shelf technology with a very high availability and reliability. Because of the very high reliability they are e.g. included for back up steam supply at nuclear power plants. Electrode boilers have been applied in both food industries, chemical industries and paper industry. TRL therefore is assumed to be the same for all sectors considered in this project.

The concept of combining an electrode steam boiler in parallel with a natural gas fired steam generator has been applied since the nineteen eighties in the Norwegian and Swedish industry and is still utilized in these countries. Hence, this combination can be regarded to have a TRL of 9 too.
Since the concept of operation in parallel has been applied in various industries, TRL level is assumed to be the same for all sectors considered in this project.

7.2.3 Conditions to allow for hybrid boilers

What type of infrastructure is required?
The site should have a 6 KV or higher voltage connection to the public power grid and a 6 kV to 24 kV cable between grid connection or on-site transformer station and location of the hybrid boiler. Both should have sufficient capacity, in view of the product specifications of the design, ranging from 5 to 50 MW_e. It is assumed it is possible to combine multiple boilers.

The utilizing company should also have access to the day ahead, the intra-day and the imbalance electricity markets. A demand response control should be implemented controlling both electricity consumption and natural gas consumption.

7.2.4 Costs and benefits of hybrid boilers

Investment costs and O&M costs

An indication of investment costs and O&M costs and several other business case relevant parameters as given by Stork and in several literature, sources are given in Table 7-5.

Table 7-5: Cost related parameters for Stork hybrid boiler concept (as far as given) – parameters for electrode boilers given for comparison

	DEA, 2020 – electrode boiler	SDE++ – electrode boiler	Stork hybrid boiler
Efficiency	99%	99%	n/a
Technical lifetime, years	20	15	25
Construction time, years	0,5	< 1 year	1
Nominal Investment (k€ per MW)	70	115	60
- equipment	60		n/a
- installation	10		excluded
Fixed O&M (€/MW/year)	1.070	49.000	n/a
Variable O&M (€/Mwh) not electricity	0,5	0	n/a

The 60k mentioned by Stork refers to the bare price for the e-boiler without valves and does not include site integration costs, which can be very significant.

Investment costs mentioned in DEA include costs for the distribution board, costs for electrical integration & grid connection fees.
Investment costs considered in SDE^{++} financial gap analysis include:

- Direct costs: boiler, superheater, pump systems, on-site electricity infrastructure, pipework, measuring equipment, civil works;
- Indirect costs: engineering, supervision.

For the concept offered by Stork it is unknown which cost items have been included in indicated investment costs.

The net costs of ownership per unit of produced heat are mainly determined by:

- The prices of natural gas, electricity and of CO_2;
- The efficiency of the reference steam generator;
- Grid connection costs – both investments for increased capacity and annual costs due to higher kW_{max}.

7.2.5 Overview of all saving potentials

7.2.5.1 Theoretical saving potential

An overview of the estimated theoretical technical savings and associated CO2-reductions are given in Table 7-6. The establishment of the estimates is elaborated below.

Table 7-6 Overview of theoretical technical energy savings and associated CO_2-reduction.

	Reduction natural gas consumption, PJ/year			Associated CO_2 reduction, Mtpy	CO_2-emissions related to electricity consumption, Mtpy		Net CO_2-reduction, Mtpy
	CHP	Steam boiler			CHP	Steam boiler	
10 Food industriy	5,5	30,9	36,3	2,06	0,14	1,62	0,29
11 Beverage and beer industry	0,6	1,3	1,9	0,11	0,02	0,07	0,02
17 Paperindustry	3,2	5,2	8,4	0,47	0,08	0,27	0,12
2011 Industrial gases - here PerGen	7,7	0,0	7,7	0,44	0,21	0,00	0,23
2012 Color and dye industry	0,0	0,6	0,6	0,04	0,00	0,03	0,00
2013 Other inorganic basic chemical industry	5,1	6,7	11,8	0,67	0,13	0,35	0,18
2014 Organic basis chemical industry	0,0	0,0	0,0	0,00	0,00	0,00	0,00
2015 Fertilizer industry - here Yara	1,2	0,0	1,2	0,07	0,03	0,00	0,04
2016 - 2017 Plastics and rubbers	1,5	5,0	6,5	0,37	0,04	0,26	0,07
202-206 Other chemical industry	0,1	4,4	4,5	0,26	0,00	0,23	0,02
Steel industry (Tata IJmuiden)			0,0	0,00	0,00	0,00	0,00
Refineries			0,0	0,00	0,00	0,00	0,00
	24,9	54,1	79,0	4,47	0,7	2,8	0,97

The potential has been estimated for food industry, drinks industry (breweries, distilleries), paper industry and for chemical industry other than petrochemical industry (steam crackers), N-fertilizer industry and industrial gases industry

The estimation has been made in three sub-steps.

First sub-step – determining which boilers and CHP-plants are relevant
The first sub-step consisted of eliminating:

- CHP plants and boilers with limited operational deployment and hence limited saving potential;
- CHP plants and boilers mainly fired (mainly) with gaseous and liquid by-products of conversion processes, e.g. :
  - Blast furnace gas and coke oven gas at Tata Steel IJmuiden,
  - Refinery gas in the refinery sector
  - Chemical product gases from steam cracking;

- CHP plants and boilers mainly supplying steam with pressures higher than 50 bar(a) – e.g. Swentibold, Elsta, Eurogen/Enecal, boilers 1 and 2 at Lyondell Botlek.

In case of CHP plants and boilers fired (mainly) with gaseous and liquid by-products of conversion processes, possibilities for ramping down conventional steam generation and substituting conventional production with e-boiler production is limited to non-existing as the by-products have to be burned due to lack of other applications.
In case of CHP plants and boilers mainly supplying superheated steam with pressures higher than 50 bar(a) e-boilers cannot provide steam of the same quality.

The remaining plants concern natural gas fired CHP plants and boilers supplying low pressure to medium pressure steam and are primarily operational in paper industry and food industry. Relevant CHP plants in refinery sector and chemical industry sector include Pergen VOF and YARA Sluiskil BV, centrale 3. The remaining relevant energy consumption is given in Table 7-7.

Table 7-7: Heat consumption (steam, hot water) relevant for potential substitution by steam production with e-boiler (all figures in PJ/year)

	Net intake heat (= steam, hot water)	Steam production CHP	Natural gas for steam boiler[23]	Heat demand relevant for substitution by e-boiler
10 Food industriy	4,2	9,2	38,6	48,1
11 Beverage and beer industry	0	1,1	1,6	2,5
17 Paperindustry	1,8	5,1	6,5	12,8
2011 Industrial gases - here PerGen		Supply of heat to third parties (Shell Pernis)		
2012 Color and dye industry	0,6		0,8	1,3
2013 Other inorganic basic chemical industry	2,5	7,1	8,4	17,2
2014 Organic basis chemical industry				
2015 Fertilizer industry				
2016 - 2017 Plastics and rubbers	9,2	2,4	6,2	17,2
202-206 Other chemical industry	2,1	0,2	5,5	7,3

Second sub-step – estimating potential natural gas consumption savings and associated gross CO_2 emission reduction

The theoretical potential energy saving has been next estimated by assuming that:

- CHP's can be ramped down to 65% of full load capacity;
- Natural gas fired steam boilers can be ramped down to 20% of full load capacity – switching to hot stand-by modus;
- Maximum operational commitment in terms of time (=8.760 hours/year).

[23] *Multiplied with assumed boiler efficiency of 90% for estimating heat consumption relevant for substitution by e-boiler*

In case of balancing with a CHP, net power generation by the CHP-plant is to be reduced to approximately 65% x 26%/32% = 50% of full load capacity (see Table 7-8), due to both ramping down (65% of full load) and a decrease in gas turbine efficiency. The e-boiler has been assumed to consume all remaining power produced by the CHP-plant.
The associated reduction in natural gas consumption amounts to (100% → 65% =) 35% of consumption at full load and approximately 2,2 GJ/GJ of heat produced by the e-boiler (see Table 7-8)[24].

The reduction percentage of approximately 35% has been estimated, based on following balancing regime (Table 7-8).

Table 7-8 Assumed balancing regime electrode boiler : CHP

	GT-HRSG efficiencies		MW supplied GT-HRSG		MW electric boiler (only when GT-HRSG in part load)	Natural gas consumption (MW)	
	GT-HRSG full load	GT-HRSG part load	GT-HRSG full load	GT-HRSG part load		GT-HRSG full load	GT-HRSG part load
electric	32%	26%	10	5,0			
thermal	51%	56%	15,9	10,9	5,0		
total CHP + electric		81,4%		15,9		31	20

As indicated the estimation is that the natural gas consumption of the gas turbine – no co-firing in HRSG assumed –can be reduced with approximately 12 ÷ 31 = ± 35%.

For the case of substitution of a natural gas fired boiler it has been assumed that the gas fired boiler has an efficiency of 90% (LHV) and that heat is substituted on a 1 GJ : 1 GJ base. This results in a 1,1 GJ reduction of natural gas consumption per GJ of substituted heat (1 GJ heat = 1/90% natural gas).

The estimated reduction in natural gas consumption is given in Table 7-9. The reductions can be calculated based on natural gas consumption figures for CHP and boiler and the reudctions in load mentioned in the text above: 35% for CHP's, 80% for boilers.
For example, reduction in natural gas consumption in the food industry associated with steam and hot water generation in boilers has been estimated as 80% of 38,6 PJ/year (see Table 7-7) and amounting to 30,9 PJ/year (see Table 7-9).

The associated avoided CO_2-emission has been calculated utilizing an emission factor for natural gas of 56,6 kg CO_2/GJ, yielding a gross CO_2-reduction of 79 x 0,0566 = 4,5 Mton CO_2/year.

[24] *Natural gas consumption decreases in the example with 11 MW, while net heat generation by the e-boiler amounts to 5 MW_{th}, giving a ratio of 11/5 = 2,2 GJ_{ng}/GJ_{th}.*

Table 7-9: Estimated reduction in natural gas consumption (all figures in PJ/year)

	Reduction natural gas consumption, PJ/year		
	CHP	Steam boiler	Sum
10 Food industriy	5,5	30,9	36,3
11 Beverage and beer industry	0,6	1,3	1,9
17 Paperindustry	3,2	5,2	8,4
2011 Industrial gases - here PerGen	7,7	0,0	7,7
2012 Color and dye industry	0,0	0,6	0,6
2013 Other inorganic basic chemical industry	5,1	6,7	11,8
2014 Organic basis chemical industry	0,0	0,0	0,0
2015 Fertilizer industry - here Yara	1,2	0,0	1,2
2016 - 2017 Plastics and rubbers	1,5	5,0	6,5
202-206 Other chemical industry	0,1	4,4	4,5
Steel industry (Tata IJmuiden)			0,0
Refineries			0,0
TOTALS	24,9	54,1	79,0

Third sub-step – correction for indirect CO_2-emissions
In case of switching natural gas fired boilers to hot stand-by, the power required for steam production with e-boilers has to be supplied from outside sources. The associated CO_2-emission has been estimated assuming an emission factor of 58 kg CO_2/GJ_e, in accordance with KEV, 2019[25].

In case of switching boilers to hot stand-by, CO_2-emissions related to natural gas-based steam generation (63 kg CO_2/GJ steam)[26] are almost on par with indirect CO_2-emissions related to electricity consumption (58 kg CO_2/GJ steam)[27] and net CO_2-reduction is limited.
In case of balancing of e-boiler and CHP, each GJ of heat generated with an e-boiler is equivalent with 2,2 GJ of natural gas, resulting in a net reduction of 2,2 x 56,6 – 58 = 124,52 – 58= 66 kg CO_2-eq/GJ heat produced by e-boiler.

The resulting net CO_2-emission reduction amounts to 1,3 Mton CO_2/year. the net reduction being achieved almost solely through energy savings by balancing existing CHP installations.

[25] *see Excel appendix, Tabel_13b_Elektr_Aanbod_VV. Emission factor value refers to power supply ad 2025 for 'integral method' as is consistent with assumed maximum operational commitment in terms of time*
[26] *Assuming natural gas fired boiler efficiency of 90% (see SDE+/SDE++ basic assumptions)*
[27] *Assuming e-boiler efficiency of 100%*

Table 7-10: Estimated resulting net CO2-emission (all figures in PJ/year)

	Reduction natural gas consumption, PJ/year			Associated CO_2 reduction, Mtpy	CO_2-emissions related to electricity consumption, Mtpy		Net CO_2-reduction, Mtpy
	CHP	Steam boiler			CHP	Steam boiler	
10 Food industriy	5,5	30,9	36,3	2.056	145	1.621	291
11 Beverage and beer industry	0,6	1,3	1,9	106	16	67	23
17 Paperindustry	3,2	5,2	8,4	474	84	273	117
2011 Industrial gases - here PerGen	7,7	0,0	7,7	439	205	0	233
2012 Color and dye industry	0,0	0,6	0,6	36	0	34	3
2013 Other inorganic basic chemical industry	5,1	6,7	11,8	668	135	353	180
2014 Organic basis chemical industry	0,0	0,0	0,0	0	0	0	0
2015 Fertilizer industry - here Yara	1,2	0,0	1,2	69	32	0	37
2016 - 2017 Plastics and rubbers	1,5	5,0	6,5	367	41	260	66
202-206 Other chemical industry	0,1	4,4	4,5	255	3	231	21
Steel industry (Tata IJmuiden)			0,0	0	0	0	0
Refineries			0,0	0	0	0	0
	24,9	54,1	79,0	4.471	661	2.839	971

7.2.5.2 Limitations due to planning

Limitations due to planning are estimated to not have a significant impact on the emission reduction potential. In food and paper industry stops for maintenance, hygienic and /or commercial reasons are common and therefore not a limiting factor. The same applies to CHP-units in chemical industry, where steam supply is assured with back-up facilities.

7.2.5.3 Maximum economic potential without discounting congestion, competition and other limiting aspects

To estimate the savings potential without discounting limiting aspects, it was first investigated to what extent using e-boilers is profitable without an SDE++ subsidy[28], based on the estimated future hourly prices for electricity as determined within the scope of the KEV, 2019 assessment. This turned out to be not the case for neither balancing with an existing CHP nor for switching natural gas fired boilers to hot stand-by (see Figure 7-3 and Figure 7-4).
It has been hence concluded that the operational period for e-boilers will be limited to a maximum of 2.000 hours/year in 2025, consistent with the basic assumptions in the SDE++ subsidy scheme for e-boilers.

[28] *The broad evaluation has been based on investment costs and O&M-costs as adhered in the SDE++ scheme.*

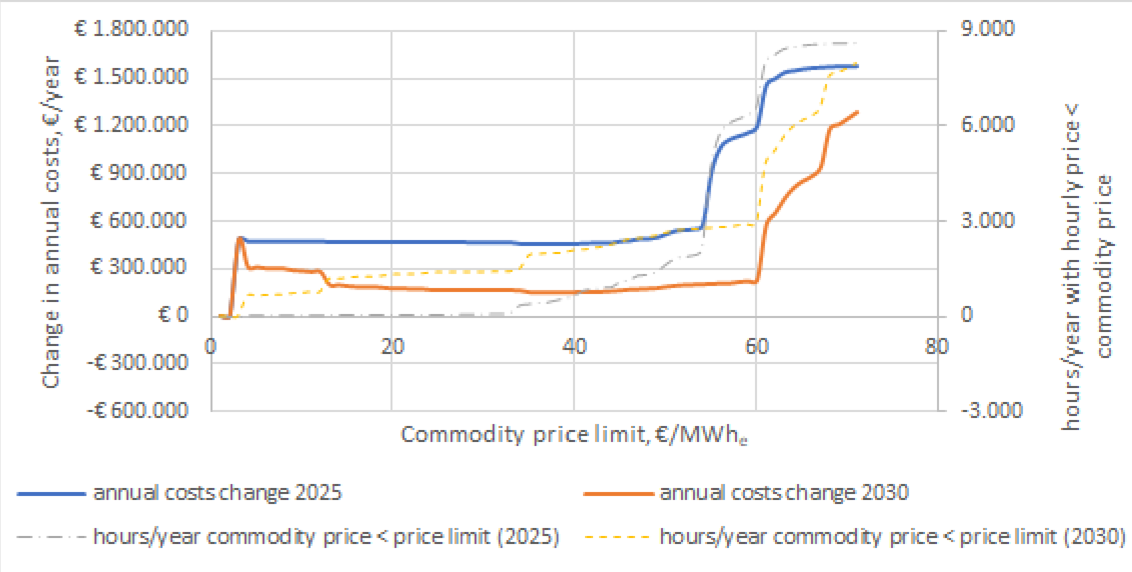


Figure 7-3: Estimated changes in annual costs as a function of annual operational period of e-boiler – switching conventional natural gas fired boiler to hot stand-by

Elucidation:
The graph shows the development of the change in annual costs (continuous lines) as a function of the hourly electricity commodity price up to which purchased electricity is utilized for steam generation.
The change in annual costs has been calculated as the reduction in costs for CO_2-emission rights and natural gas purchase costs and the increase in electricity purchase costs with addition of the annual capex and opex costs for an e-boiler.
The dashed line shows the number of hours per year that the hourly electricity commodity price is lower than the price limit value on the horizontal axis.

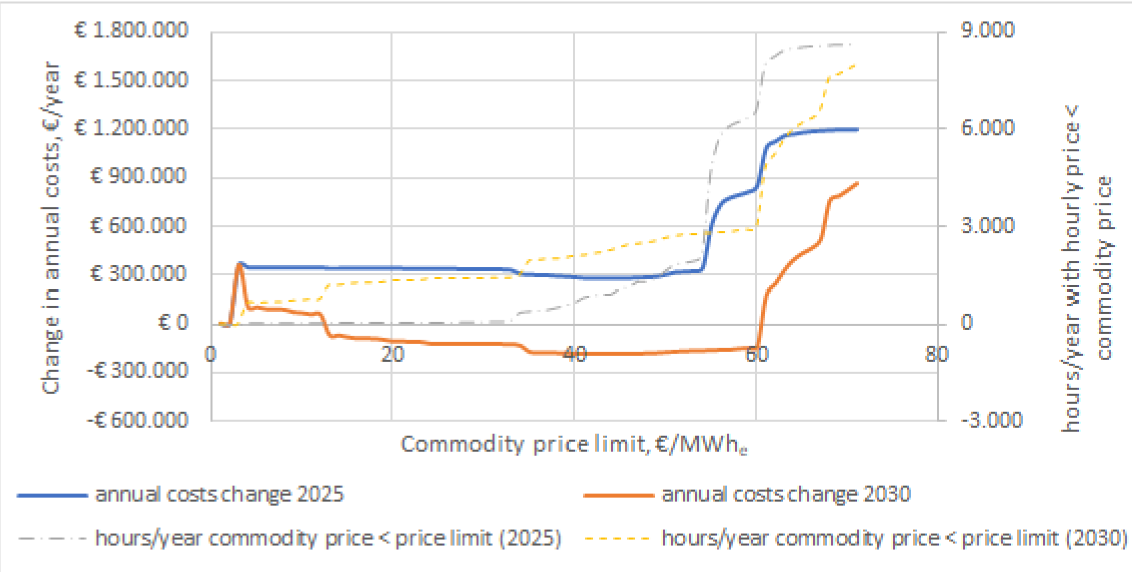


Figure 7-4: Estimated changes in annual costs as a function of annual operational period of e-boiler – balancing with CHP

The associated calculation of the net CO_2-reduction is included in Table 7-11. Indirect CO_2-emissions related with electricity purchases have been estimated assuming an emission factor of 20 kg CO_2/GJ_e for electricity generated within this period of 2.000 hours/year.
The considered emission factor for indirect CO_2-emissions is lower compared with the emission factor for the theoretical maximum potential because it has been assumed that the considered 2.000 hours/year refer to the hours with the lowest electricity price, during which electricity from renewable sources provide all or the larger part of power supplied to the grid.

Table 7-11: Overview of savings and associated CO_2-reduction estimates for economic potential without limiting aspects.

	Reduction natural gas consumption, PJ/year (2.000 hours/year)[29]			Associated CO_2 reduction, Mtpy	CO_2-emissions related to electricity consumption, Mtpy		Net CO_2-reduction, Mtpy
	CHP	Steam boiler			CHP	Steam boiler	
10 Food industriy	1,2	7,1	8,3	2,06	0,14	1,62	0,29
11 Beverage and beer industry	0,1	0,3	0,4	0,11	0,02	0,07	0,02
17 Paperindustry	0,7	1,2	1,9	0,47	0,08	0,27	0,12
2011 Industrial gases - here PerGen	1,8	0,0	1,8	0,44	0,21	0,00	0,23
2012 Color and dye industry	0,0	0,1	0,1	0,04	0,00	0,03	0,00
2013 Other inorganic basic chemical industry	1,2	1,5	2,7	0,67	0,13	0,35	0,18
2014 Organic basis chemical industry	0,0	0,0	0,0	0,00	0,00	0,00	0,00
2015 Fertilizer industry - here Yara	0,3	0,0	0,3	0,07	0,03	0,00	0,04
2016 - 2017 Plastics and rubbers	0,3	1,1	1,5	0,37	0,04	0,26	0,07
202-206 Other chemical industry	0,0	1,0	1,0	0,26	0,00	0,23	0,02
Steel industry (Tata IJmuiden)				0,00	0,00	0,00	0,00
Refineries				0,00	0,00	0,00	0,00
	5,7	12,3	18,0	4,47	0,66	2,84	0,97

In 2030 balancing of e-boiler with a CHP – but not switching a conventional boiler to hot stand-by - is estimated to be economically viable (change in annual costs < 0).

7.2.5.4 Maximum reliable potential

As indicated in paragraph 7.2.1, the potential for implementation of e-boilers as an alternative for natural gas fired boilers can be significantly influenced by aspects such as availability of transmission capacity on the public grid, the capacity of the grid connection and cabling onsite and competition with other sectors (horticulture, district heating) and other technologies (charging of electric vehicles). These factors are very location dependent and cannot be estimated within this abridged study.
Indications given by experts during confidential interviews for the percentages of e-boilers that may be implemented as an addition to natural gas fired steam boilers amount to values of 20% for food, beverage and paper industries and 10% for other sectors.

[29] *Indicated savings amount to 2.000 ÷ 8.760 = 23% of the saving potential considered for the theoretical saving potential as indicated in Table 7-10 (three leftmost columns).*

For balancing of an e-boiler with an existing CHP the uncertainties mentioned in paragraph 7.2.1 are not applicable. Moreover, balancing is economically more attractive, after 2030 possibly also economically viable without subsidy. This concept is therefore more likely to be implemented after 2025.
Aspects that may reduce potential savings and economic feasibility related to combining an e-boiler with an existing CHP are:

- Energy savings and reduced on-site heat demand;
- Effect of co-firing in HRSG.

With increasing energy savings the CHP may have to be ramped down and a point may be reached where it is technically or economically no longer viable to keep the CHP in operation, not even in periods with higher electricity prices. At that point implementation of an e-boiler is also no longer feasible and the potential energy savings and CO_2-emission reduction will evaporate.

Specifically, at GT/HRSG installations in paper industry and food industry a significant percentage of the generated heat is produced by co-firing of natural gas in the HRSG. At such plants it is technically more logical to reduce the co-fired amount of natural gas when implementing an e-boiler. In that case the substituted amount of natural gas is significantly lower compared with the implementation strategy considered in this broad analysis (1,25 : 1 instead of 2,2 : 1 (see Table 7-8)). The associated CO_2-reduction will hence be less than estimated in this evaluation and the business case will be more unfavourable.
Both aspects have been ignored in this high-level analysis but may have a decreasing effect on CO_2-emission reduction potential and a degrading effect on the business case for e-boiler implementation.

The remaining feasible energy saving potential for 2025 amounts to approximately 8 PJ/year and the associated avoided CO_2-emission to approximately 400 ktpy (see Table 7-12).

Table 7-12: Overview of estimated feasible economic CO_2-reductions.

	Net CO_2-reduction, Mtpy	For steam boilers	for CHP
10 Food industriy	0,12	0,06	0,06
11 Beverage and beer industry	0,01	0,00	0,01
17 Paperindustry	0,05	0,01	0,04
2011 Industrial gases - here PerGen	0,09	0,00	0,09
2012 Color and dye industry	0,00	0,00	0,00
2013 Other inorganic basic chemical industry	0,06	0,01	0,06
2014 Organic basis chemical industry	0,00	0,00	0,00
2015 Fertilizer industry - here Yara	0,01	0,00	0,01
2016 - 2017 Plastics and rubbers	0,02	0,00	0,02
202-206 Other chemical industry	0,01	0,00	0,00
Steel industry (Tata IJmuiden)	0,00	0,00	0,00
Refineries	0,00	0,00	0,00
	0,36	0,09	0,28

7.2.5.5 Sensitivity analysis

We performed sensitivity analysis on certain crucial parameters which are expected to influence the outcomes and can be stimulated by policy measures.

Therefore, we analyzed the effect on feasible economic CO_2 saving potential when:

1 A **payback period of 10 years or less** is considered financially attractive;

2 A **WACC of 4%** is used to:

- analyze the future cash flow instead of 8% and,
- calculate savings for technologies with payback period of 5 years or less.

7.2.6 Overview of all CO_2 reduction potentials

Table 7-13: Theoretical and feasible CO_2 reduction potential (kton/y)

		Theoretical potential		Feasible potential			
Total top 8 industrial sectors		**Theoretical Technical**	**Theoretical Economical**	**Feasible Technical**	**Feasible Economical**	**Sensitivity analysis**	
						Pay back ≤10 yrs	*WACC 4%*
Chemical industry	Industrial gasses	230	230	90	90	90	90
	Steam crackers	0	0	0	0	0	0
	N-Fertilizer	40	40	10	10	10	10
	Wider chemical industry	270	270	90	90	90	90
Refineries		0	0	0	0	0	0
Iron and Steel		0	0	0	0	0	0
Food		310	310	130	130	130	130
Paper and Board		120	120	50	50	50	50
Total		970	970	370	370	370	370

8 Overlap Correction

We analysed 15 technologies on their CO_2 reduction potential. Most of these technologies affect specific processes and therefore do not influence each other's CO_2 reduction potential. There are some exceptions. Below we analyse the mutual influence and quantify the overlap correction that is required to account for these effects:

Below we first discuss why overlap does not occur between technologies or is negligible.

- Energy efficient motor systems and all other technology groups: the only technology that could influence the potential of electromotor systems is the technology group of ICT, but we divided our assumptions in such a way that there is no or negligible overlap between those two categories;
- Separation and all other technology groups: the potential of the technology group separation is so specific that there is no other technology group that interferes with its CO_2 reduction potential.

Technologies that influence each other's CO_2 reduction potentials are:

- MVR, heat pumps and heat transformers;
- Hybrid boiler potential and heat storage;
- ICT and both technology groups described above.

8.1 MVR, heat pumps and heat transformers

MVR, heat pumps and heat transformers are different technologies, each with their own limitations, temperature range, scale of operations and specific costs and benefit. But they aim for the same: upgrade heat from a temperature level in the process where there is a heat excess to a temperature level where there is a heat shortage.
If we look at the calculated potentials than we see the following, totaling a CO_2 emission reduction potential of 793 kton:

Table 8-1: Feasible economic reduction potential before correction

Sector	MVR	Heat transformer	Heat pump
Industrial gasses	0	0	0
Steam crackers industry	15	29	4
Ammonia and N-fertiliser	2	0	1
Wider chemical industry	127	86	52
Steel	8	0	2
Refineries	23	76	6
Food industry	165	16	165
Paper Industry	88	0	38
	428	**207**	**267**

First, we corrected for the fact that for the demand for heat at temperatures below 100oC the heat pump potential does not overlap with MVR and heat transformers (82 kton CO_2/year in food and 17 kton /year in remaining chemical= 99 kton without overlap)

Table 8-2: Feasible economic reduction potential of heat pumps above 100 degrees Celsius.

Sector	Heat pump potential above 100 oC
Industrial gasses	0
Steam crackers industry	4
Ammonia and N-fertiliser	1
Wider chemical industry	35
Steel	2
Refineries	6
Food industry	83
Paper Industry	38
	267

Second, we corrected for the limitations in overlap between MVR and Heat pumps. The overlap between MVR and heat pumps is approximately 75% due to differences in type of streams that can be upgrades and temperature ranges.

Table 8-3: Remaining potential above 100 degrees Celsius after correction for overlap between MVR and Heat Pumps

Sector	MVR	Part of HP that does not overlap with MVR above 100 oC	MVR/HP
Industrial gasses	0	0	0
Steam crackers industry	15	1	16
Ammonia and N-fertiliser	2	0	3
Wider chemical industry	127	9	136
Steel	8	1	8
Refineries	23	2	25
Food industry	165	21	186
Paper Industry	88	9	98
			470

Third, we correct the combined potential of MVR and heat pumps (MVR/HP) for overlap with heat transformers. The combined potential of MVR and heat pumps (MVR/HP) overlaps with heat transformers. Only a heat transformer is capable of upgrading condensate streams and MVR is not. While a heat pump is capable of upgrading condensate streams but not to the high temperatures a heat transformer is capable of. Based on these reasons we expect that the combined potential of MVR/HP and heat transformer overlap for approximately 75%.

Table 8-4: Remaining potential for MVR/Heat pumps and heat transformers above 100 degrees Celsius after correction.

Sector	Heat transformers	Part of MVR/HP that does not overlap with heat transformers above 100 oC	MVR/HP/HT
Industrial gasses	-	-	-
Steam crackers industry	29	4	33
Ammonia and N-fertiliser	-	3	3
Wider chemical industry	86	34	120
Steel	-	8	8
Refineries	76	6	82
Food industry	16	46	62
Paper Industry	-	98	98
			406

Finally, we add the part of potential of food and remaining chemicals below 100^{o}C.

This means that from the original 903 kton combined economical saving potential 505 kton remains valid (minus 397 kton).

Table 8-5: Economic feasible potential before correction (columns MVR/HT/HP) and after (column Combined potential)

Sector	MVR	Heat transformer	Heat pump	combined potential
Industrial gasses	0	0	0	0
Steam crackers industry	15	29	4	33
Ammonia and N-fertiliser	2	0	1	3
Wider chemical industry	127	86	52	137
Steel	8	0	2	8
Refineries	23	76	6	82
Food industry	165	16	165	145
Paper Industry	88	0	38	98
	428	**207**	**267**	**506**

Combined effect of the technology group Heat and the Hybrid boiler potential
Part of the Hybrid boiler demand depends on balancing of CHP generation. This is only an economically valid option if the CHP generation has a solid business case. However, in most sectors the business case of the CHP generation is already precarious.
So if a technology significantly reduces the heat demand this may further weaken the business case of the CHP generation. Making it necessary to choose between the one and the other option.

When determining the potential for heat pumps, MVR and heat transformers we already took this limitation into account. So thre is no overlap with these technologies. However, there is some overlap with flue gas heat recovery, see table 8-6.

Table 8-6: Economic feasible potential before and after (column combined potential) correction for overlap between heat integration and the hybrid boiler.

Sector	Flue gas heat recuperation	Hybrid boiler	Combined potential
Industrial gasses	5	90	91
Steam crackers industry	55		55
Ammonia and N-fertiliser	10	10	10
Wider chemical industry	59	80	95
Steel	85		85
Refineries	49		49
Food industry	67	60	82
Paper Industry	20	40	45
	350	280	512

This shows the following:

- No or a negligible overlap for the sectors: industrial gasses, steam crackers, steel and refineries, thus no correction there;
- There is a very similar potential for Flue gas heat recuperation and Hybrid boiler by means of CHP balancing in the N-fertilizers sector, the Wider chemical industry sector, the food and the paper sector.
    - For the N-fertilizer industry we expect that the combined potential of Heat recuperation and Hybrid boiler is halved either because there is no longer a CHP to be balanced or the heat recuperation is not installed to keep the CHP running. Reducing the combined potential to 11 kton;
    - For the other sectors this potential is divided over a large number of factories. Changes are that the hybrid boiler potential to balance a CHP occurs at site A while the flue gas recuperation occurs at site B and C. So, it is possible that these two potentials do not overlap. Therefore, we divide the smallest of the two potentials by four before we combine the two of them to the total potential after overlap.

This means that the previous total combined potential of 630 kton CO_2 is reduced to 512 kton (minus 118 kton).

8.2 ICT and both technology groups described above.

ICT measures overlap with the other measures mentioned above. But since they do not overlap 100% and the ICT saving potential is limited, we expect that this effect is lower than the accuracy of this study. Therefore, we neglect this effect.

This means that the total feasible economical potential of the 8 sectors is to be decreased with 266 kton.

9 References

Below you can find all references, they all start with the corresponding letter of the technique, followed by the number regarding the correct reference.

B Basis (chapter 1)
E Electric Motors
H Heat
I ICT
S Separation
P Power flexibility

Basis

B1	KEV 2019- vastgesteld en voorgenomen beleid
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B3	Energie-investeringsaftrek (EIA) https://www.rvo.nl/subsidie-en-financieringswijzer/energie-investeringsaftrek-eia
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B6	International Energy Agency (2019), World Energy Outlook 2019, IEA, Paris
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B8	MONIT-versie 3 september 2019
B9	CE Delft, Denktank Energiemarkt Industriele Warmtemarkt
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I17	Emerson Steam Header Optimization Factsheet - Rev2.0
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Appendices

A1 Overall Process Design Validation Methodology "Project 6-25 Technology Validation

A1.1 Introduction

This document describes the overall process design of the validation methodology of "Project 6-25 Technology Validation". Acceptance of the results of this validation study by various stakeholders is crucial. Therefor transparency of the methodology, of the used data and of the calculations leading to the results is important.

Validation = Transparency (as much confidentiality allows)

The concept of "Auditable trail" is applied, which means that all data, calculations and assumptions are documented and accessible in the public domain. This concept of transparency is limited by confidentiality requirements.

This document describes the data flow during the validation of the "Project 6-25 Technology Validation". The actual validation of the input data, calculations, results and conclusions will be delivered in the report of the Final Results (Task 3)

A1.2 Challenges

The main challenges are:

1. Transparency can be limited by confidentially issues. This is limited to specific and described data. Most of these confidential data are shared for review with the project team of Project 6-25 under NDA. Data available at Royal HaskoningDHV/PDC under NDA will not be shared with the Project Team of Project 6-25 as agreed contractually at assignment;
2. Lack of data or level of detail can ask for expert judgements;
3. Expert judgement will be required to avoid overlay of different technologies that could result in double counting.

A1.3 Objective

The objective of this validation methodology report is to demonstrate as much as confidentially limitations allows:

1. Transparency in assumptions as stated in the Terms of Reference and further assumptions identified during the execution of the Validation study;
2. Transparency in data sources;
3. Transparency in calculations.

And for all these items how these will be documented in the final report.

A1.4 Assurance

The validation methodology of the “Project 6-25 Technology Validation” will be assured and discussed in the following steps:

1. Review the overall data flow during validation with the project team Project 6-25 (this memo discussed on 6 April);
2. The algorithms and data of the technical and economical CO_2-emission reduction potential in Report 1 (reviewed with the Steering Group during the first workshop with the steering group on 23 April);
3. The limitations in the implementation of CO_2-emission reduction potential at industrial sites and the sensitivity analysis argumentation in Report 2 (reviewed with the Steering Group on 8 June).

A1.5 Starting points and assumptions

The following starting points are applied:

1. Calculation algorithms, scope of technologies to be investigated and selection of hot spots investigated in Task 2 are defined in the Request for Proposal, our Proposal, the clarification letter dated 24th February 2020 and the assignment letter and further agreements during Steering Group meetings. Changes and further assumptions will be shared timely with the project team. All starting points and assumptions will be documented in the final report.
2. All data and calculation algorithms are transparent and documented unless confidentially restricts publication. We identified the following levels of confidentiality:
   - 2.1 Public;
   - 2.2 Project team;
   - 2.3 Royal HaskoningDHV/PDC.

In the tale below the level of confidentiality is defined per Source

Appendix Table 1: Sources

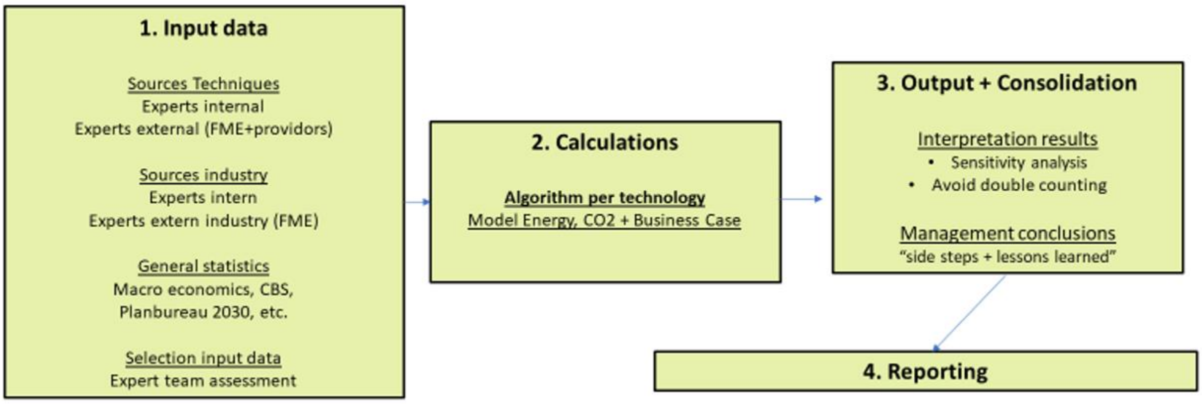
Source	Level of confidentiality
Agreement with FME/SG (e.g. ToR); Starting points and calculation algorithms (e.g. Pay Back Time)	Public
Technology provider data:	
Factsheets prepared by FME (list in report)	Project Team
Meeting notes Technology providers	Project Team
Brochures, leaflets Technology providers	Public
Industry data	
Meeting notes industry	Project Team
Email / communications --> linked to meeting reports	Project Team
Statistics (PBL, CBS, KEV, …)	Public
Studies third parties (with reference)	Public
Expert judgement	Public*
Personal communications	Public*
Data Royal HaskoningDHV/PDC restricted by NDA with 3rd party	Royal HaskoningDHV/PDC

** except for confidential input data: project team under NDA*

Data received in interviews with Technology providers (source 2) and Industry (source 3) will be reported in meeting notes. Before sharing with the Steering Group, the meeting notes will be submitted to the interviewee for approval.

A1.6 Validation Methodology

The validation methodology of “Project 6-25 Technology Validation” is presented schematically in *Appendix Figure 1*. Validation Methodology and Auditable trail.



Appendix Figure 1: Validation Methodology and Auditable trail

Step 1. Input data
Data derived from various sources are evaluated and assessed by the technology teams. This results in the input data that will be used in the energy saving and CO_2-emission reduction calculations.

Step 2. Calculations
For each technology a calculation module is developed with a specific algorithm. In Task 1 the first drafts for the algorithms for potential energy saving and potential CO_2 emission reduction are developed and discussed with suppliers. In task 2 improved algorithms for the impact of implementation limitations and avoidance of double counting are developed and discussed with industries. The approach is put in a calculation model that will be applied to generate the required output.

Step 3. Output + Consolidation
The calculation model will be applied to generate the Feasible (Technical and Economical) CO_2 emission reduction potential. To get an impresson of the best approach for policy meansures also sensitivity analysis will be done on the effect of the height of the WACC and the duration of the payback period. These outputs will be interpreted, analysed and consolidated in management conclusions

Step 4. Reporting
All previous step will be documented in a concise report with reference to sources in Annexes

A1.7 Reporting

Leading principle is that the reader can derive the results and conclusion from the reported data, calculation algorithms and assumptions.

Input data
The way we gathered the input data from public sources, fact sheets, communications and interviews with technology providers and approved interview reports etc. will be described for all technologies.

All input data including sources used in the calculations will be reported in annexes to the report.

Calculation
We will describe the calculation methods in the report. This includes the selection of technology industry combinations that are selected to be validated in more depth in the 2nd stage. Also, the calculation methods and assessment methodology applied during the 2nd stage to identify the limitations in the implementation of CO_2-emission reduction potential at industrial sites and the sensitivity analysis will be described.

All used calculation algorithms will be reported in annexes to the report.

A1.8 Output and Consolidation

The aggregation and consolidation of calculation results will be described in the report. The interpretation and sensitivity analysis will be described and documented in the report as well.

When applicable, details and additional data applied will be documented in annexes.

A1.9 Validation Protocol information from interviews with Industry

Introduction
In task 2 we develop methods to estimate the changes and limitations to implementation of technologies per industrial sector. To validate our assumptiosn we want to interview a selected number of people form industry. This note addresses the validation methodology of the assessment of industry interviews on the limitations of the identified Economical CO_2 emission reduction potential. This is a further detailed approach of the validation methodology agreed already

Challenge
Industry experts / employees are very careful and reluctant to share information and views on process and energy related issues. If this information would become available in the public domain industry experts would limit sharing information or even decline requests for interviews. This would negatively impact the reliability of the assessment of the industrial limitations.

On the other hand, FME and related stakeholders want to have insight in the validation methodology and an auditable trail of information and calculations

Approach
We will share information from industry interviews with represents of VEMW and FME under NDA as far as this is not limited by confidentiality requirements of the interviewed industry experts.

We will apply the following protocol and share under these conditions for the industry validation:

1. **Questionnaire** guideline for interviews
2. The number of **interviewed** industries per sector (names industries, unless not allowed)
3. A summary of **general observations** like which technologies are familiar, considered and/or implemented
4. Would none of the interviewees be familiar with a technology further external validation of limitations is not available and the consortium will make its own **assessment**. This will be indicated in the final report
5. An industry limitation validation **feedback call/meeting** of the interviews in which the consortium is available for clarifications with Participants from VEMW, FME, RHDHV and PDC
6. The results will be discussed in the report **without being traceable** to the interviewed company
7. The results (content) of this industry limitation validation feedback call/meeting will **remain confidential** and will not become part of the final report

Overview sectors and number interviewed experts

Appendix Table 2: Overview sectors and number interviewed experts

Industry Sector	Number of interviewed experts
Industrial gasses	2
Steam crackers	8
Ammonia & N- fertilizer	2
Remaining chemical industry	1
Refineries	5
Iron and Steel	2
Food	6
Paper & Board	3

A2 Compressor types and control options in industry

Appendix Table 3: Compressor load control mechanisms for major types of compressors in the industry

COMPRESSOR TYPE	Reciprocating (double acting)	Screw	Centrifugal	Axial
APPLICATION	**WIDE**	**WIDE**	**WIDE**	**Specific, e.g. large air compressors**
CONTROL OPTIONS *(usually 2 or more are combined)*				
Pump around recycles (loss proportional to not-used flowrate, POWER = CONSTANT)	STANDARD in combination with **50%-75%-100% switching**	POSSIBLE but UNLIKELY (more likely modulation or load-unload)	USUALLY (antisurge protection)	USUALLY (antisurge protection)
LOAD-UNLOAD	-	COMMON (internal small recycling/ only portion of full compression ratio for the recycle)	-	-
On – OFF SWITCHING (some minor loss during switching, efficiency depends on how often it happens, too often is a reliability problem)	POSSIBLE	COMMON (for longer idle operation)	POSSIBLE (start-stop/load-unload)	NOT REALLY (huge fully continuous applications)
VFD (small loss on VFD, efficiency of compressor may change a bit, but practically POWER = A x FLOW)	POSSIBLE	POSSIBLE	POSSIBLE (potential limited by surge)	POSSIBLE (potential limited by surge)
HYDROCOM (no-loss, power proportional to flowrate, POWER = A x FLOW)	POSSIBLE (preferred over VFD based on own experience)	-	-	-
50%-75%-100% switching (no loss at the three operation points)	ALWAYS	-	-	-
***INLET VALVE/ INLET GUIDE vanes** (comparable to additional VFD inefficiency, 20% flow reduction, 5% loss of power efficiency for IGV. Better efficiency for IGV than IBV)	**-**	POSSIBLE (only IV for “modulation” control)	COMON (IGV is standard, IV possible)	COMON (IGV only)

**unlike throttling for pumps affects more flowrate & power via density change and momentum impact of compressor blades rather than pressure – much more efficient as compared to choking of pumps.*

ESTIMATED MAXIMUM SAVINGS FOR INDIVIDUAL COMPRESSOR TYPES:
Potential by hardware limits.

Reciprocating: Maximum 12.5% for single compressor with and no HYDROCOM/no VFD installed due to cascading power by 25%. The saving potential is reduced by utilization of multiple compressors in parallel as typical for fluctuating refrigeration or plant air demand. In general, maximum potential saving of 3-5% is anticipated by installation of VFDs or HYDROCOM.

SCREW: 5% saving of VFD vs. Load/Unload control at 80% of the design flowrate. For less power demand (more fluctuating) on-off switching is utilized as well and it is 100% efficient. Larger savings possible in case of modulation control of the compressor, up to 15% of power consumption for operation of the compressor at 80% load. All potential savings are reduced by multiple compressors in parallel, as typical for fluctuating refrigeration or plant air demand (2-5 compressors in parallel). IN general, maximum 3-5% saving is anticipated.

CENTRIFUGAL and AXIAL: IGV are a standard performance control solution now. Power saving of 5% can be achieved by replacing inlet butterfly valves (older systems) by inlet guide vanes (standard now) or VFD, in case of flowrates lower by 20% as compared to BEP. This saving is applicable only in significantly lower flowrates as compared to BEP (design point). Inlet guide vanes or VFDs present efficient flowrate control. In reality, maximum of 1-2% savings in total.

In total, the estimate of potential power savings by more efficient performance control hardware is maximum of 3-5% for air and refrigeration compressors. For large continuously operating compressors in chemical industry and refineries, it is maximum of 1-2 %.

NOTE 1: Efficient hardware solutions of flowrate control are typically complemented by less efficient controls (e.g. throttled recycles), which are in place for startups/shutdowns or e.g. surge protection. All control systems are in general active at the same time to respond to emergency situations. Proper control of this complex hardware, or efficient control of e.g. on-off cycles of screw compressors is needed to achieve energy figures to the limits of the installed hardware possibilities.

NOTE 2: Significant part of the saving can be achieved by replacement of the electromotor for a more efficient typ. This is covered in a separate section of the report.

NOTE 3. Replacement of the whole compressors by new – more efficient design is not considered this P-625 report. The efficiency of the compressors varies between types / applications / considered number of compressor stages, intercooling system and age of the compressor (e.g. polytropic efficiency of centrifugal compressors was improved from 70% to 85% between 1970 and 1990 and further to ~87-89% as presently standard. The aerodynamic limit is ~91%).

These considerations are significantly affected by the specific application and economy of the project. No clear way is foreseen to generate a representative statistic for efficiency of the compressors which currently installed in the industry and especially for its potential improvement **without assessing each case individually**. Economically, diminishing efficiency gains needs to be further balanced against additional costs for each individual project. In general, due to large CAPEX of compressors affecting economic considerations of the whole installations, the replacement of compressors is considered ONLY when close to EOL. Efficiency of the new compressor acquisition is one of the main topics assed in energy audit/permit studies and this needs to be carefully evaluated in context of the wider parameters of the application.

NOTE 4. Larger savings are possible for optimization of the whole systems for e.g. plant air, refrigeration or parameters of industrial processes with compression of gases or vapors as part of the technology (identifiable through energy audits/detailed permits). This wider consideration is however less related to the compressor performance but rather to demand of compressor load by the process.

A3 Power saving in different pump arrangements in industry

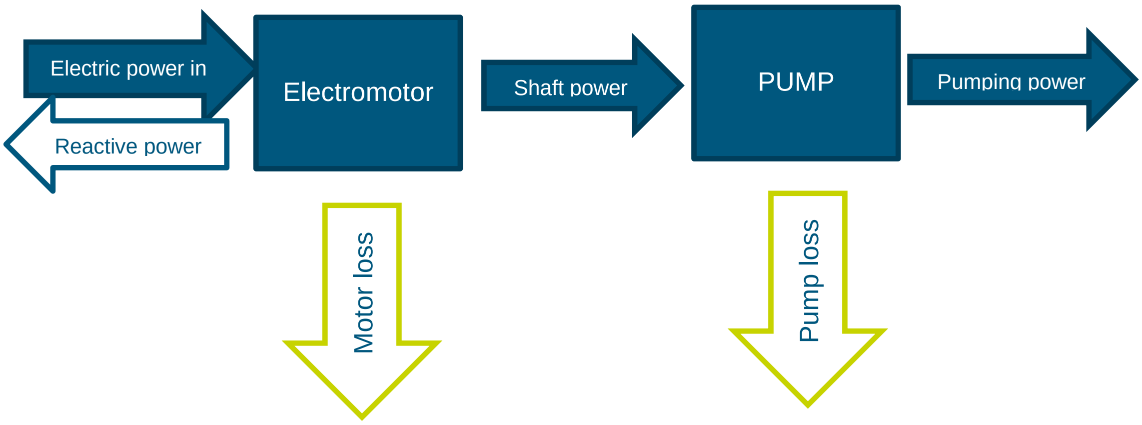
This appendix describes the combination of an electromotor and a pump

Based on this combination the relation between power consumption and pumping power is described and strategies to control volumetric rate are compared.

Based on this analysis numbers for energy saving by optimisation of pump configurations in industry are estimated.

Description of a pump system

The electric power consumption required for pumping power depends on a number of variables. Which variables vary with the arrangement of the pumping system. Below we give a schematical representation of an electromotor and a pump:



When we exclude for sake of simplicity shaft loss (<1% in general) the power conversion of the electric power to pumping power in the electromotor + pump arrangement is proportional to the pump power and the power factor divided by the efficiency of the motor and the pump, as described by the following equation:

$$P_{ELECTRIC} = \frac{P_{PUMP}}{\eta_{motor}\eta_{pump}} X$$

In which $P_{electric}$ is the power consumption by the motor, P_{pump} is the pumping power, X is the power factor, $\boldsymbol{\eta_{motor}}$, the motor efficiency, and $\boldsymbol{\eta_{pump}}$ is the pump efficiency. In the following we discuss the different variables mentioned in the equations above.
$P_{Electric}$ is the power consumption by the motor.

P_{Pump} indicates the pumping power. The pumping power is needed to transport the fluid (liquid) between process unit operations. The pumping power has two contributions, see Appendix Figure 2:

1 Static head contribution $P_{Pump-Stat}$

2 Dynamic head contribution $P_{Pump-Dyn}$

$$P_{Pump} = P_{Pump-Stat} + P_{Pump-Dyn}$$

Static head contribution $P_{PUMP-Stat}$ consists of the so-called useful duty. Static head includes also pressure losses that are unavoidable because of a technology choice and therefore considered useful, like pressure drops due to large velocity to improve mass transfer (packed columns/reactors), or heat transfer in heat exchangers, or to atomize liquid to small drops in nozzles, etc..

Static head is a constant given by pressures at the ends of the pipe.
The static aspect of pump power consumption is proportional to volumetric flowrate linearly:

$$P_{Pump-Stat} = A \cdot V$$

Dynamic head contribution $P_{PUMP-Dyn}$ consistis of pressure drops due to losses in pipes, bends, valves etc
Losses in pipes / bends /valves due to pressure drop
Dynamic head is proportional to flowrate squared
The dynamic aspect of pump power consumption is proportional to flowrate cubed

$$P_{Pump-Dyn} = B \cdot V^3$$

This means that the pumping power is proportional to the squared of the cubed power of the flow depending on the ratio of dynamic and static head.

$$P_{Pump} = P_{Pump-Stat} + P_{Pump-Dyn} = (A + B \cdot V^2) \cdot V$$

X is the power factor , the power factor X expresses what portion of the power input to motor is used and what portion is returned to grid as reactive power. For X = 1, no power is returned. For X = 0.8, 20% of power is returned as reactive power. Returned reactive power is not lost, but:
Increases load of the power grid (power traffic), therefore also the grid transmission losses

Grid needs to be sized for larger power traffic – larger CAPEX
The power factor decreases with decreasing power load of the motor (% of the nominal motor power utilized)[E13]. It is therefore advantageous to match the size of the motor (nominal power rating) to the actual requirement of the application and avoid excessive oversizing.

We consider 3 types of motors:

1 Induction (99% of motors in industry)

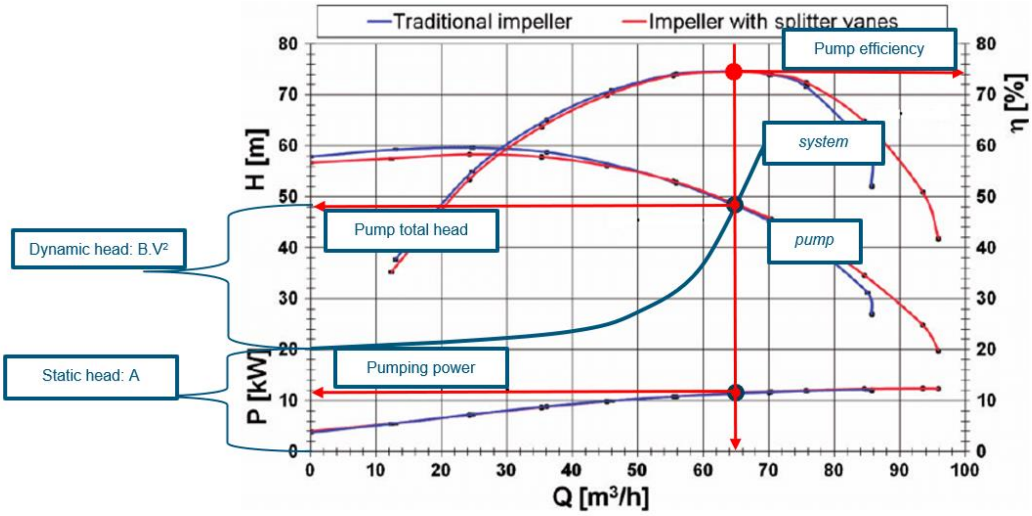
2 Synchronous reluctance (novel, more efficient than induction, require VFD for operation)

3 Synchronous (only large applications, custom made, > 350 kW, > 2 kV)

The three different types of motors we take into consideration have different power factors.

- Induction motors have a power factor of 0.7-0.85.
- Synchronous reluctance motors have a power factor of 0.6-0.73 [E14].
- Reactive power can be turned back in “normal power” by additional equipment (capacitors) but that requires additional investments (CAPEX increase). Therefore, it is relevant that SynRM motors have a lower power factor than induction motors.

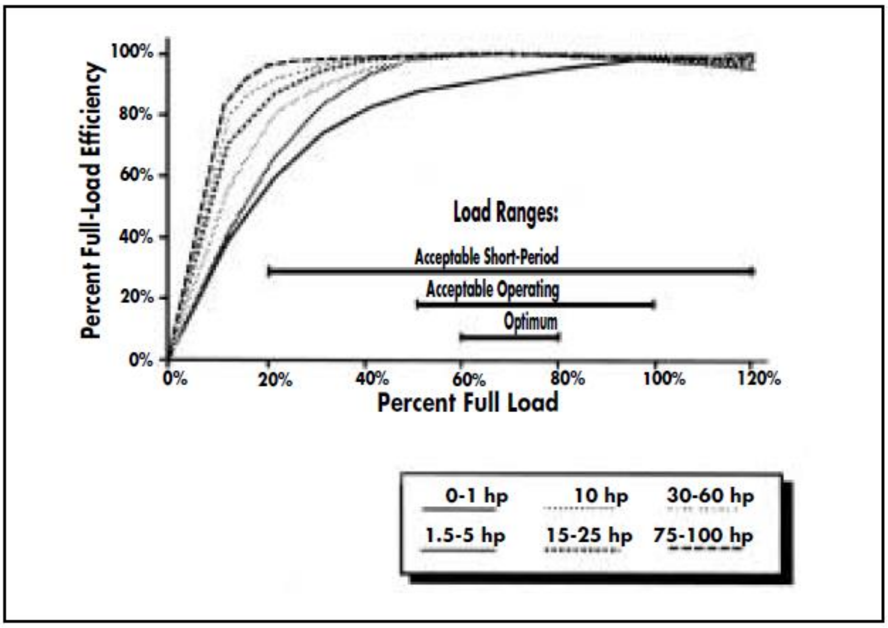
η_{pump} **is the pump efficiency**. The pump efficiency depends on volumetric flowrate. Maximum efficiency for pumps occurs around 60-70% of maximum volumetric capacity of the impeller, this is called the design point of the pump. Typical maximum pump efficiency is 70-85%
At flowrates larger or lower compared to maximum efficiency point, the pump efficiency is lower than at the design point of the pump (see Appendix Figure 2).



Appendix Figure 2: Pump performance curve, pumping power, pump efficiency static dynamic and total head

η_{motor}, i.e. efficiency of the motor. The larger the motor power the larger the interval that the motor works at maximum efficiency. For very low motor load, efficiency sharply decreases. Therefore, it is best to match the motor size for the application (see Appendix Figure 3). The Actual maximum efficiency of the motors is 70-97% depending on the motor efficiency class (IE1, IE2…) and motor size [IEC60034-30-1; E3]. The motor efficiency decreases with the decreasing motor size because of the following reasons:

- Some motor losses are size dependent;
- Economy of scale, higher level solutions makes more sense for larger applications.
- The efficiency of the synchronous reluctance motors is better than for the induction motors



Appendix Figure 3: Motor part-load efficiency (as a function of % full-load efficiency) [E13]

Pump flowrate control strategies

If the pump requires less flow than the electromotor may provide there are in general 3 ways to limit the power supplied to the pump:

1 Throttling of pump outflow

Throttling valve controls the flow to the pump by increasing the pipe resistance. The more the control valve is closed the higher the pipe resistance the more the valve is opened the lower the pipe resistance increases the pump. Thus, addition of a throttling valve to our system of an electromotor and pump modifies the dynamic head contribution to the pressure. This is denoted by valve coefficient “C” in the electric power consumption function:

$$P_{Electric} = \frac{P_{Pump}}{\eta_{motor}\eta_{pump}} X$$

$$P_{Pump} = P_{Pump-Stat} + P_{Pump-Dyn} = (A + \{B + C\} \cdot V^2) \cdot V$$

$$P_{Electric} = \frac{(A + \{B + C\} \cdot V^2) \cdot V}{\eta_{motor}\eta_{pump}} X$$

Pumping around recycle streams
In some systems the flow to the pump is regulated by recycling part of the flow through a pump-around valve. The further this valve is opened the more flow is recycled and the less flow goes to the application. This means that the pumping head remains the same but that the volume of the flowrate is increased by the volume of the recycle flow. The pumping head is given by the system, the flowrate of pumped liquid is increased by the volume of the recycle stream ($V_{recycle}$).

$$P_{Electric} = \frac{P_{Pump}}{\eta_{motor}\eta_{pump}} X$$

$$P_{Pump} = P_{Pump-Stat} + P_{Pump-Dyn} = (A + B \cdot V^2) \cdot (V + V_{Recycle})$$

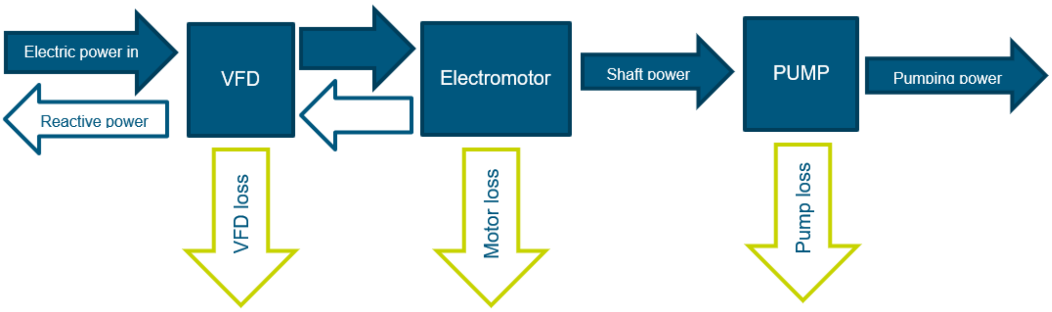
$$P_{Electric} = \frac{(A + B \cdot V^2) \cdot (V + V_{Recycle})}{\eta_{motor}\eta_{pump}} X$$

Motor drive

There are two types of motor drives: variable frequency drive (VFD) and magnetic coupling (MC). The application of VFD and MC modify the power demanded from the electro motor by increasing or decreasing rotation of the shaft

The needed head and the volumetric flowrate are precisely set by VFD or MC, but electric (VFD) or mechanic (MC) losses are introduced by this equipment.

Below we first explain the VFD using a schematical representation of the application of a VFD to a electromotor and pump:



The power conversion of the electric power to pumping power in the VFD + electromotor + pump arrangement is described by the following equation:

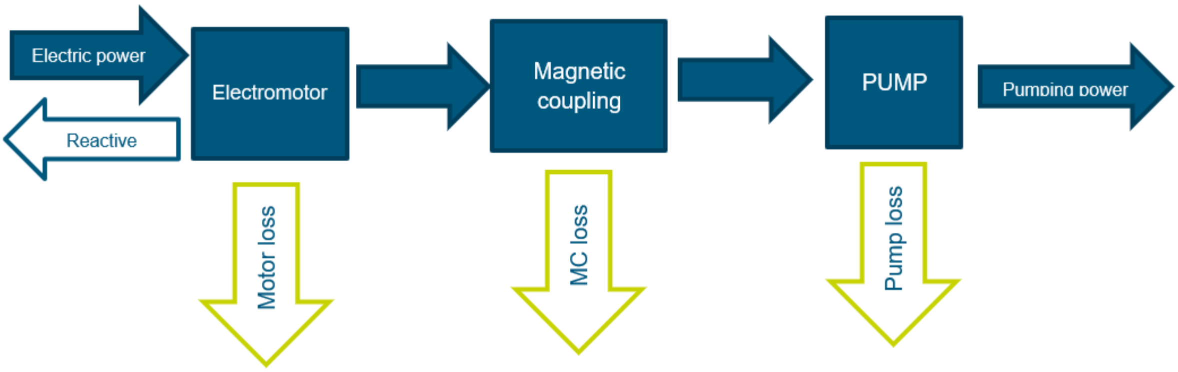
$$P_{Electric} = \frac{P_{Pump}}{\eta_{VFD}\eta_{motor}\eta_{pump}} X$$

$$P_{Pump} = P_{Pump-Stat} + P_{Pump-Dyn} = (A + B \cdot V^2) \cdot V$$

$$P_{Electric} = \frac{(A + B \cdot V^2) \cdot V}{\eta_{VFD}\eta_{motor}\eta_{pump}} X$$

In which $P_{electric}$ is the power consumption by the motor, P_{pump} is the pumping power, X is the power factor, $\boldsymbol{\eta_{motor}}$, the motor efficiency, $\boldsymbol{\eta_{pump}}$ is the pump efficiency, and $\boldsymbol{\eta_{VFD}}$ efficiency of the VFD -Based on norm IEC60034-30-1 $\boldsymbol{\eta_{VFD}}$ is ~ 90% - 97% depending on the torque and power load of VFD (power utilized / nominal power).

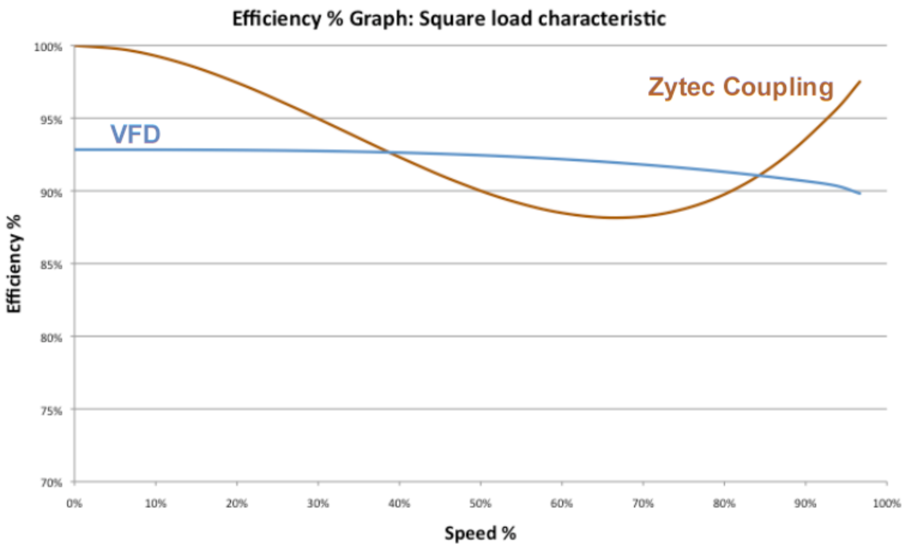
Below we schematically represent the application of a magnetic coupling between an electromotor and a pump.



The relation between the electric power and the pumping power is affected to pumping power in the VFD + electromotor + pump arrangement is described by the following equation:

$$P_{Electric} = \frac{P_{Pump}}{\eta_{motor}\eta_{MC}\eta_{pump}} X$$

In which $P_{electric}$ is the power consumption by the motor, P_{pump} is the pumping power, X is the power factor, $\boldsymbol{\eta_{motor}}$, the motor efficiency, $\boldsymbol{\eta_{pump}}$ is the pump efficiency, and $\boldsymbol{\eta_{MC}}$ efficiency of a magnetic coupling: dependent on the speed, between 100% at full speed (solid coupling) to efficiency 88% at 60% speed, see *Appendix Figure 4*.



Appendix Figure 4: Efficiency of Magnetic coupling compared to a variable frequency drive (as a function of speed) [E15]

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It is important to realise that VFD and MC modify the performance curve of a pump. To recalculate the pump performance curve for different frequency (shaft rotation speed), following affinity laws are used:

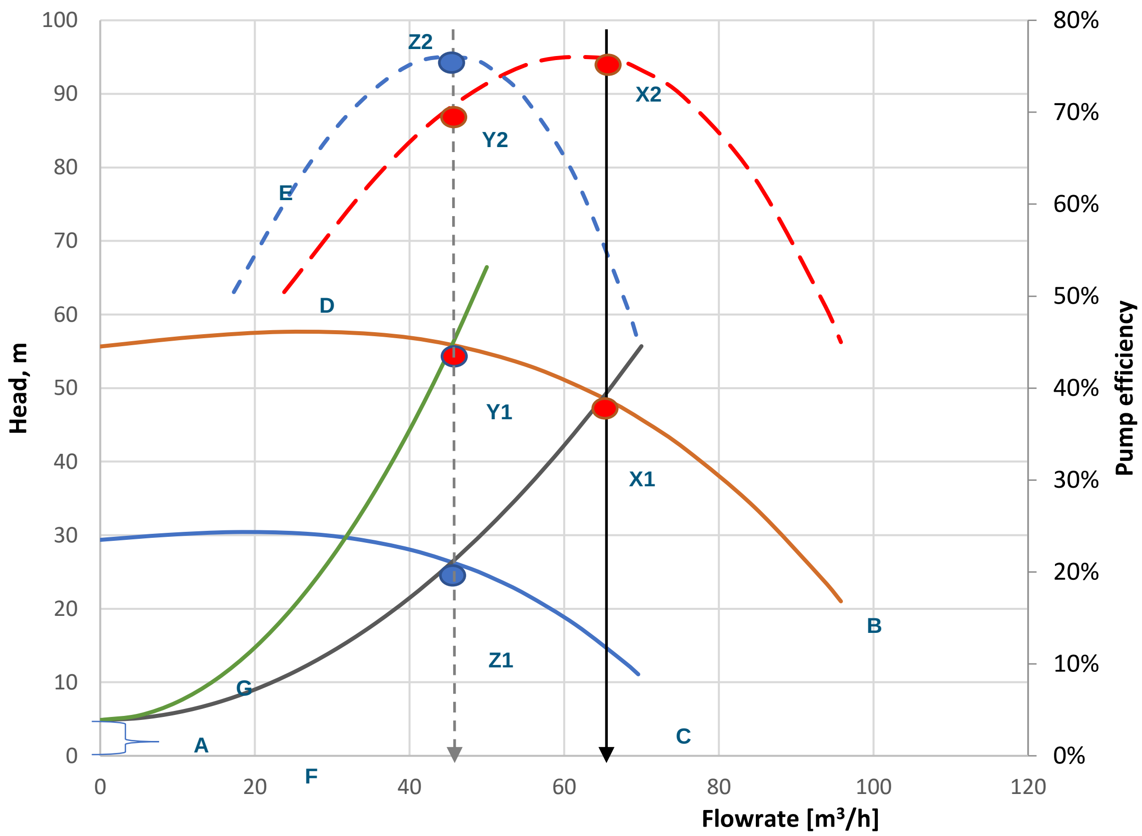
Volumetric flowrate [m³/h] $$\frac{V_1}{V_2} = \frac{f_1}{f_2}$$

Head [m] $$\frac{H_1}{H_2} = \left(\frac{f_1}{f_2}\right)^2$$

Pump power [kW] $$\frac{P_{PUMP-1}}{P_{PUMP-2}} = \left(\frac{f_1}{f_2}\right)^3$$

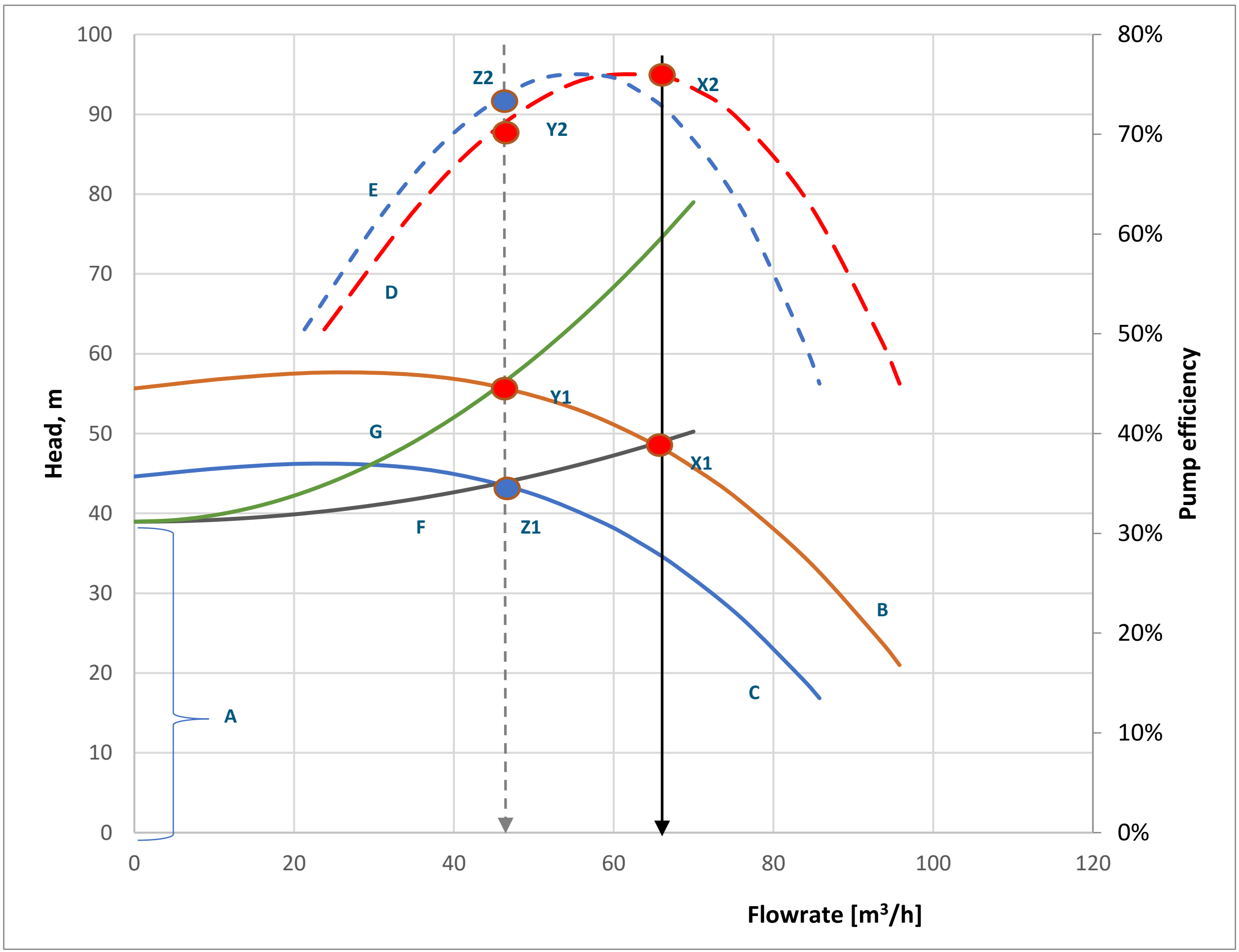
The results of the recalculated performance curve for a system with a motor drive are shown in *Appendix Figure 5:* and *Appendix Figure 6*. *Appendix Figure 5:* shows the situation with limited static heat (30% less flow than designed and respectively 10% static head over total head pressure) that due to application of the motor drive the efficiency of the two flow rates is the same as if the flowr ate had 100% design flow, see points (1&2).

Appendix Figure 6 shows the situation of 30% less flow than designed and 80% static head over total head pressure.



Appendix Figure 5: Change in efficiency curves due to application of VFD and MC in case of 30% less flow than design, 10% of the design is static head

A	Static head [m]
B	Pump performance curve (head vs. flowrate) for full rotation speed (100% frequency)
C	Pump performance curve (head vs. flowrate) for reduced rotation speed (73% frequency) after installation of VFD or MC. Curve calculated from 100% frequency using affinity laws. *For the option of introducing new pump, this represents new pump's performance curve at 100% speed.*
D	Pump efficiency curve for full rotation speed (100% frequency)
F	Curve of head required to push through pipe resistance vs. flowrate
G	Curve of head required to push through pipe resistance including partially closed throttling valve vs. flowrate
X1	Design pump operation point
X2	Design pump efficiency
Y1	New pump operation point, volume flowrate control by throttling valve (100% pump speed).
Y2	New pump efficiency, volume flowrate control by throttling valve (100% pump speed)
Z1	New pump operation point, no throttling but reduced pump speed (73% pump frequency). *For the option of introduction of new smaller pump, this is the design operation point for the new pump at 100% speed.*
Z2	New pump efficiency. No throttling but reduced pump speed (73% pump frequency)



Appendix Figure 6: Change in efficiency curves due to application of VFD and MC in case of 30% less flow than design, 80% of the design is static head. Meaning letters in the figure see above.

Pump energy efficiency problems and solutions (several cases)

Motor drives can provide a solution to types of efficiency problems:

- Pump is fluctuating between design point and low flowrates, no VFD or MC;
- Pump is systematically oversized, no VFD or MC.

In the first case the pump needs to meet a variable demand and consequently fluctuates between the design point and low flowrates. Flow is regulates using throttling control or recycling control adding to the dynamic head. The SOLUTION in this case is to install a VFD or MC. This allow to control the capacity of the pump by changing the speed. Pump efficiency is improved and additional head (C factor) for throttling control or pump around flowrate ($V_{RECYCLE}$) are eliminated. Additional losses are introduced by VFD or MC (η_{VFD}, η_{MC}). Potential savings are dependent on the share of the static head (A factor) and dynamic losses (B and C factor) in the specific application.

In the second case the **pump is systematically oversized, more or less constant flow**, and no VFD or MC present. Resulting in a low pump efficiency. Throttling control or recycle control further increase the power consumption. There are two solutions to this:

- **SOLUTION 1 (good recommended practice):** Change impeller, adjust angle of the impeller blades, trim the blades or change the pump completely. This will permanently decrease the capacity of the pump, but pump efficiency is improved and additional head (*C* factor) for throttling control or pump around flowrate ($V_{Recycle}$) are eliminated. This change is (with exception of adjusting angle of impeller blades) irreversible, to be done only if the flow demand is consistently low.
- **SOLUTION 2 (possible, preferable in combination with solution 1):** Install VFD or MC. This allows to control the capacity of the pump by changing the speed. Pump efficiency is improved and additional head (*C* factor) for throttling control or pump around flowrate ($V_{Recycle}$) are eliminated. Additional losses are introduced by VFD or MC (η_{VFD}, η_{MC}). Potential savings depend on the share of the static head (*A* factor) and dynamic losses (*B* and *C* factor) in the specific application.

Pump systems do not always need a motor drive. For example, a well-designed combination of an electromotor, pump and outflow throttling or pump around recycle can function efficiently if the pump operates close to maximum efficiency, i.e. in case that the throttling valve is practically open or the recycle valve is practically closed. In this case the situation is fine as it is.

Even in case of a not so well performing combination of an electromotor and a pump, motor drives are not always the solution. We provide two cases:

- If the motor efficiency is low, you better replace motor with better rating. Consider additional measures(below) to evaluate if smaller motor is applicable due to additional improvements possible of pump;
- If the pump is systematically oversized, while the flowrate practically equals the design flow rate (60-70% of the pump's maximal flowrate). You better check whether the impellor or the whole pump needs to be replaced. In addition, check the current power rating of the motor and consider buying a new and possibly smaller motor.

Conclusion:

Apart from using a more efficient and smaller electro motor there are basically three strategies to safe energy in a system with an oversized pump:

1. Replacing the throttling valve by a VfD;
2. Replacing the throttling valve by a MC;
3. Making the throttling valve obsolete by choosing a pump that matches the demand.

How large the saving is that can be realised depends on two variables: the degree to which the pump is oversized (flow rate reduction), the type of motor drive and the ratio between static head contribution and total pressure head (m/m).

Estimated savings

Based on the calculations described above, the saving potential is calculated for both VSD, MC and pump optimisation. These results are summarised in the following tables. The outcomes show clearly that pump optimisation provides the best results independent of pressure head and that the performance of VSD is favourable over the performance of magnetic coupling.

*Appendix Table 4: Saving potential by means of **pump optimisation** as a function of flow rate and static pressure [see appendix A3]*

Static head/Total head [%]		Flow/design flow [%]					
		100%	90%	80%	70%	60%	50%
	0%	5%	27%	43%	54%	60%	63%
	10%	5%	25%	40%	50%	57%	59%
	20%	5%	23%	37%	47%	53%	56%
	30%	5%	22%	34%	44%	49%	52%
	40%	5%	20%	32%	40%	46%	49%
	50%	5%	19%	29%	37%	42%	45%
	60%	5%	17%	26%	33%	39%	42%
	70%	5%	15%	24%	30%	35%	38%
	80%	5%	14%	21%	27%	31%	35%
	90%	5%	12%	18%	23%	28%	31%

**Application of a well-designed pump with an efficiency increase in BEP of 4% as compared to the replaced older pump was assumed (76% -> 81%). Larger efficiency gain is outside BEP of the replaced pump at lower flowrates.*

*Appendix Table 5: Saving potential by means of the application of a **magnetic coupling** as a function of flow rate and static pressure [see appendix A3].*

Static head/Total head [%]		Flow/design flow [%]					
		100%	90%	80%	70%	60%	50%
	0%	0%	12%	23%	32%	39%	47%
	10%	0%	11%	22%	30%	36%	41%
	20%	0%	10%	20%	27%	32%	36%
	30%	0%	9%	18%	24%	29%	32%
	40%	0%	8%	16%	22%	26%	28%
	50%	0%	7%	14%	19%	23%	25%
	60%	0%	6%	12%	17%	20%	21%
	70%	0%	5%	10%	14%	17%	18%
	80%	0%	4%	9%	12%	14%	14%
	90%	0%	3%	7%	9%	10%	11%

**Efficiency of MC is between 40% and 100% depending on the shaft rotation frequency vs. maximum frequency in BEP design point was assumed, The efficiency dependence on shaft speed is based on data in Figure 3-1.*

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Appendix Table 6: Saving potential as a function of flow rate and static pressure for VFD [see appendix A3]

		Flow/design flow [%]					
		100%	90%	80%	70%	60%	50%
Static head/Total head [%]	0%	0%	18%	37%	50%	58%	62%
	10%	0%	17%	34%	46%	54%	58%
	20%	0%	15%	31%	42%	50%	53%
	30%	0%	13%	28%	38%	45%	49%
	40%	0%	11%	25%	34%	41%	44%
	50%	0%	9%	21%	30%	36%	39%
	60%	0%	8%	18%	26%	31%	33%
	70%	0%	6%	15%	22%	26%	28%
	80%	0%	4%	12%	17%	21%	22%
	90%	0%	2%	8%	13%	15%	16%

**Single value of VFD efficiency of 94% was assumed in this document, as an average of range of efficiencies due to minor influence of the rotation speed and the power rating of the VFD. The selected value is in a good correspondence to the defined IEC standards for VFD.*

Appendix Table 7: results of saving calculations in stead of 30% lower flowrate than designed and 10 % static pressure , see Appendix Figure 5:

	Design (100% flow)	30% less flowrate			
		Throttling	VFD	MC	New Pump
Volume V [m3/h]	65	65	45.5	45.5	45.5
Pump frequency	100%	100%	73%	73%	100%
Static head [m]	**4.9**	**4.9**	**4.9**	**4.9**	**4.9**
Dynamic head [m]	**43.8**	51.0	21.5	21.5	21.5
[a]Total head [m]	**48.7**	55.9	26.3	26.3	26.3
[a]Pump efficiency (η_{pump})	76%	76%	71%	76%	[d]80%
[b]A [kPa]	48	48	48	48	48
[b]B [kPa/m^6/H_2]	0.102	0.102	0.102	0.102	0.102
[b]C [kPa/m^6/H_2]	-	-	0.140	-	-
Pumping power [kW]	8.6	6.9	3.3	3.3	3.3
VFD / MC efficiency (η_{VFD}) or (η_{MC})	-	-	94%	92%	-
[c]Electric power in [kW]	14.9	12.8	6.0	6.1	5.3
Power saving vs design	-	14%	60%	59%	64%
Power saving vs. throttling	-	0%	**46%**	**45%**	**50%**

[a]See in the performance curves in the figure
[b]Coefficients of equation for head: $H = \frac{A+\{B+C\}\cdot V^2}{\rho.g}$, A – static part, B – dynamic resistance of the piping network, C additional dynamic resistance due to partially closed control throttling valve. Used for the calculation of lines for piping in the figure. Water was assumed as pumped liquid (ρ=1000 kg/m^3) and g=9.81 m/s^2.
[c]Electric power is calculated as $P_{ELECTRIC} = \frac{P_{PUMP}}{\eta_{motor}\eta_{pump}}X$. Efficiency of motor ($\eta_{motor}$) of 90% and power factor X = 0.8. The motor efficiency and power factor have no effect on estimated relative savings of the different pump control strategies.
[d]In case of replacement of the pump, it is assumed that the lower head and flowrate corresponds to its design point with efficiency of 80%.

Appendix Table 8: results of saving calculations in stead of 30% lower flowrate than designed and 80 % static pressure , see Appendix Figure 6

	Design (100% flow)	**30% less flowrate**			
		Throttling	VFD	MC	New Pump
V [m3/h]	65	65	45.5	45.5	45.5
Pump frequency	100%	100%	90%	90%	100%
Static head [m]	**39.0**	**39.0**	**39.0**	**39.0**	**39.0**
Dynamic head [m]	**9.7**	16.9	4.8	4.8	4.8
[a]Total head [m]	**48.7**	55.9	43.7	43.7	43.7
[a]Pump efficiency (η_{pump})	76%	76%	71%	76%	[d]80%
[b]A [kPa]	382	382	382	382	382
[b]B [kPa/m^6/H$_2$]	0.023	0.023	0.023	0.023	0.023
[b]C [kPa/m^6/H$_2$]	-	0.058	-	-	-
Pumping power [kW]	8.6	6.9	5.4	5.4	5.4
VFD / MC efficiency (η_{VFD}) or (η_{MC})	-	-	94%	97%	-
[c]Electric power in [kW]	14.9	12.8	10.2	9.9	8.9
Power saving vs design	-	14%	31%	33%	40%
Power saving vs. throttling	-	0%	**17%**	**19%**	**27%**

A4 ICT – Dimension 2 analysis

Compare top-down to bottom-up numbers

To make a reliable comparison between top-down and bottom-up numbers general energy numbers per industry are used based on an aggregated survey based on ~50 international energy efficiency benchmark data from PDC, see also https://www.process-design-center.com/energy-benchmarks.html. These numbers are displayed in below table.

Appendix Table 9: General energy numbers per industry.

Topic	Explanation	Cracker sites, fertilizer complexes, industrial gasses, refineries and the steel sector	Remaining industry	Food	Paper & board
Energy Management, Utility Optimization	If 50% of the site energy usage is going through the central utility system one could indeed save substantial amounts of energy by matching steam supply and demand. Point is that most sites in all sectors, except food and paper, have these things already installed. We expect potential for site Energy Management + Utility optimization in the Wider chemical industry. A 1% saving potential can be justified. For food and paper: potential for site Energy Management is expected. A conservative number of 2% can probably be justified.	0.0%	1.0%	2.0%	2.0%
Equipment Performance Optimization	50% of the total energy use is supposed to go through the heat exchangers and rotating equipment. So if we put 1% savings on average this could represent 0.5% overall until 2025. If almost 100% of the energy use is supposed to go through the heat exchangers and rotating equipment we estimate this number for the Wider chemical industry 1%. If almost 100% of the energy use is supposed to go through the heat exchangers and rotating equipment we estimate this numbers for Food 1% and for Paper 0.5% because in the paper industry less steam is going through heat exchangers.	0.5%	1.0%	1.0%	0.5%
Compressed air monitoring	The very small relative energy use related to compressed air can be ignored for large industries.	0.0%	0.0%	0.0%	0.0%
Steam trap monitoring	We have seen such a project on a big site where this indeed represented energy savings in the order of 0.1% of the total energy consumed. Also in the Food & Paper industry we estimate the steam trap monitoring (maintenance) in the order of 0.1%.	0.1%	0.1%	0.1%	0.1%
Steam Header Optimization	This means increasing or decreasing the pressure of the headers where we have power generation. The additional power generation by these pressure changes represent new saving potential which can be	1.0%	0.0%	0.0%	0.0%

Topic	Explanation	Cracker sites, fertilizer complexes, industrial gasses, refineries and the steel sector	Remaining industry	Food	Paper & board
	substantial at complex integrated sides with letdown turbines. When we take an average of 10% energy saving/power generation on 20% of the headers that cover 50% over the total energy usage, we arrive at 0,1 x 0.2 x 0.5 x 100% = 1% on those integrated sites with different steam levels and letdown turbines. We see this as interesting new emerging technology with a substantial energy saving potential. In remaining industry, food and paper we do not see a lot of complex steam grids with let down turbines that could further be optimized by steam header optimization. So we keep this potential on 0%.				
Boiler optimization	Boilers in the advanced process industries (Crackers, Refineries, Steel, Fertilizer complexes, Industrial gasses) are already at high efficiencies and they have those type of excess air control and boiler optimization. Boilers in remaining industry, food and paper might have (in total) a remaining optimization potential of 1%.	0.0%	1.0%	1.0%	1.0%
Process unit Energy Optimization	We assessed the total percentage of savings of APC on 2%, also for the remaining industry. We originally assessed the total percentage of savings of APC in the Food and Paper industry to be around 4%, but after talking to a more companies it seems that APC is more commonly applied than expected and based on this we estimate the 2025 potential to be more around 3%.	2.0%	2.0%	3.0%	3.0%
Flare system monitoring	There is a difference in product recovery and energy (steam) savings on flares. Based on 1 real industrial case we estimate the total saving is in the order of 0,03% of the total energy usage.	0.03%	0.03%	n/a	n/a

A5 ICT – Three dimensions of theoretical CO_2 savings

Appendix Table 10: ICT- Dimension 1: Theoretical economical saving potential from 2021-2025 based on supplier factsheets

Total top 8 industrial sectors		Advanced Process Control [savings (kton)]	Asset Management [savings (kton)]	Energy Management [savings (kton)]
Total		**651**	**455**	**204**
Chemical industry	Industrial gasses (Air Products, Air Liquide, Linde)	30	43	11
	Steam crackers (Dow, Shell Moerdijk, Sabic Chemelot)	106	98	30
	N-Fertilizer (YARA, OCI)	100	26	17
	Wider chemical industry	114	96	31
Refineries (BP, ExxonMobil, Gunvor, Koch, Shell Pernis, Zeeland Refinery)		104	69	25
Iron and Steel (TATA)		62	13	19
Food (large number of factories producing diary, sugar, oils and fats, etc.)		111	84	58
Paper and Board (21 factories)		24	26	13

Appendix Table 11: ICT- Dimension 2: Theoretical economical saving potential from 2021-2025 based on industry experts from PDC

Total top 8 industrial sectors		Advanced Process Control [savings (kton)]	Asset Management [savings (kton)]	Energy Management [savings (kton)]
Total		**596**	**165**	**186**
Chemical industry	Industrial gasses (Air Products, Air Liquide, Linde)	26	6	0
	Steam crackers (Dow, Shell Moerdijk, Sabic Chemelot)	74	17	0
	N-Fertilizer (YARA, OCI)	49	10	0
	Wider chemical industry	78	34	33
Refineries (BP, ExxonMobil, Gunvor, Koch, Shell Pernis, Zeeland Refinery)		65	15	0
Iron and Steel (TATA)		46	11	0
Food (large number of factories producing diary, sugar, oils and fats, etc.)		213	65	125
Paper and Board (21 factories)		45	7	28

Appendix Table 12: ICT- Dimension 3: Theoretical economical saving potential from 2021-2025, additional numbers on Energy Management based on EU study "151201 DG ENER Industrial EE study - final report_clean_stc"

Total top 8 industrial sectors		Energy Management [savings (kton)]
Total		**125**
Chemical industry	Industrial gasses (Air Products, Air Liquide, Linde)	14
	Steam crackers (Dow, Shell Moerdijk, Sabic Chemelot)	36
	N-Fertilizer (YARA, OCI)	21
Refineries (BP, ExxonMobil, Gunvor, Koch, Shell Pernis, Zeeland Refinery)		31
Iron and Steel (TATA)		23

A6 Insulation potential from literature

As an addition to the potential of the innovative technologies we were asked to give an indication of the CO_2 reduction potential of insulation measures.
Since a thorough investigation of the insulation potential in the Dutch market is out of scope of this study we offered to apply the insights from this study on the results reported by Ecofys in literature.
This implies that we only present the theoretic CO_2 reduction potential and do not take responsibility for the feasibility of the results from literature.

Below we discuss the results of this exercise. First, we report the main findings from literature that will form the basis of our calculation in the second part.
In the second part we apply the findings from literature to the Dutch industry and calculate an estimate of the technical CO_2 reduction potential and the economical CO_2 reduction potential.

A6.1 Findings from literature

The main findings from literature are:
The current heat loss in industry per temperature range;
The potential reduction in heat loss;
The measures that are cost effective in terms of a payback time of 5 years or less.

The current heat loss in industry per temperature range is summarised in *Appendix Table 13*.There are three different types of heat loss identified: heat loss over surfaces without insulation or damaged insulation, heat losses over currently insulated surfaces and the sum of the two.

To convert these numbers to an energy saving potential we both need the current heat use and the reduction of heat loss over isolated surfaces and surfaces without insulation of damaged insulation, i.e. the potential reduction in heat loss. The numbers on potential for het loss reduction are summarised in *Appendix Table 14*.

Based on these values and the current energy use in industry per sector and temperature level mentioned in the table heat consumption per industrial sector in Chapter 1, we can make an estimate of the Theoretic Technical CO_2 reduction potential in industry per industrial sector and temperature level.

Appendix Table 13: Current heat loss in industry per temperature range [A1]

Temperature range	Total share of energy use input that is currently lost	Share of energy use that is lost over insulated surfaces	Share of energy use that is lost over surfaces without insulation of damaged insulation
Low temperature surfaces (< 100ºC)	9,6%	5,4%	4,2%
Middle temperature surfaces (100ºC-300ºC)	6,7%	3,8%	2,9%
High temperature surfaces (>300ºC)	5,0%	2,0%	3,1%

Source: table 2-2 [A1]

Appendix Table 14: Potential for reduction in heat loss per temperature range [A1]

Reduction in Heat Loss	Low temperature surfaces (< 100°C)	Middle temperature surfaces (100°C-300°C)	High temperature surfaces (>300°C)
Insulated surfaces	30%	33%	27%
Surfaces without insultation	90%	94%	99%

Source: figure 3-3 heat loss and cost effective level at 10 €/GJ [A1]

To convert this theoretic technical level to a theoretic feasible level we have to discriminate between the cost effective and the non-costeffective measures potential. The Ecofys report uses a different definition for cost effectiveness that used in this report. In the Ecofys report measures are cost effective if they are paid by the savings resulting over their complete lifetime. For some insulation measures a lifetime of 20 year is assumed. While in this report we assume that a measure is cost effective if the payback period is 5 years or less.

This problem is solved by discriminating between savings over insulated surfaces and non-insulated surfaces or surfaces with damaged insulation. Savings over insulated surfaces have on average a payback period longer than 5 years. Savings over surfaces without insulation or with damaged insulation tend to have a payback period shorter than 5 years [A2].

A6.2 Theoretic CO_2 reduction potential of insulation

To calculate the theoretic CO_2 potential of insulation we first calculate the energy saving potential in PJ and convert this saving potential to CO_2 reduction potential by assuming the consumed heat was based on burning of natural gas.

The first step in determining the total energy saving potential by means of insulation is to calculate the percentage of total heat loss reduction that is possible per temperature range as the sum of two products: share of energy use that is lost over insulated surfaces*reduction in heat loss over insulated surfaces + the product of the share of energy use that is lost over surfaces without insulation*reduction in heat loss over surfaces without insulation.
To give an example: *Appendix Table 13* shows that the he percentage heat loss over insulated surfaces in the low temperature range is 5.4%. For surfaces without insulation the heat loss over the surface is 4.2%.

Table 6 shows that the potential for heat loss reduction of insulated surfaces in the low temperature range is 30% and 90% for surfaces without insulation.
Thus, the theoretical technical saving percentage is 5.4%*30%+4.2*90% = 5,4%.

To calculate the cost-effective technical saving percentage, we determine the product of the numbers over surfaces without insulation: the share of energy use that is lost over surfaces without insulation * the reduction in heat loss over surfaces without insulation.
Thus, the theoretical economical saving percentage is 4.2*90% = 3,8%.

To convert these saving percentages to energy savings per industrial sector we combine the above-mentioned approach with the heat consumption per industrial sector as presented in chapter 1.
The temperature ranges used in this table and the temperature ranges in Appendix Table 5 and Appendix Table 6 differ slightly. We apply the percentages of the temperature range from 100oC-300oC to the 100oC-250oC temperature range of the numbers on industrial heat demand, see *Table 1-5*.

The results are summarised in *Appendix Table 15* for the theoretical **technical** saving potential and in *Appendix Table 16* for the theoretical **economical** saving.

Appendix Table 15: Theoretical technical energy saving potential by means of insulation per sector in PJ

TECH potential [PJ]		<100 ºC	100-250 ºC	250-500 ºC	>500 ºC	Energy saving per sector [PJ]
Food industry		1,6	1,2	0,0	0,0	**2,8**
Paper Industry		0,0	0,7	0,0	0,0	**0,7**
Chemical industry		0,7	1,1	2,4	5,1	**9,2**
	Industrial gasses	0,0	0,0	0,0	0,2	**0,2**
	Steam crackers industry	0,0	0,1	1,7	3,9	**5,8**
	Ammonia and N-fertiliser	0,0	0,0	0,1	0,9	**1,0**
	Remaining	0,7	1,0	0,6	0,0	**2,2**
Steel		0,0	0,0	0,3	0,8	**1,1**
Refineries		0,0	0,1	1,8	2,5	**4,3**
Energy saving per temperature range [PJ]		**3,0**	**4,2**	**6,8**	**13,4**	**27,4**

We converted the theoretical technical energy saving potential to a theoretical technical CO_2 reduction potential by assuming all heat is generated by burning natural gas. Particularly in the case of the steel sector this causes an under estimation of the CO_2 reduction potential.
Nevertheless the theoretical economical potential is still significant.

Appendix Table 16: Theoretical economical energy saving potential by means of insulation per sector in PJ

TECH potential [PJ]		<100 ºC	100-250 ºC	250-500 ºC	>500 ºC	Energy saving per sector [PJ]
Food industry		1,1	0,8	0,0	0,0	**2,0**
Paper Industry		0,0	0,4	0,0	0,0	**0,4**
Chemical industry		0,5	0,8	2,0	4,3	**7,6**
	0,0	0,0	0,0	0,2	0,2	**0,2**
	0,0	0,1	1,4	3,3	4,9	**5,8**
	0,0	0,0	0,1	0,7	0,8	**1,0**
	0,5	0,7	0,5	0,0	1,6	**2,2**
Steel		0,0	0,0	0,2	0,7	**1,0**
Refineries		0,0	0,0	1,5	2,1	**3,7**
Energy saving per temperature range [PJ]		**2,1**	**2,8**	**5,8**	**11,4**	**22,2**

Appendix Table 17: Theoretical technical energy saving potential and CO_2 reduction potential per sector

Theoretical		energy saving potential [PJ]	CO_2 reduction potential [kton CO_2/y	energy saving potential [PJ]	CO_2 reduction potential [kton CO_2/y
Food industry		2,8	**161**	2,0	**112**
Paper Industry		0,7	**37**	0,4	**25**
Chemical industry		9,2	**521**	7,6	**428**
	Industrial gasses	0,2	**0,2**	11	**13**
	Steam crackers industry	5,8	**5,8**	276	**326**
	Ammonia and N-fertiliser	1,0	**1,0**	48	**56**
	Remaining	2,2	**2,2**	92	**126**
Steel		1,1	**64**	1,0	**54**
Refineries		4,3	**244**	3,7	**207**
Total		26,2	**1.485**	22,2	**1.254**

A6.3 Literature

A1 Climate protection with rapid payback Ecofys, https://www.eiif.org/sites/default/files/2020-02/ClimateProtectionWithRapidPayback

A2 Laaghangend Fruit in de industrie, energiebesparende maatregelen voor vergunningsplichtige industriele bedrijven, CE Delft februari 2014