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# Energy transition: mission (im)possible for industry?

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# Preface

The Dutch industrial sector is an economic powerhouse that provides the Netherlands with 9 percent of jobs, 21 percent of GDP, and 60 percent of spending on research and development. At the same time, it is a major source of greenhouse gas (GHG) emissions, particularly carbon dioxide. More than 40 percent of the carbon dioxide ($CO_2$) emitted by the Netherlands comes from industry's processes and its use of electric power. Achieving the EU's target of an 80 to 95 percent emissions reduction by 2050 will require Dutch industry to continue reducing its emissions by 1 million metric tons of $CO_2e$ per year—the rate it sustained since 1990— from 2014 to 2050.

The challenge ahead for the Dutch industrial sector is a demanding one: to increase its environmental efficiency at the same rate that it has in recent years, while maintaining or improving its economic standing. Two main factors make this complicated. First, it is technically difficult to decarbonize certain industrial processes. Few methods exist today, at a proven scale, for generating large quantities of high temperature heat, other than burning fossil fuels and using process gases—both of which are emissions-intensive. Several industrial processes, such as manufacturing ammonia and cement, generate emissions directly. And numerous industrial processes such as refining are integrated to such an extent that changing a single step in these process requires other steps to be modified as well, usually at great cost. The second factor is that much of industry, especially the most energy intensive sectors such as chemicals, steel and refining, operates in highly competitive international or global markets. Any capital investments or increases in operating costs could put them at a competitive disadvantage when 'disproportional' local measures are taken.

Under these conditions, is it possible to decarbonize the Dutch industrial sector? And what would be the economic and financial implications of such a shift? In our report published last year *'Accelerating the energy transition: cost or opportunity?'*[1], we concluded that the Netherlands stands to realize economic gains from accelerating the nationwide pursuit of the EU's emissions-reduction goals.

This report builds on that work by evaluating processes and technologies—along with the investments required to implement them—that might allow the Dutch industrial sector to lower its carbon emissions in line with the EU's goals. Our overall finding is that the Dutch industrial sector can lower its carbon dioxide emissions by 60 percent in 2040 and by 80 to 95 percent by 2050, in line with the EU's goals, by creating, refining, and applying new processes, technologies, and feedstocks on a large scale. None of this will be easy, or inexpensive. Though subject to uncertainty, we estimate that the cost of implementing the menu of six most promising decarbonization options amounts to EUR 21 - 23 billion by 2040, and about EUR 55 billion by 2050, under current commodity prices. It would also further increase the demand for electricity by 215 PJ and thereby the need for renewable power build out by 6 GW (to 64 GW) and additional back up or flexibility measures. This undertaking could, however, generate opportunities for industrial companies and a wide variety of stakeholders to create sustainable value, preserve jobs, and possibly stimulate economic growth.

1 https://www.mckinsey.com/global-themes/europe/accelerating-the-energy-transition-cost-or-opportunity.

Dutch industrial companies have a key role to play in repositioning the Netherlands to thrive in a low-carbon future. We are therefore grateful to the leadership and members of VEMW, a Dutch industrial consortium, for supporting our research and sharing their views with us.

Making this report would not have been possible without the valuable input of many other external and internal industry and energy experts. In particular we would like to thank Energy Insights, our global energy market intelligence and analytics group, as well as a number of colleagues for their support and insights: Dieuwert Inia, Theo Jan Simons, Ken Somers and Margriet Hooghiemstra.

The findings presented here represent our own, independent perspective. We share them in the hope that these insights will inform public discussion about the decarbonization challenge and provide industrial companies with useful guidance about how they can sustain their economic, environmental, and social contributions to the Netherlands' development. We also invite industrial businesses around the world to consider these ideas and how they might be used to meet the international reduction targets agreed in 2015 at the COP 21 Climate Conference in Paris.

Occo Roelofsen, Arnout de Pee, Eveline Speelman, and Maaike Witteveen

# Executive Summary

From 1990 to 2014, industrial companies in the Netherlands lowered their greenhouse gas (GHG) emissions from direct operations by 32 percent—three times as much as other sectors of the Dutch economy. Were this trend to continue, the sector would reach the EU's intermediate goal of cutting GHG emissions 40 percent by 2030 well before that year. Sustaining the recent rate of emissions reduction won't be easy, though. Industrial companies have reduced their emissions of GHGs other than carbon dioxide by about 70 percent, yet their carbon dioxide emissions remain significant (67 million metric tons in 2014 or over 40 percent of Dutch $CO_2$ emissions). Many of the new, or yet to be developed, technologies may be expensive or difficult to implement.

When assessing decarbonization options, industry needs to understand their technical feasibility, effectiveness, costs, and benefits, including impacts further up and down the value chains—and do this amid uncertainty about factors like the future prices of different forms of energy. To provide some initial answers, we analyzed and compared the options likely available to Dutch industrial businesses. The results of our study point to a comprehensive program for implementing options in a manner that may create value for industrial companies, as well as for the Netherlands as a whole.

Our primary findings are as follows:

### Decarbonizing industry 60 percent by 2040 will cost approximately EUR 23 billion

- The Dutch industrial sector can lower its carbon dioxide emissions by 60 percent by 2040 compared to 1990, and 80 percent by 2050, which would be consistent with the European Union's goals of an 80 to 95 percent reduction by 2050. This reduction can be achieved without reducing industrial output.

- The total cost of decarbonizing the Dutch industrial sector would be approximately EUR 21 billion to 23 billion, between now and 2040, which is consistent with our previous findings[2]. About EUR 6 billion would be spent on capital investments, and the remaining EUR 17 billion would cover increased operating costs (at current commodity prices).

- Under current commodity and technology prices, only about 20 percent of investments have a positive business case. This assumes that the cost of carbon emissions ranges between -10 and 300 EUR per ton avoided $CO_2$.

### Decarbonizing industry 95 percent is also possible but more costly

- It is technically feasible for the Dutch industrial sector to lower its carbon dioxide emissions by 95 percent by 2050 compared to 1990, also while keeping industrial outputs at current levels.

2 In our previous report *'Accelerating the energy transition: cost or opportunity?'*, we estimated that the total cost of lowering GHG emissions from industry by less approximately 50 percent by 2040 would be in the order of EUR 20 billion. This is consistent with our current findings, where we use a slightly steeper decarbonization path (60% by 2040) - see also Appendix I.

- The cost of decarbonizing the Dutch industrial sector by that much could be as high as EUR 71 billion between now and 2050. About EUR 24 billion comprises capital investments, and the remaining EUR 46 billion pays for higher operating costs (at current commodity prices). If energy prices fall from their current levels, the total cost could be closer to EUR 36 billion.

- Aiming for 95 percent reduction will see fewer investments with a positive business case (under current technology and commodity price outlooks). More investments become financially viable as the price of carbon increases.

### A portfolio of different decarbonization measures will be needed

Industrial $CO_2$ emissions (45 Mton direct and 22 Mton indirect) in the Netherlands now consist of ~10% process emissions, ~30% electricity-consumption related emissions, and ~60% of emissions related to heat production.

Reducing process and heat production emissions will require the application of multiple decarbonization options at once: efficiency improvements; electrification of heat production; change of feedstock (e.g. switch to bio-based); changes in demand by increasing reuse, remanufacturing, and recycling; changes in the steel production process; and carbon capture and storage or usage. Together the selected combination of options could reduce direct $CO_2$ emissions by 20 million metric tons by 2040. Overall, this would lead to a reduction of $CO_2e$ of 60% by 2040 compared to 1990. Of course application of different combinations and contributions of the individual options is also possible and may turn out to be more economical over time.

- **Efficiency improvement** (2 Mton or more)—Most 'quick wins' for energy efficiency have been captured. There is still further gain possible as some of the other options go hand-in-hand with efficiency improvement. For instance, electric heat-pumps for low temperature offer an efficiency increase of at least 50 percent.

- **Electrification of medium-and high-temperature heat generation** (11 Mtons by 2040, up to 17 Mton by 2050)—Electrification of heat production will play a major role in decarbonizing Dutch industry under any scenario. Some electrification measures are ready to implement such as hybrid or dual-fuel systems to generate medium temperature heat (100+ degrees Celsius). Other measures would benefit from targeted research and development or further commercialization. These include the development of heat-pumps capable of producing medium temperature heat and development of electric furnaces to provide high temperature heat (400+ degrees Celsius) for refining and ethylene production. Also production of hydrogen would benefit from innovation to bring down cost levels. In the longer run, the hybrid or dual-fuel systems could then switch to electricity and hydrogen instead of electricity and natural gas.

- **Change of feedstock** (0.5 Mton)—Through using bio-based feedstock for chemical production processes (e.g. ethylene and specialty chemicals production), both production and downstream emissions can be tackled. The first technologies to do so are around, but would benefit from further innovation and scale up to make them more economical. Likewise, for ammonia production, hydrogen produced from electricity and water can be used as feedstock, replacing natural gas. However, electrolysis technology (replacing the current steam methane reforming) is far from cost competitive and would thus benefit from innovation in combination with lower electricity prices.

- **Change in demand by increasing reuse, remanufacturing or recycling** (approximately 1 Mton)—Increasing reuse and recycling would reduce local, and perhaps global, demand for certain products (e.g. ethylene-based plastics, steel). This would directly lower the carbon emissions resulting from production of those goods. This option would thus reduce industrial output of e.g. virgin plastics as such.

- **Change in the steel production process** (approximately 3 Mton)—Steel production in the Netherlands could be decarbonized in several ways that resemble other options: changing the feedstock and fuel source (e.g. using charcoal fed blast furnaces, setting up a Direct Reducing Iron–Electric Arc Furnace process fed with iron ore and powered by biogas or hydrogen instead of coal, increasing recycling of steel by using scrap in Electric Arc Furnaces, or applying carbon capture and storage (which would require a switch to the so-called HIsarna process). These are all major decisions. For this report, we have assumed that by 2040 half of the Netherlands' current steel production would switch to a low- or zero-carbon option, equivalent to the output of one of the 2 existing blast furnaces.

- **Carbon capture and storage or usage (CCS/CCU)** (approximately 3 Mton)—Carbon capture can be used to reduce any emissions that cannot be eliminated by other means. At the capital investment costs which are currently associated with many decarbonization measures, and more importantly with commodity prices (with electricity power being more expensive than gas), carbon capture and storage seems more economical than several alternatives for decarbonization.

The majority of the (indirect) emissions related to electricity consumption (resulting from using gas or coal for power generation in the power sector) will have to be reduced through installation of renewables. Theoretically, industry's use of electricity generated from renewables (in the power sector) would lower $CO_2$ emissions by 16 million metric tons[3]. Given an ambitious penetration level of 80 percent for renewables - as per our previous report-, 10 million metric tons of emissions (60%) from current electricity use and 11 million metric tons of emissions (100%) from added electricity use would be abated. This means that 'greening' the Dutch electricity supply represents an impactful and necessary means of decarbonizing industrial emissions. All in all, this would reduce direct industrial $CO_2$ emissions by 25 to 50 percent.

3 These indirect emissions include 6 Mton of $CO_2$ emissions from steel production. Application of renewable electricity supply would only partially reduce these emissions. Hence we here include 16 Mton of emissions.

### The cheaper route: 60 percent decarbonization by 2040

At current cost levels, the cheapest route to decarbonize industry by 60 percent by 2040 would involve a combination of energy efficiency, electrification, and CCS/U. We estimate that a capital investment of EUR 9 billion would be needed, along with an increase in operational expenses of EUR 12 billion. Overall, the additional cost would be approximately EUR 21 billion over 20 years, though the actual cost would depend greatly on the pace of technological improvements that could reduce capex and commodity price differentials, potentially reducing operational expenditure.

### The steeper route: 80 percent decarbonization by 2040 and 95 percent by 2050

Upping the ambition level to reach 80 percent reduction in 2040 and 95 percent by 2050, is possible even with current and expected near-term technology. It would, however, involve applying more expensive decarbonization options sooner, mainly in two areas: more extensive electrification, through application of electric furnaces in refining and ethylene production; and more extensive use of CCS in refining and chemicals. These methods would reduce emissions 80 percent by 2040 compared to 1990 (32 Mton of direct industry emissions). The estimated cost of this approach is EUR 51 billion.

### Implications for the broader energy system

- A shift from fossil-based electricity generation to renewables is needed. This would lower current electricity-related industrial emissions of 16 million metric tons $CO_2$e to 6 or even 0 million metric tons.

- Increasing the roll-out of renewables would be needed to enable proposed electrification of industry (electricity demand increases from 118 PJ (excl. cogen) in 2014 to 340 up to 560 PJ in 2040). Towards 2040 industry would account for about two thirds of the projected power demand increase. It would also have significant implications for utilities, for the power grid, and for other elements of the national energy infrastructure: 6 GW of renewable generation would be needed on top of the 58 GW calculated in our previous report.

- The electricity price will have a major influence on cost effectiveness and feasibility. The development of the Dutch power system over the coming years, and the resulting energy prices and changes in the availability of low-carbon energy sources, will have a major influence on the feasibility and cost effectiveness of industrial decarbonization. It will also determine further technology choices and affect industry's international competitiveness.

- Many business cases hinge on these commodity price outlooks. De-risking is needed to make the  investment choices required.

- Over time, a diversification of supply may be needed to meet baseload industrial renewable energy demand more effectively. Increased application of hydrogen can play a role here (either through use in hybrid or gas boilers, or for back up power generation).

### A way forward:

Given these conditions, and the long horizons that most industrial companies use to plan their capital spending, it will be advantageous to develop a comprehensive (master) plan for decarbonization (incl. energy system design), and to begin developing and implementing each of the six decarbonization measures in the near term.

Getting a fast start will increase the likelihood that industrial companies will have effective decarbonization options to choose from as they adjust to changes in the energy system, and thereby stay on track to meet their long-term emissions reduction goals. Moreover, in some – if not all – areas advancing decarbonization more quickly can help ensure that industry remains competitive over the long term.

It is a delicate balance however, as the uncertainty about the future (costs) of the energy system is high (and those costs have an enormous impact on the operational cost development of many of the options), waiting might be economically beneficial. A plan for industrial decarbonization thus needs to be flexible enough to enable industry to pursue and invest in options according to the conditions and trends that actually unfold.

# Chapter 1: Targeting opportunities to lower industrial greenhouse gas emissions

Recent trends in the environmental efficiency of Dutch industrial companies have been encouraging. The World Bank estimates that Dutch industrial output increased by some 24 percent from 1990 to 2014. During the same period, direct greenhouse gas (GHG) emissions from Dutch industry fell by 32 percent—nearly three times the rate at which direct GHG emissions from other sources went down. By decoupling growth from environmental impact over a quarter-century, Dutch industry demonstrated one of the most important priorities for sustainable development.

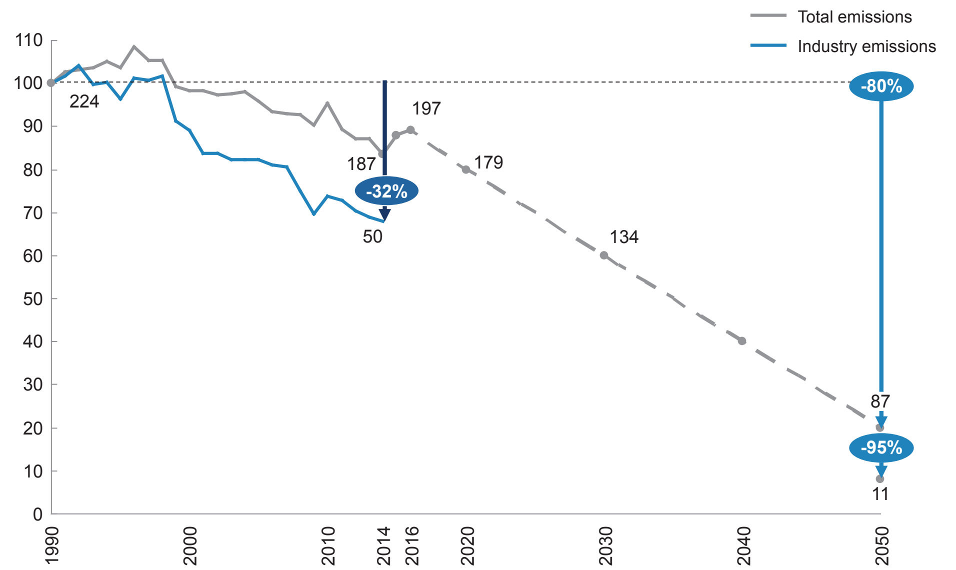
Yet further effort will be needed for the Netherlands to attain the EU's emissions-reduction goals. In 2015, during the lead up to the international negotiations that established the Paris Agreement, the EU pledged to make a 40 percent reduction in GHG emissions by 2030 (compared with 1990 levels). An earlier EU pledge, made under the Copenhagen Accord of 2009, calls for lowering emissions 80 to 95 percent by 2050.

In 2014, industry produced 50 million metric tons of $CO_2e$ of direct GHG emissions (usually emissions from sources onsite) and another approximately 22.3 million metric tons of $CO_2e$ of indirect GHG emissions (emissions from the use of electricity purchased from the grid). Industry thus accounted for almost 39 percent of the Netherlands' 187 million metric tons of $CO_2e$ of GHG emissions that year (Figure 1).

Figure 1

Industry $CO_2e$ emissions reduced 2x faster than total Netherlands

**$CO_2$ equivalent emission,** % change as of 1990



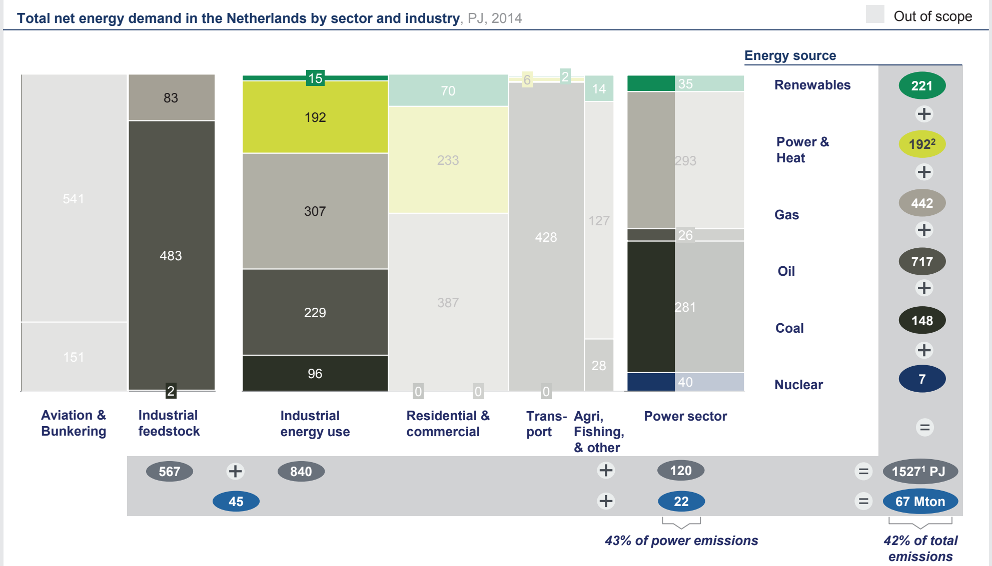

SOURCE: CBS, National Inventory Report (1990-2014)

Because Dutch industrial companies have already eliminated a significant portion of their GHG emissions, additional reductions could be more difficult to attain than earlier ones. Industry has reduced its emissions of GHGs other than carbon dioxide by more than 70 percent since 1990, from 18.2 million metric tons $CO_2e$ in 1990 to 5.1 million metric tons $CO_2e$ in 2014. Those emissions of methane, fluorinated gases, and nitrous oxide, which stem from specific industrial processes and applications (e.g. use of fluor in refrigeration, emissions of nitrous oxide from producing nitric acid and glyoxylic acid, emissions of methane from black-carbon production), are here assumed to reduce to close to zero by 2050—in line with other reports.

Following these reductions of GHGs other than carbon dioxide, carbon dioxide makes up some 90 percent of direct GHG emissions from industry, or 45 million metric tons of $CO_2$ in 2014. Industry produced another 22 million metric tons of indirect carbon dioxide emissions by purchasing electricity from the power sector. Together, the 67 Mton of carbon dioxide emitted by industry account for more than 40 percent of all the carbon dioxide emitted from the Netherlands (158 Mton in 2014). These carbon dioxide emissions represent Dutch industry's biggest opportunities for GHG reduction (Figures 2 and 3), and are the focus of this report. Our analysis thus focuses on potential reductions affecting 45 million metric tons of direct carbon dioxide emissions, as well as 22 million metric tons of indirect emissions.

**Figure 2**

## Industrial activities – including fair share of power, causes 42% of $CO_2$ emissions




1 Sum of industry energy use (1407 PJ: sum of 567 PJ and 840 PJ) and fair share energy use for power generation (120 PJ: industry electricity demand / centrally generated electricity * net energy consumption for production (320 PJ))
2 118 PJ of centrally generated electricity is used, and 74 PJ of heat

SOURCE: Centraal Bureau voor de Statistiek (2014), "Energiebalans" and "Energieverbruik" databases, National Inventory Report 2016

Because all companies are deeply integrated into value chains, they influence upstream and downstream GHG emissions (Figure 3: estimated to be around 120 Mton). For example, Dutch industrial companies purchase chemicals or other feedstocks whose production results in GHG emissions. Similarly, the products sold by Dutch companies cause emissions at the ends of their lives, such as products that are incinerated in waste-processing facilities or produced petrol used to fuel cars. Many of the actions that can help Dutch industrial companies to reduce their direct emissions of carbon dioxide will also reduce upstream and downstream GHG emissions. We have not quantified these secondary order effects, but have indicated where measures will have a positive influence on downstream emissions.

This report focuses on four large industrial subsectors: chemicals; steel[4]; petroleum refining; and food processing, beverages, and tobacco. Smaller industrial subsectors (including mining and quarrying; non-metallic minerals; pulp, paper, and print; and manufacturing of machinery) are grouped together.

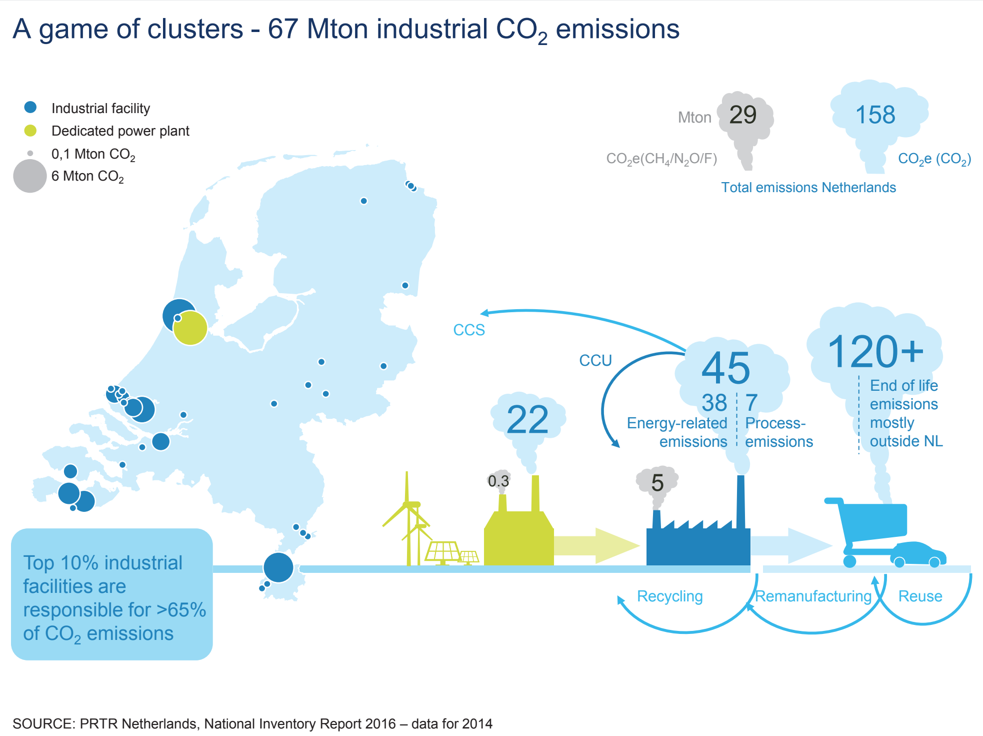
For this study, we have assumed that the structure and mix of industrial activity in the Netherlands will not change significantly through 2050. These conditions are sure to change; some of the changes will result from the efforts that industrial companies make to lower carbon emissions. For example, transportation systems are expected to rely increasingly on electricity as an energy source, which will reduce the overall demand for oil and could cause Dutch refineries to scale back their activity in the long run. Nonetheless, assuming that Dutch industrial activity will remain stable allows us to identify the opportunities for reduction that exist today, and the decisions that Dutch companies would need to make in order to pursue those opportunities.

### How industrial companies produce emissions

Five activities account for nearly all of industry's carbon dioxide emissions. Low- and medium-, and high-temperature heat production, electricity consumption, and transportation produce emissions because they involve the use of energy, mostly fossil fuels. Overall, industry uses 840 PJ of energy, of which about 570 PJ is used for heating purposes. Some industrial processes also generate carbon dioxide emissions; these are known as process emissions. Sources of industrial emissions are highly concentrated geographically: the ten facilities that emit the most carbon dioxide account for more than 65 percent of direct carbon dioxide emissions.

4 Steelmaking accounted for 6 Mton of direct carbon dioxide emissions and 6 Mton of carbon dioxide emissions that are commonly attributed to electricity generation. This is because the waste gases containing carbon dioxide are piped to a power plants so they can be reused before being released into the air. Since those emissions come from one industrial process rather than from electricity generation, we will show them in addition to the 45 Mton of direct carbon dioxide emissions from industry (and subtract them from industry's 22 Mton of indirect carbon dioxide emissions).

Figure 3




The five industrial activities that emit large amounts of carbon dioxide are described below, and shown in Figure 4, in order from most emissions to least.

**High-temperature heat production (22 Mton $CO_2$)**—Industrial processes, such as steam cracking processes or steel production, require large amounts (close to 300 PJ) of high-temperature heat (500 °C and above). Companies generally produce this heat with fossil fuel-powered furnaces.

**Electricity consumption (19 Mton $CO_2$)**—In the Netherlands, generating electricity produces carbon dioxide and other GHG emissions because a substantial part of Dutch power is produced with fossil fuels (gas, coal). The electricity consumed by Dutch industrial companies thus accounts for a portion of the carbon dioxide emissions from power generation. Out of the 22 million metric tons indirect carbon emissions, 16 million metric tons come from electricity drawn from the grid. Six million metric tons come from power generated, using waste gases from steel production, by the dedicated power plant for Tata Steel IJmuiden. An additional three million metric tons[5] of direct emissions result from net on-site electricity generation.

**Medium-temperature heat production (14 Mton $CO_2$)**—Industrial companies use medium-temperature (100–500 °C) heat in many different applications, such as evaporation

5 This includes approximately 1 $MtCO_2$ of the Tata steel emissions that can be attributed to electricity production

and distillation during chemical production and food processing, and driving turbines. Industrial companies generally produce medium-temperature heat by burning natural gas in boilers or cogeneration units. In almost all facilities, heat use is cascaded: heat is generated at the highest temperature needed for the industrial process, and the lower temperature residual heat is used in other parts of the process or elsewhere in an industrial cluster. This means that decarbonization measures for the heat-production process must be customized according to the operational requirements of the entire heat system of a site or cluster.

**Industrial process emissions (7 Mton $CO_2$)**—The chemical reactions involved in making cement, hydrogen, ammonia, and other chemicals and materials can emit streams of carbon dioxide and other waste gases. These come from transformations of the feedstock and are not related to the use of energy to drive the process.

**Low-temperature heat production (4 Mton $CO_2$)**—Industrial companies mostly use low-temperature heat (0–100 °C) for drying and distillation. In some industrial facilities, low-temperature heat is not produced directly, but obtained from the residual heat that is left over from processes requiring medium- and high-temperature heat.

**On-site transportation (1 Mton $CO_2$)**—Carbon dioxide emissions result from the burning of fuel to power vehicles at industrial facilities.

The amounts of carbon dioxide that come from these six activities varies considerably among industrial segments, depending on their operations and processes, the energy efficiency of their equipment, and other factors (Figure 4). Below, we describe the main sources of carbon dioxide emissions within each sector and highlight the sector-specific sources of emissions that present major reduction opportunities.

**Chemicals (22 Mton $CO_2$)**—Making chemicals involves many different processes. While these processes have various levels of emissions and energy intensity, two processes account for approximately half of the sector's carbon dioxide emissions: ethylene production and ammonia production. Ethylene production generated about 7 Mton $CO_2$ in 2014; the emissions mainly come from high-temperature steam cracking furnaces. Ammonia production resulted in more than 4 Mton $CO_2$ in the same year: majority of these emissions consist of nearly pure carbon dioxide resulting from the steam-methane-reforming step. Otherwise, the chemicals sector's direct carbon dioxide emissions predominantly stem from heat production and electricity generation.

**Steel (12 Mton $CO_2$)**—A single facility in the Netherlands, Tata Steel in IJmuiden, produces steel. Coal is the main fuel employed there; it is turned into coke before being burned in blast furnaces and blast oxygen furnaces for heat and to supply carbon molecules. The exhaust gas from those furnaces contains carbon dioxide and carbon monoxide. The gas is piped to two nearby power plants, which use the carbon monoxide to generate electricity, before being released into the air.[6]

6 As noted above, even though this carbon dioxide is released from the power plants next to the site of Tata Steel, we do include it here into the emissions associated with steel production: 12 Mton instead of 6 Mton.

About 10 Mton of carbon dioxide emissions resulted from the steel sector's production of high-temperature heat in 2014, an amount equivalent to more than 80 percent of the sector's total emissions. Process emissions are directly and indirectly (used to generate power) responsible for the remaining emissions.

**Petroleum refining (11 Mton $CO_2$)**—Nearly all of the petroleum sector's carbon dioxide emissions come from the production of medium- and high-temperature heat (9 Mton $CO_2$) for the distillation and cracking of crude oil. Refineries typically have integrated processes that make efficient use of energy and heat, for example, by residual gases and waste heat from furnaces to preheat feedstock. Also process emissions occur (1 Mton $CO_2$), mainly as a result of on-site hydrogen production for desulfurization.

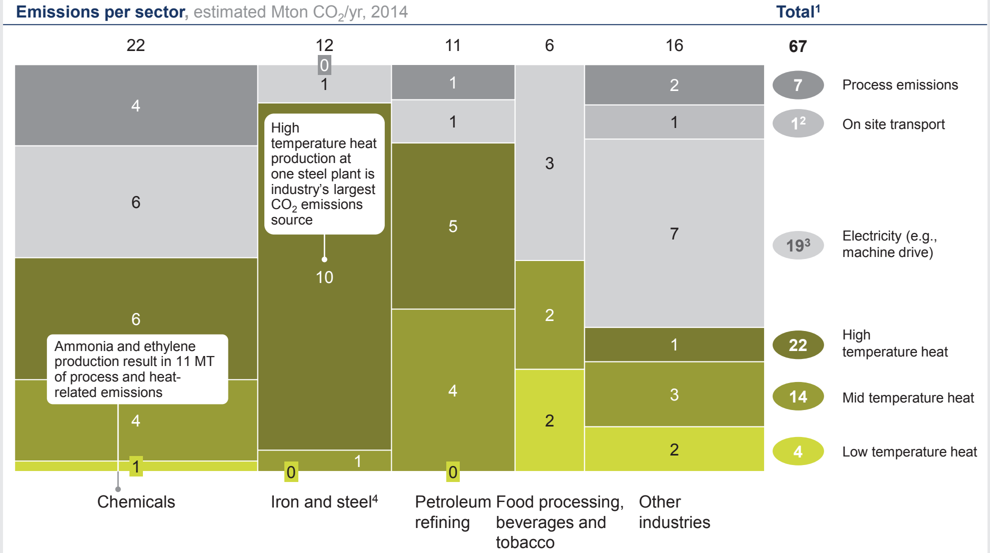
**Food processing, beverages, and tobacco (6 Mton $CO_2$)**—This sector comprises many small-scale facilities, each producing modest amounts of direct carbon dioxide emissions. More than half of these emissions come from making low- and medium-temperature heat, mostly by burning natural gas in boilers or cogeneration units. The other (smaller) half is electricity use for for instance machine drive.

**Other industrial sectors (16 Mton $CO_2$)**—This is a grouping of the remaining industrial sectors, each of which is smaller than the ones discussed above. The largest sectors included in this grouping are mining and quarrying (4 Mton $CO_2$, including production of oil and gas), non-metallic minerals (3 Mton $CO_2$, this includes cement), pulp paper and print (2 Mton $CO_2$) and manufacturing of machinery (2 Mton $CO_2$). On site transportation is treated as separate sector (1 Mton $CO_2$), as in reporting it is not specified by sector.

The scale and extent of industrial activity in the Netherlands mean that companies can consider a variety of opportunities to reduce their carbon dioxide emissions. Some of these involve becoming more energy efficient. Some require the adoption of new processes or extensive process changes. Others can only be achieved through greater integration across sectors. Implementing the necessary changes can be complicated, if not challenging, because of financial and operational hurdles. In the next chapter, we look at the conditions in which Dutch industrial companies operate today, and how these conditions might influence their efforts to reduce emissions.

Figure 4

## Heating causes majority (40 Mton) of industrial $CO_2$ emissions




NOTE: Difference in totals due to rounding
1 Emissions from biomass are excluded; 2 On-site transport not allocated to specific sectors; 3 3 Mton of onsite power generation and 16 Mton of $CO_2$ emissions from the power industry (out of 22; 6 Mton included in steel); 4 Iron and steel includes 6 Mton of emissions from dedicated power plant

SOURCE: Manufacturing Energy Consumption Survey (2013); National Inventory Report (2016); expert interviews; CE Delft Denktank energiemarkt Industrielewarmtemarkt 2013; expert interviews

# Chapter 2: The main barriers to reducing industrial carbon emissions

Reducing direct carbon dioxide emissions by 1 million metric tons each year—the rate required to reach the EU's carbon-reduction goals—will not be easy for the Dutch industrial sector. We see four factors that present challenges.

**The need to maintain a competitive edge in global markets**—Dutch industrial companies sell many of their products in Europe and abroad. Making investments in emissions-reduction programs could raise the costs of doing business, thereby making Dutch products more expensive. For example, emission reduction measures of EUR 10 billion would increase the price of steel by 10 – 20 percent (~60 euro/tn steel produced). All measures thus need to be ranked and screened in an international context. Likewise, given the international nature of the companies, investments also need to surpass internal investment hurdles, effectively competing with other locations / assets.

**The uncertainty of operational costs**—The cumulative costs of operating industrial equipment and facilities into the future typically exceed the upfront capital expenditure of buying and installing those assets. This makes it risky to invest in new capital equipment that runs on an alternative fuel, such as electricity: the exposure of these investments to unpredictable and wide-ranging power prices creates uncertainty about how long it will take for the investments to pay back (if at all). For instance, for an investment in a heat-pump, the payback time can be reduced with 5 years (e.g. from 9 to 4 years) if the electricity price is 20 EUR/MWh instead of 50 EUR/MWh.

**The cost of prematurely replacing industrial assets**—The payback periods for replacing industrial assets are often quite long and most assets and systems have long lifetimes. A typical ammonia plant, for example, has a lifetime of over 50 years, and boilers at least 30 years. The savings produced by replacing them with alternatives that are more efficient or less expensive to operate tend to be modest. For example, replacing a conventional gas boiler (capex of ~130 kEUR/MW heat output) by a heat-pump (capex of~650 kEUR/MW heat output) to generate low temperature heat will still see a payback time of 9 years. Companies are therefore less likely to replace expensive, long-lived assets before they absolutely must—that is, before the asset fails or becomes costly to maintain, or before a markedly superior alternative becomes available.

**The unique circumstances and requirements of every industrial facility**—Even though some technologies can be applied in a wide range of industrial settings—for example, hybrid or dual boilers to generate medium temperature heat—these technologies are not equally easy to implement in every setting. Industrial facilities tend to be engineered with great precision. This means that individual pieces of equipment can't simply be swapped out; entire systems might need to be redesigned to accommodate new assets. For example, in petroleum refineries, even relatively small equipment changes require part of the site to be redesigned and rebuilt, because the processes are highly integrated within a small, optimized area. Likewise, in sugar beet processing heat flows through different steps of the process. If a single step in the process has its heat demand altered by a change of equipment, then many of the other steps will need to be adjusted as well.

# Chapter 3: A portfolio of different decarbonization measures will be needed

A variety of emissions-mitigation options is available to (Dutch) industrial companies, each offering particular advantages and disadvantages. Here we present a set of six options that we believe have the most potential to help Dutch industry reach a 60 percent carbon emissions reduction by 2040, in line with the EU's emissions-reduction targets. Together, these six advanced processes and technologies can even enable the Dutch industrial sector to reduce its carbon emissions 95 percent by 2050, in line with the upper end of the EU's long-term emissions goals (see also Box II – the steeper way – striving for a more ambitious decarbonization path).

This integrated menu of promising decarbonization options can provide industrial companies with a basis for planning investments and operational changes, as well as supporting research and development of technologies that will be important in the long run. This chapter presents the criteria we have used to evaluate and select decarbonization options, describes the six options that appear to be most practical and effective, and offers an integrated outlook on the costs and the emissions impact of implementing the six options.

### Selection and evaluation criteria for decarbonization options

The challenges of adopting industrial processes and technologies that emit less carbon dioxide impose particular constraints on the selection of decarbonization options. Some options that have significant emissions-reduction potential might be too costly to be feasible under current conditions; others might be technically impractical. These considerations and trade-offs informed the development of the following criteria for evaluating potential decarbonization options (for more information about these criteria, see Appendix section II):

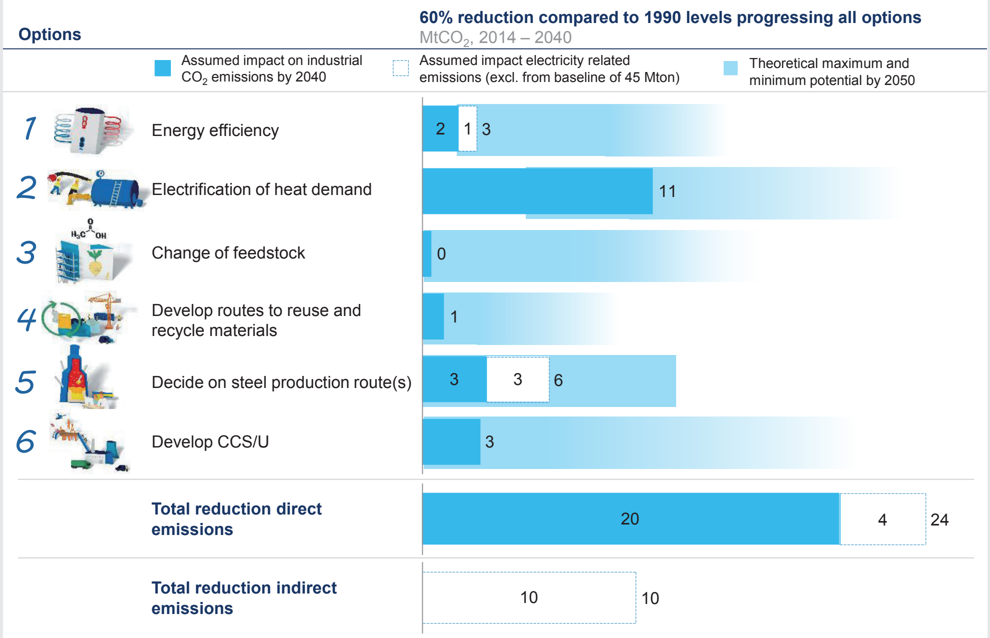
- The financial requirements associated with each option, which is largely determined by two factors: the investment cost and the operating cost[7]
- The emissions impact, measured in terms of the option's potential to prevent emissions across the entire industrial system
- The robustness of the option under various scenarios: for the future availability and prices of electricity, natural gas, and hydrogen as energy sources; and for the adoption of circular economy principles – reducing resource extraction and consumption
- The potential economic and societal value that the option would create for the Netherlands

Our findings with regard to the effectiveness and feasibility of the six decarbonization options with the most potential for Dutch industry are described below (Figures 5, 6 and 7).

7 In our earlier report, we estimated the capital expenditure required to implement decarbonization measures by calculating the difference between the capital cost of low-carbon measures and the capital cost of conventional measures. In this report, we only accounted for the capital cost of low-carbon measures, without deducting the capital cost of more conventional measures. The main reason for the alternative approach is that we expect that assets will have to be replaced before the end of their technical lifetime, and industrial players may thus face the full investment

Figure 5

Six ways to move industrial decarbonization forward – reaching 60% by 2040




SOURCE: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014)

## 1. Upgrading to energy-efficient equipment

Dutch industrial companies have already made extensive upgrades to more energy-efficient equipment, which accounts for most of the $CO_2$ emissions reductions they have achieved to date. Nevertheless, some opportunities for further improvement remain. Energy-efficient equipment, such as heat-pumps and mechanical vapour recompression units, is available to companies across the industrial sector and is advantageous regardless of how energy prices develop in the future. For the Netherlands as a whole, widespread adoption of energy-efficient equipment would help to reduce the country’s energy consumption and thereby make it less dependent on imported sources of energy. Our estimates suggest that this option would reduce carbon emissions by 3 million to 12 million metric tons.

Installing energy-efficient equipment can require significant capital expenditures. Besides the cost of the equipment itself, industrial companies might also need to pay for modifications of other assets and operating processes. For example, adding mechanical vapour recompression requires the evaporation or distillation unit to be rebuilt completely. Similarly, to install heat-pumps a company needs to have a source of heat for them. If heat networks are tightly integrated with other equipment, then those networks might need to be redesigned in order to feed heat into heat-pumps. The cost of these redesigns can make the upgrades prohibitively expensive, even if the equipment itself is cost-effective.

## 2. Electrification of medium and high temperature heat

The falling cost of renewable electricity generation makes electrification of industrial heat demand an attractive decarbonization option for medium-temperature as well as high-temperature heat. The estimated impact of electrifying heat production ranges from 6 million metric tons to 18 million metric tons.

**Switching to hybrid or dual system boilers for medium temperature heat**—Boilers that can run on either electricity or natural gas are available. A hybrid boiler or a dual system of a natural gas boiler and an electric boiler can replace a fossil fuel boiler. These setups allow industrial companies to use electricity or natural gas as energy sources, depending on which source is less expensive at any given time (see Box II: 'The logic of using dual-fuel or hybrid energy systems').

Switching to boilers with optionality in fuel choice is most economical when an existing boiler reaches the end of its life or requires significant maintenance. As these boilers have long life-spans of 30 years or more, they should be changed as soon as they are up for replacement. It must be said, however, that the additional cost of hybrid boilers could be problematic for some industrial companies. The hybrid boiler itself costs at most 50 percent more than a conventional gas boiler, but the additional cost is unlikely to be covered by savings on purchases of energy in the near-term. However, the ancillary services (e.g., flexibility, buffer, storage) that industrial companies could provide to the power system may strengthen the business case.

Changing boiler types can also require modifications to other equipment or to surrounding facilities, since they require more space than gas boilers and must be connected to the electric system in an industrial plant. The latter can require the expansion of on-site power lines or even off-site connection capacity and substations.

**Innovating in high and medium temperature electric-powered heat systems**—Both high-temperature electric furnaces for industrial applications, as well as medium-temperature heat-pumps, have yet to be developed as mainstream technology. The equipment could be used in multiple sectors. High temperature furnaces would offer a relatively economical decarbonization option for industrial plants where alternatives like CCS or a process change are expensive, especially when electricity prices are low. In principle, these furnaces could reach the market within 5 years if there is demand and research funding available. Medium temperature heat-pumps (functioning well above 100 °C), would present a viable alternative for must-run medium temperature boilers and will lower overall energy demand from industry as these are expected to be – just like the low temperature heat-pumps – more efficient than electric, hybrid or dual-system boilers. Pending the availability of low-cost (and/or excess) hydrogen, some of these high temperature heat furnaces could also (partially) run on hydrogen.

# Box I: The logic of using dual-fuel or hybrid energy systems

Dual-fuel or hybrid boilers offer industrial companies a valuable degree of optionality in fuel consumption. They can consume more electricity when electricity prices drop during periods of peak renewable-energy production, then switch to gas during periods when electricity prices rise as renewable-energy generation slows down. This not only enables companies to take advantage of low electricity prices, but also helps to balance loads on the electric grid.

For the time being, the financial case surrounding dual-fuel and hybrid energy systems does not support their adoption on a large-scale. In 2016, electricity prices in the Netherlands dropped below gas day-ahead prices for just 170 hours or so. At those energy prices, the payback periods for investments in dual-fuel or hybrid boilers would likely be 10 years or more. However, as the Netherlands adds renewable-energy generation capacity at the ever-decreasing costs that have been observed in recent years, it is expected that there will be more times when electricity is a more economical fuel source than natural gas. Such a trend, either on its own or along with increases in the price of natural gas, would significantly shorten the payback periods for dual-fuel and hybrid boilers and other heat systems.

### 3. Changing feedstock

**Developing bio-to-chemicals processing routes**—Using biomass/biofuels instead of fossil fuels helps to prevent carbon emissions in several ways. First, renewable biomass has recently taken up $CO_2$ from the atmosphere. If $CO_2$ is released back in the atmosphere when processing a feedstock or when using residual gasses for heat, there are no net emissions. Similarly, when $CO_2$ is emitted at the end of life of a product, the net emission is still zero. In contrast, net emissions from fossil based materials are positive. Secondly, bio-based processes for the production of specialty chemicals often require less energy than comparable non-bio-based production processes, because they operate at lower temperatures and pressures - emitting less $CO_2$. Bio-based chemicals production can also help maximize use of biomaterials when biomass is used in a cascaded way e.g., food, feed, fuel towards functional molecules.

Bulk chemicals, or chemicals that are produced in large volumes, can technically be made from biomass, such as biodiesel. However, these processes need large supplies of biomass and are therefore limited by the cost and availability of currently renewable biomass supply. Consider the example of ethylene. The Netherlands produces approximately 3 percent of the world's ethylene. We estimate that using biomass as the sole feedstock for ethylene production in the Netherlands would require 600 PJ of energy from biomass (16 Mt biofuel).

That is approximately half as much the biofuel as was produced globally in 2016. It is more than the amount of biomass that the Netherlands would consume if its demand for biomass were proportional to its share of the world's population or its share of the world's economic output. Other examples of bio-based ethylene production methods include ethylene production from bio-ethanol and ethylene production using cyanobacteria. The latter is in lab stage, but could in time become a promising route. Using ethanol route is viable, using less biomass than in the ethylene cracking route, but does not produce propylene and other products that are widely used as 'by-products' of steam cracking, making it only a partial solution.

Specialty chemicals are produced on a smaller scale and in smaller quantities than bulk chemicals. They have higher margins, and therefore offer more room for experimentation with new processes than bulk chemicals. Indeed, for some specialty chemicals, bio-based processing methods, relying on fast-growing renewable biomass or microorganisms as a feedstock, are already more economical than conventional alternatives. Examples include several vitamins (B2, B12), propanediols, glycols, and epichlorohydrin amongst others. But some factors could limit the roll-out of bio-routes for specialty chemicals. One is that chemical plants would need to be overhauled to use the new methods. Another challenge is technical and economic feasibility. Bio-based processes are not available for all specialty chemicals, so new bio-based methods would need to be developed, or made more cost-effective, for additional specialty chemicals.

Even given the limitations, we expect that producing chemicals from biomass can reduce carbon emissions by at least 2 million metric tons, with the potential to play a larger role in the future.

**Using 'renewable' hydrogen as feedstock, e.g. for ammonia production**—In the Netherlands, hydrogen is mainly produced through steam methane reforming, a process that uses natural gas as feedstock. Electrolysis offers a zero-carbon[8] alternative to hydrogen production. It is a process for producing hydrogen that involves using electricity to split water molecules into atoms of hydrogen and oxygen.

Implementing electrolysis systems would require new production facilities to be set up. However, existing steam methane reforming units have not reached the end of their useful lives yet. Producing hydrogen to feed a 500 ktn/yr ammonia plant would require a continuous electricity supply of 600 MW, which is about the amount of energy generated in the planned Borssele I-IV offshore wind parks.

More investment in research and development will be needed to reduce the cost of large-scale and smaller scale electrolysis plants and to make the electrolysis process more efficient, or to develop other ways to produce 'renewable hydrogen'. We estimate that this option could lower carbon emissions by more than 4 million metric tons of carbon dioxide, provided that

8 Note: it only lowers carbon emissions if the electricity used to power the process comes from renewable sources. If electricity from gas or coal plants is used instead of renewable energy, then using electrolysis for hydrogen production produces more carbon emissions than making hydrogen from natural gas.

sustainable electricity prices are very low and the equipment has improved efficiency and lower investment costs. Interestingly, once a cost effective way of hydrogen production has been found, and when electricity prices falls, hydrogen could be applied in many different ways: as an energy source that could replace fossil fuels in industry, transport, and built environment, and as a backup that helps to balance the power system and energy markets as a whole.

### 4. Reusing, refurbishing, remanufacturing, and recycling more material

Collecting the by-products and waste products of industrial processes and household consumption, then reusing, remanufacturing, or recycling them, would eliminate the carbon emissions that result from the processing of virgin materials. Also, it eliminates the carbon dioxide that would otherwise be emitted at end-of-life of the products, increasing its impact at least twofold.

Various possibilities exist for waste recycling and reuse; examples include recycling of plastics, feeding steel scrap back into production, and extracting minerals and biogas from biomass waste. Some of the necessary technologies exist already, and the advanced Dutch logistics sector could support the scaling-up of recycling and reuse by making it economical to transport materials to processing facilities. But more efficient and sophisticated methods, including enhanced collection and sorting schemes, still need to be developed. Ethylene and propylene are both formed in the ethylene steam cracking process, together with other base chemicals such as benzene. Ethylene and propylene are together the largest share of products produced in ethylene steam cracking.[9] About 60% of ethylene and propylene end up in various kinds of plastics. In Europe over 40% of plastics are used in packaging, 20% is used in construction, and less than 10% goes into the automotive industry. The European Union has set a prospective target of 55% plastic packaging recycling in 2025.

At least 2 million metric tons of carbon dioxide emissions could be prevented each year by increasing recycling and reuse of ethylene- and propylene-based plastics, assuming that 50% of all plastics can be produced from recycled feedstocks.[10]

### 5. Introducing alternative steel-production routes

More $CO_2$-efficient methods of steel production should save approximately 12 million metric tons of carbon dioxide per year, the most of any of the decarbonization options we have identified. In their existing forms, however, these methods have drawbacks that would need to be resolved by additional research and development.

Electric arc furnaces, for example, are less emissions-intensive because they use less energy and are powered by electricity. They use steel scrap as a feedstock, thereby creating more ‘circular’ steel and lowering resource demand (iron ore).  However, they require the complete retooling of steel plants and their operations and would need a larger

9 This is only true for steam crackers that use naphtha as a feedstock, which is the case for most steam crackers in the Netherlands

10 This is based on a reduction of steam cracking by 30%. It is 50% of the 60% of ethylene and propylene based plastics being recycled, and it is assumed that 30% of the other base chemicals produced in steam cracking can come from recycled sources

supply of high-quality scrap than is available today, as well as a steady supply of low-cost renewable electricity. Another alternative, producing steel by the HIsarna process, consumes approximately 20 percent less energy and is conducive to carbon capture because the waste gases are higher in carbon dioxide. This process would continue to use fossil fuels (coal) as a power source and would require CCS to fully decarbonize – likely leading to an increase in the steel price. Likewise, experiments with top gas recycling are ongoing, essentially recycling useful gases back into the furnace reducing the amount of coke needed, potentially also complemented with CCS. Also switching to (smaller scale) charcoal blast furnaces could be an option, if a cheap and sustainable source of charcoal / woodchips can be found. Finally, there is the possibility of switching from coal-powered blast oxygen furnaces to bio- or hydrogen-powered direct-reduced iron or blast furnaces. This would nearly eliminate the need for fossil fuels, while still allowing production of virgin (iron-ore-based) steel. This option, though, would require a rebuild of most of the site and the use of (currently) more expensive hydrogen or biogas. Ultimately, a combination of these options may materialize, depending on commodity prices such as scrap steel and renewable electricity.

### 6. Developing carbon-capture storage and/or usage technology

Capturing carbon dioxide is most practical for industrial processes that emit large volumes of concentrated, high-pressure carbon dioxide. Such processes include hydrogen production in ammonia plants and certain parts of petroleum refining. Once the carbon dioxide has been collected, it can either be confined underground (an approach known as carbon capture and storage, or CCS) or used as an industrial feedstock for making products (an approach known as carbon capture and usage, or CCU).

While carbon-capture technology has been developed, it has not been widely applied, largely because of its high cost. Given current commodity and technology prices, decarbonization with CCS is more economical, in terms of costs per ton of $CO_2$ avoided, than many alternatives. An example is the production of hydrogen for ammonia production. Producing hydrogen through steam methane reforming, with carbon captured and storage (at around 40 EUR/ ton $CO_2$), costs less than producing hydrogen through electrolysis (>70 EUR/ ton $CO_2$). Likewise, for petroleum refining (at around 100 EUR/ ton $CO_2$), CCS is a cost-effective solution for high-concentration $CO_2$ emissions, which account for about 25 percent of all carbon dioxide emissions from the refining process.

If the captured carbon can be put to use instead of being stored, it could replace fossil-based feedstocks, further reducing resource needs and possibly making this route more economical. Examples of CCU include use of captured carbon dioxide in greenhouse to stimulate vegetation growth, in fertilizer production (urea), in production of methane or methanol using hydrogen.

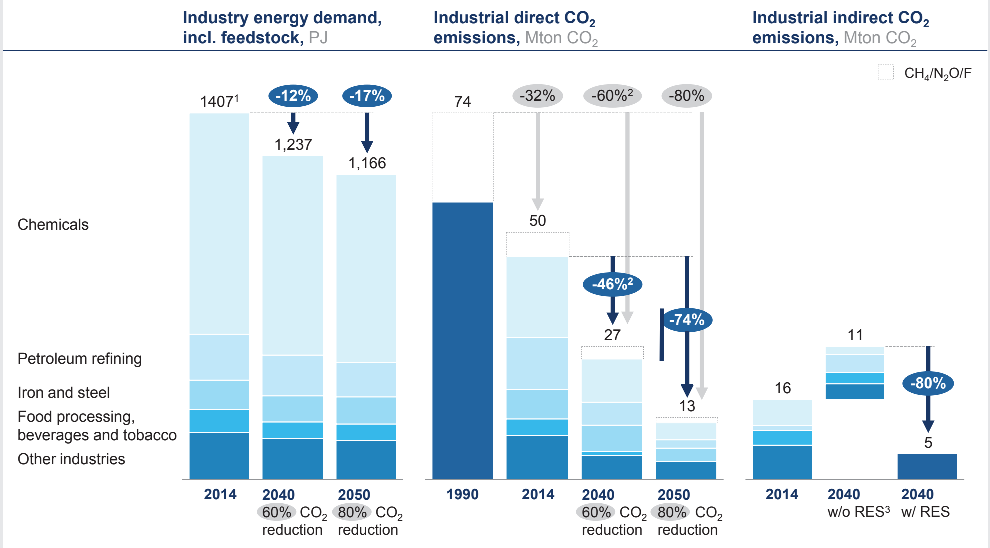
We estimate that, under current commodity prices, full-scale carbon capture (storage and usage) would reduce industrial emissions by up to 15 million metric tons—the second-most of any of the six options.

In practice, though, CCS's impact could be more modest. One reason is that it does not add value to industrial products. Second, it is an option that always leads to extra costs vis-à-vis the current set up. Third, alternative solutions might become more economical (e.g. when prices of alternative commodities such as sustainable electricity decrease compared to fossil fuels). This would stimulate a shift away from CCS and towards more electrification. For instance, when electricity prices get very low, it might be more economical to electrify ethylene production than to decarbonize it with CCS. Similarly, for ammonia production, electrolysis will be more economical than steam-methane-reforming with CCS. And finally, as the economy as a whole moves away from fossil fuels, the need for other solutions that apply to sectors such as refining may become less pressing.

As noted at the beginning of this chapter, we estimate that implementing the six options could reduce Dutch industry's emissions of carbon dioxide, both direct and indirect, by 60 percent in 2040: a carbon dioxide emission reduction of close to 20 Mton. Energy consumption will be lower by 15 percent, mainly resulting from efficiency improvements en reduced use of feedstock due to recycling / reuse (Figures 6 and 7).

**Figure 6**

Energy demand is reduced by 15% and $CO_2$ emissions by 46% (20 Mton)




1 840 PJ of energy demand and 567 PJ of feedstock. Data used in our previous report is based on a preliminary publication of the energieverbruik and energiebalans numbers of CBS, which is shown here and adds up to 840 PJ energy consumption for industry. The final CBS reporting on energieverbruik and energiebalans adds up to 833 PJ.
2 Assumes overall decarbonization of electricity for industry of ~100%, or when including indirect emissions ~80%.
3 With/without installation of renewable energy supply (80% renewable). 11 Mton is capped by reduction of 11 Mton.

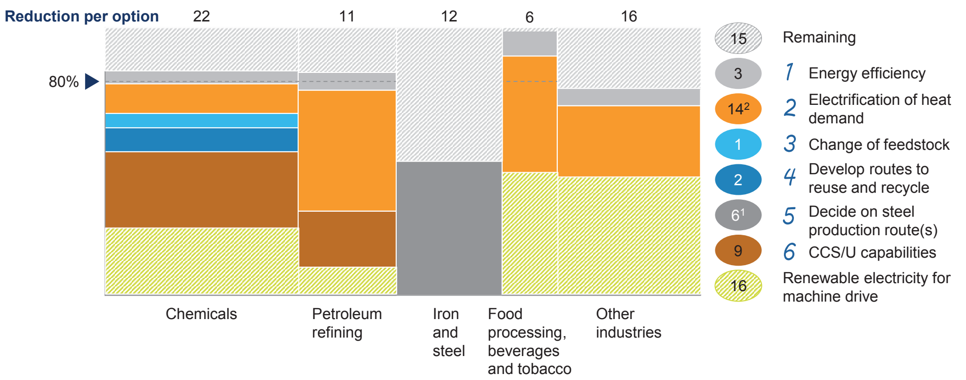
SOURCE: CBS-data for 2014

The relative contributions of the six options will vary with a number of factors. These factors include commodity prices, and equipment costs, and the extent to which industrial companies pursue other priorities, such as the implementation of circular-economy models and the reduction of downstream and upstream GHG emissions in their value chains. But the most influential factor of them all is the future price of energy.

Figure 7

## Impact of the 6 options on industrial emissions, leading to 80% reduction by 2050

**Emission reduction per option,** 2050, Mton $CO_2$ **Total**




| | Chemicals | Petroleum refining | Iron and steel | Food processing, beverages and tobacco | Other industries | Total |
|---|---|---|---|---|---|---|
| Direct and indirect emissions 2014 | 22 | 11 | 12 | 6 | 16 | 67 |
| Direct emissions 2014 | 17 | 10 | 6[1] | 3 | 9 | 45 |
| Remaining direct emissions 2050 | 4 | 2 | 3[1] | 1 | 5 | 15 |

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Differences in totals due to rounding
1. Reduction of 6 Mton includes 3 Mton reduction from dedicated power plant. Hence remaining emissions include 3 Mton direct emissions and 3 Mton indirect emissions from steel. 2. This would assume 100% decarbonization of power supply to lead to 14 Mton emission reduction. When taking the indirect emissions into scope (of 22 Mton) it would correspond to decarbonization of power supply of 80% - in line with our previous report.
SOURCE: Centraal Bureau voor de Statistiek (2014), "Energiebalans" and "Energieverbruik" databases, National Inventory Report (1990-2014)

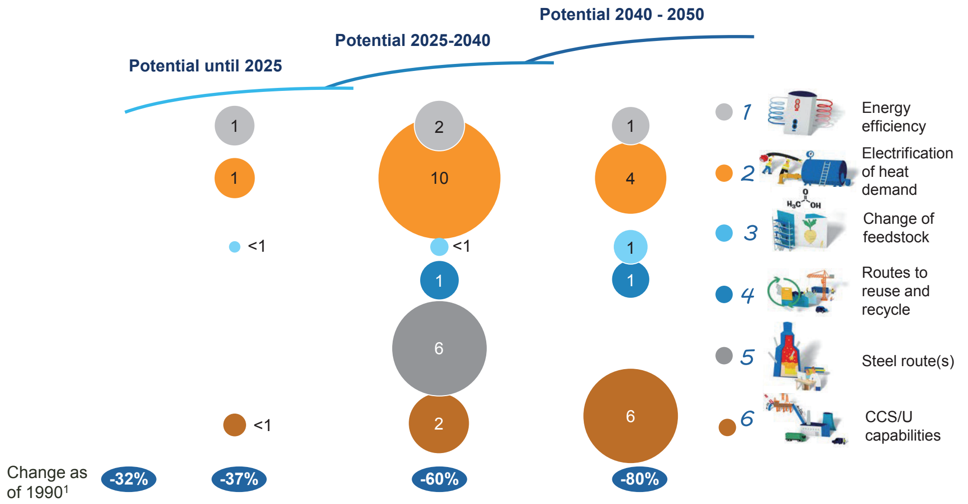
# Chapter 4: The outlook for industrial decarbonization – required investment levels

As noted in the previous chapter, we estimate that implementing the six options could reduce Dutch industry's emissions of carbon dioxide, both direct and indirect, by 60 percent in 2040. Achieving this goal would involve reducing annual emissions by 2 million metric tons $CO_2$ from current levels in 2025 and by another 18 million metric tons $CO_2$ in 2040.

Figure 8

**Projection of $CO_2$ emissions of industry with the 6 options**

**$CO_2$ equivalent emission,** Mton $CO_2$ change as of 2014, progressing all options




NOTE: Difference in totals due to rounding
1 For industry projection only direct emissions included. Assumed that non-$CO_2$ emissions are reduced at the same speed as $CO_2$ emissions. Assumes assume 100% decarbonization of power supply to lead to 14 Mton emission reduction. When taking the indirect emissions into scope (of 22 Mton) it would correspond to decarbonization of power supply of 80% - in line with our previous report.

SOURCE: CBS, National Inventory Report (1990-2014)

Some of the options, namely energy efficiency (#1) and certain electrification technologies such as hybrid boilers (#2), are technically feasible today and have relatively attractive business cases. Other options are in early stages of development and need several years before they can be applied at scale cost effectively. These include electrification of high temperature heat (#2), and some of the alternative steel production routes (#5). Because these options are mostly in R&D phase and not implemented at scale yet, their costs are difficult to estimate, but they could be on the order of 100+ EUR per ton $CO_2$ abated.

The third category of options is closer to scale up but would benefit from cost reductions. These include options like increasing recycling and reuse (#4) and changing industrial feedstocks (#3). Some companies will find specific applications useful in the near term. For each of these, costs can be expected to come down as production of the technologies scales up or as new business models emerge. For now, costs would be on the order of 100 - 300 EUR per ton $CO_2$ abated.

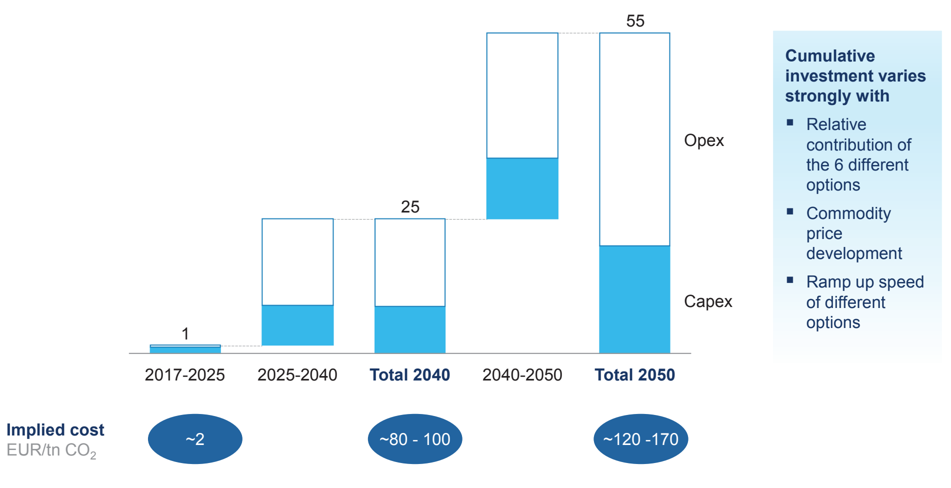
Because the feasibility of almost all the decarbonization options would rely on either steep cost reductions, carbon pricing, or subsidies or other alternative financing schemes, we conservatively assume that most impact will come after 2025. Over the coming years, the actual pace at which companies implement decarbonization options will largely be determined by factors such as technology prices (capital expenditure), the price of electricity (operational expenditure), carbon pricing, and other incentives to reduce carbon dioxide emissions or resource consumption through implementing of circular economy models for prolonging the lives of materials and products.

A plausible selection of the six options would cost EUR 23 billion between now and 2040, based on current commodity prices and technology prices. Of these investments, about 20% has a viable business case with payback times in the order of 10 – 15 years, while 80% does not have a positive payback yet. Around EUR 6 billion consists of capital investment, while EUR 17 billion would be spent on higher operating costs (Figure 9).

Figure 9

Under current commodity prices, it would cost EUR 55 billion to reduce industrial emissions with 80% compared to 1990

**Capex and cumulative opex[1],** EUR billion; 2020 - 2050



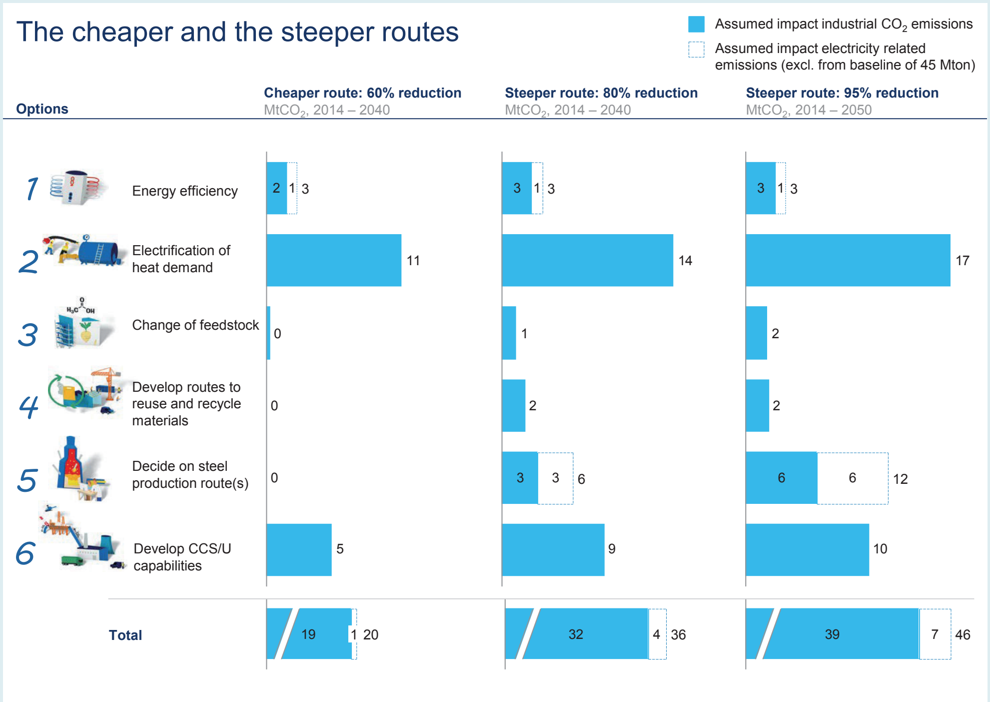

NOTE Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Difference in totals due to rounding
1 Assumed 2/3 of yearly Opex as ramp up

# Box II: The steeper way – striving for a more ambitious decarbonization path

Our indication of relative contributions of the six options, and the associated costs, target 80% industrial emission reduction by 2040. But what if we were to aim for 95% reduction for industry?

The good, and perhaps surprising, news is that it is possible to reach a 95% carbon dioxide emission reduction by 2050. This does come—at least based on the current state and cost of technologies—with at a significantly higher cost. Given current energy prices, the six options would require capital spending of EUR 1 billion by 2025, EUR 17 billion between 2025 and 2040, and EUR 7 billion between 2040 and 2050. Industrial companies would also experience increases in their annual operating costs, primarily for energy and feedstocks: less than EUR 100 million per year in 2025, EUR 2.5 billion per year in 2040, and EUR 4 billion per year in 2050. We estimate the total cost of implementing the six decarbonization measures, at current energy prices, would be in the order of EUR 70 billion.

**Figure 1**




SOURCE: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014)

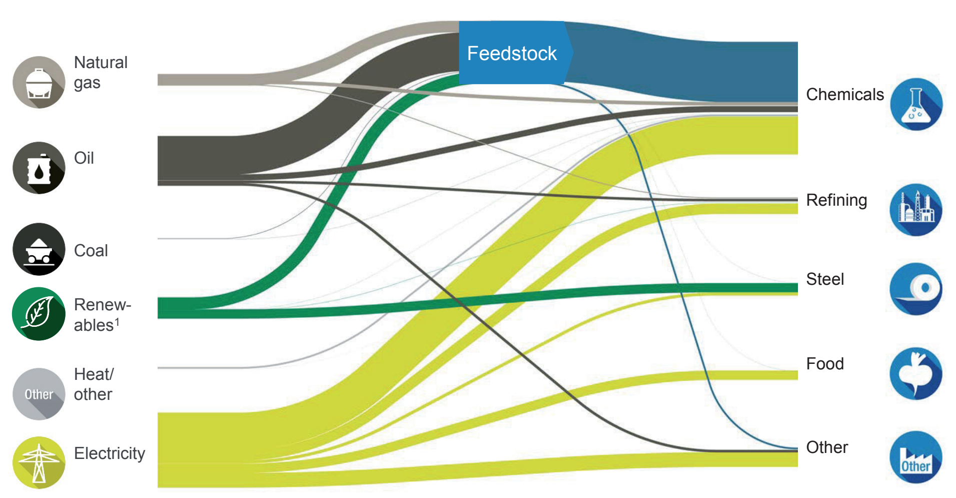
In alternative scenarios where the prices of electricity and hydrogen are lower than they are now, capital expenditures remain around the same level, but annual operating costs do not increase as much (see also Appendix section III Figures A5 & A6). If electricity prices were to fall to average levels of EUR 20/MWh (from EUR 50/MWh today including transmission and distribution costs), then the entire cost of the decarbonization program would be lowered by more than 40 percent (from about  EUR 70 billion to approximately EUR 36 billion.

Lower electricity prices also affect the costs of the six options relative to one another. For example, more ethylene could be produced with electric pyrolysis furnaces[1], and less ethylene would be produced using conventional methods with the addition of CCS/CCU.

**Figure 2**

### Netherlands energy demand in 2050; flow between energy sources and industry

**Energy sources,** PJ **Industry**




1 Biomass excluding waste

1 Currently electric pyrolysis furnaces are not commercially available. Electric pyrolysis furnaces are more attractive than CCS when the electricity price is very low. To achieve full decarbonization of electric ethylene production, the residual gasses (among others methane) now used for process heat should be put to use elsewhere where these will not emit carbon dioxide.

### The cheaper way

If we were to chart all the available decarbonization measures according to their current costs and their abatement potential, we would come up with a different distribution of options. It would – at least in the period till 2040 – create a greater role for electrification and CCS, and limit investments in recycling and reuse, substitution of alternative feedstocks, or changes to steel production.

Although this seems to be the most economical path, we believe it will be useful (and economically beneficial) to start taking steps and making investments in the other 3 options as well, because industry will need most of if not all of the six options to attain an 80 percent emissions reduction by 2050. Not making investments will limit the chance of economic gain from these options, which should have commercial potential on a global scale.

### Impact of the six options on the energy system

Under the chosen set of options and relative contributions thereof, the (energetic) energy demand of the industrial sector will see a modest decrease somewhat from 840 PJ today to 740 PJ per year.  At the same time, demand for electricity will increase threefold, as will the demand for bio-based renewables. Feedstock demand  changes from 569 PJ in 2014 to 500 PJ in 2040, under our relatively modest assumptions (Figures 10 an 11).

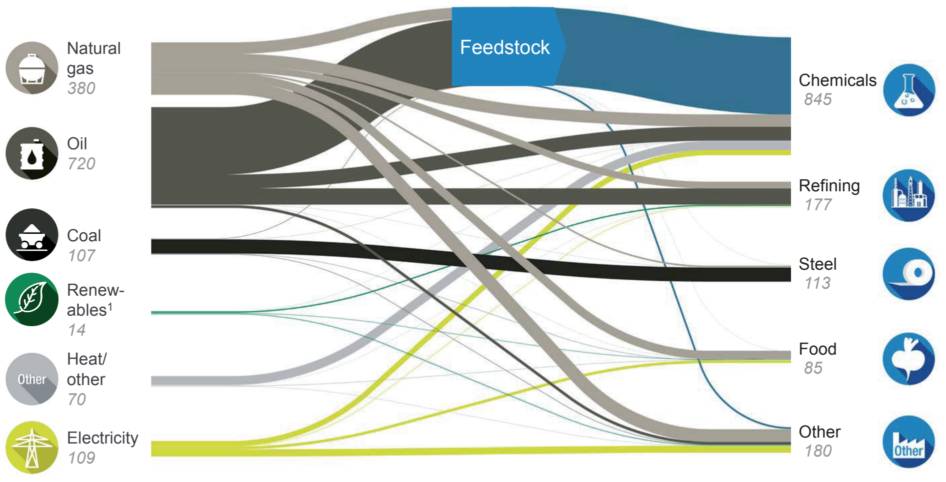
The modest increase in energy efficiency (most of the decrease is due to recycling of plastics) results from lack of efficiency-gains through the six options: many of the equipment and process substitutions that the six options involve only result in reductions in carbon dioxide emissions. For example, hybrid and electric boilers are hardly more energy efficient than conventional gas-fired boilers. (By contrast, electric vehicles use about one-third of the energy used by vehicles with internal-combustion engines). Of course, some technologies do increase energy efficiency; such as those included in option one, like heat-pumps for low-temperature heat.

We must reinforce, however, that the shift to low-carbon energy and technology will involve significant changes to industrial facilities and processes, and could have some permanent effects on the structure of the industrial sector and its energy use.

## Figure 10

### Netherlands energy demand in 2014; flow between energy sources and industry

**Energy sources,** PJ | **Industry**

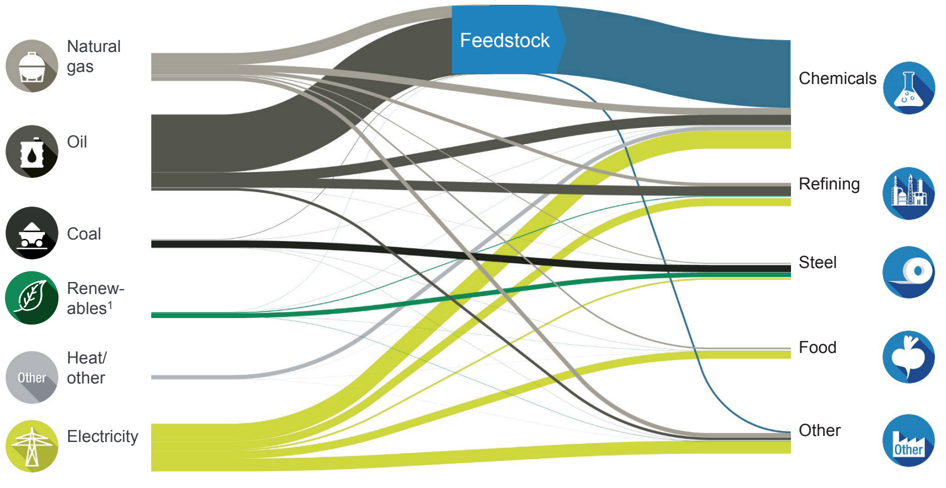



1 Biomass excluding waste

## Figure 11

### Netherlands energy demand in 2040; flow between energy sources and industry

**Energy sources,** PJ | **Industry**



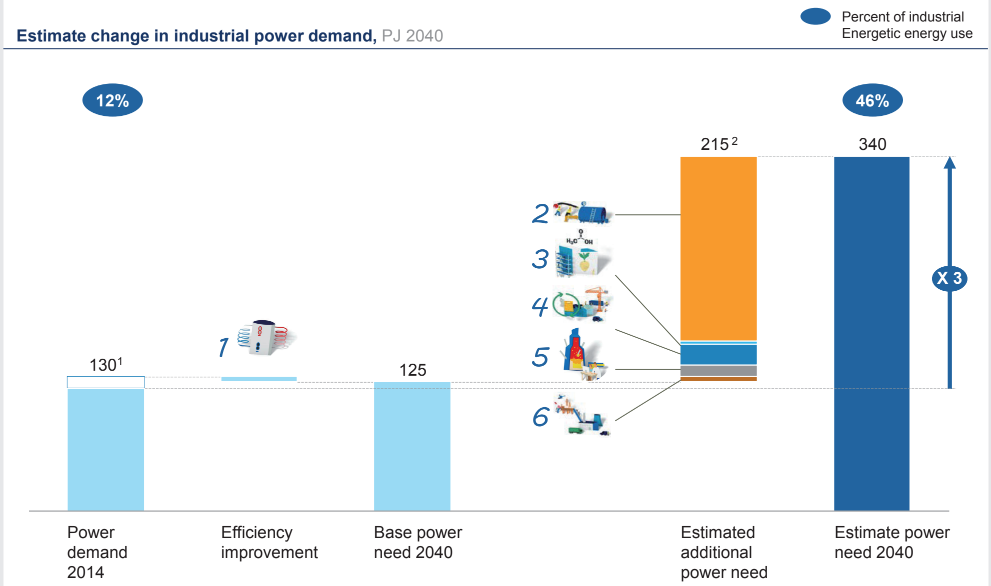

1 Biomass excluding waste

## Impact of the six options on electricity: tripling of industrial electricity demand

All six options will affect industry's demand for electric power. In our base case, electricity demand would triple: more than 45 percent of the energy used by industry (excluding feedstock) would be electric power, compared with 12 percent today. Most of the increase would come from the application of hybrid boilers and electric-powered heat systems (170 PJ of added electricity demand). Other increases would result from CCS (5 PJ), expanded recycling and reuse and bio-to-chemicals processing (20 PJ) (see Figure 12). Should power prices decrease, electricity demand could increase further (up to 560 PJ). This increase in power demand is greater than we anticipated in our previous report - the overall increase there totalled at 212 PJ for all three sectors together, and 125 PJ for industry.

**Figure 12**

### Estimate increase in power demand due to electrification and other options




1 Including cogeneration of 21 PJ, corrected for differences in base year numbers CBS (industry energy use of 840 vs 833 PJ).
2 This is much (~100 PJ) higher than anticipated in our previous report.
SOURCE: CBS Statline (2014 data)

To meet this increased demand for electricity and associated decarbonization impact, some 20 GW of renewable-power generation capacity will be needed - or some 6 GW of renewable capacity more than we listed in our previous report *'Accelerating the energy transition: cost or opportunity?'*[11]. An example of what the Dutch power system could look like, is shown in Figure 13 - this combines the outlook we created in our previous report with the electricity demand numbers presented here.

11 https://www.mckinsey.com/global-themes/europe/accelerating-the-energy-transition-cost-or-opportunity.

# Box III: Sensitivity for future energy prices

Electrifying the industrial sector—that is, replacing assets and updating processes to use electricity as an energy source instead of fossil fuels—is essential to reducing carbon emissions. An outlook on the future of the energy market is therefore needed as the basis for evaluating the operating costs of various solutions.

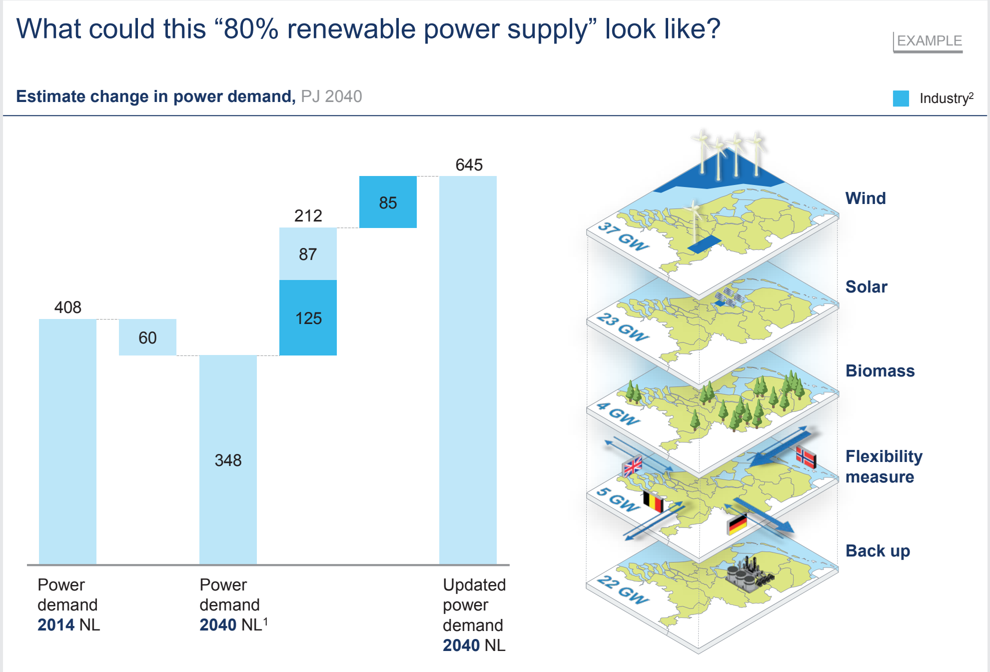
During the past ten years, the electricity market in the Netherlands has experienced a decline in demand and a significant decrease in wholesale prices. These developments can be attributed to the slowdown of the economy, increasing energy efficiency, falling commodity prices, and buildup of the Netherlands' renewable-energy generation capacity, particularly in solar, wind, and biomass.

Further additions of intermittent renewable-energy capacity will have to match increases in demand for electricity. Since electricity prices are now set by marginal producers, the use of technologies that have zero marginal costs will put downward pressure on electricity prices under current 'energy only' markets pricing. At the same time, increasing commodity and $CO_2$ prices, combined with capacity phase-outs, could push electricity prices temporarily upward.

These conflicting forces make the future price of electricity difficult to predict. Electricity prices also seem likely to become more volatile as more generation capacity comes from intermittent sources. To allow for the uncertainty of energy prices, we modelled the impact of the six decarbonization solutions under different energy-price scenarios. This shows that reducing electricity prices from about 50 EUR/MWh (including transmission and distribution costs) to 20 EUR/MWh will have major implications for the economic viability of the business cases. In essence, it would reduce the required investment levels from EUR 23 billion to EUR 8 billion by 2040 (60% emissions reduction). Likewise, towards 2050 the difference would amount to close EUR 35 billion (see Appendix III for more detailed outcomes).

Given the extent of the effect of lower electricity prices, competitively priced renewable electricity will be key in making this transition a success, both in national and international context.

Figure 13




1 In our previous report *"Accelerating the energy transition: cost or opportunity?"*
2 In our previous report we estimated that power demand increase for industry would be 125 PJ. Here we find an additional demand of 90 PJ (minus 5 PJ of efficiency increases).

In addition, these, mostly intermittent, renewable sources will have to be integrated in the system: making sure power demand of industry can be met over the days and seasons. Adjustments and upgrades to the transmission and distribution grid as well as additional back up capacity and flexibility measures will thus be needed.

The decarbonization approach we describe here offers some advantages in this regard, for it has the potential to stabilize and strengthen the Dutch energy system. Switching to hybrid boilers, as noted above, could help industrial companies to balance loads on the power grid. Similar effects could be achieved by the use of electrolysis to produce hydrogen, which can also store energy and thereby provide a backup, portable source of energy. Electric furnaces in steelmaking and electric-powered heat systems can also help to balance loads on the power grid, if industrial companies ramp up their processes when electricity prices are low, though they also have minimum electricity demands (to keep facilities running at all times) that increase the base load on the grid. A way to circumvent part of the electricity demand increase would be to make use of medium-temperature heat-pumps (once developed), which would theoretically reduce demand for medium temperature heat dramatically and thereby demand for electricity.

## Impact of the six options on the economy of Netherlands

Implementing the recommended set of six options should ultimately help Dutch industrial companies to serve global markets more effectively. For the Netherlands, a stronger industrial sector would offer several societal benefits.

**Economic stability**—The six decarbonization options have the potential to reduce industry's energy consumption, and thus its sensitivity to future energy prices. They would also prepare Dutch industrial companies for a future in which emissions regulations are more stringent. Both improvements would help Dutch industrial businesses to compete more effectively. For the Netherlands, a strong industrial sector is important to the economy overall. Dutch industry accounts for approximately one-fifth of the country's GDP and about 1 million jobs. Decarbonizing the sector will help safeguard its future, as an important source of economic production, against global and regional disruptions.

**Economic and industrial development**—The thematic investments described have the potential to serve as catalysts for new economic and industrial activity. This could work in two ways. First, the capital and effort required to create low-carbon processes and technologies for industrial companies could also stimulate innovation in other domains, which should lead to further advances and entrepreneurial endeavours. For example, the Dutch offshore and petroleum sectors are both well-suited to the development and application of CCS and CCU technologies. Another example is experience with development, installation and integration in existing processes of electric equipment across the Netherlands. Second, investments in utility-scale generation and transmission infrastructure for zero-carbon energy, captured carbon dioxide, syngas, and hydrogen will create backbone systems that lower the cost of doing business in the Netherlands. This should attract more industrial companies to the country and encourage the ones that are already there to expand their Dutch operations.

**Job creation**—We estimate that implementing the six carbonization options would require capital expenditures of about EUR 10 billion by 2040 and EUR 18 billion by 2050, although that number would increase if Dutch companies pursue a different selection of options. Most of this capital spending would be incremental additions to Dutch economic activity. It would impact employment in four ways: (i) during the development and installation and integration phase, a wave of employment of mainly technical personnel can be foreseen. (ii) resulting operations and maintenance may be equal or lower than today. (iii) in the longer term, new jobs may be created through the emergence of new economic and industrial activity (e.g. become leading in electric equipment or application of bio-based processes). (iv) last but not least, decarbonization of current industry may lead to safeguard current jobs.

Sectors in which the Netherlands has a strong competitive advantage could be the recipients of much of this spending—in which case the investments should generate thousands of new jobs.

# Box IV: Intrinsic capabilities of the Netherlands that support effective decarbonization

Some aspects of the Dutch industrial sector favour decarbonization, or yield competitive advantages in a low-carbon world.

**Dutch industrial companies are top performers**—The Netherlands is home to some of Europe's best-performing chemicals factories, petroleum refiners, and steel plants. This positions them well to thrive in the long run, and therefore to make long(er) term investments.

**Dutch industry is densely organized**—Industrial facilities in the Netherlands are located close to one another; most are situated in industrial clusters. This compact setup makes it less costly or even beneficial for industrial firms to build integrated systems, such as networks that carry heat, hydrogen, or waste gases (e.g. Delfzijl's steam connection, Chemelot's flue gases and steam network).

**The chemicals and agrifood sectors are innovative and sophisticated**—Nineteen of the top 25 chemical companies in the world have significant operations in the Netherlands. The country is also the base for 12 of the world's largest agrifood companies, the second-largest food exporter in the world, and has the world's top-ranked school of agriculture, the University of Wageningen. These qualities make the Netherlands a center for experimentation and innovation in chemicals and agrifood, which should speed the uptake of new bio-to-chem or waste-to-chem technologies and solutions.

**The logistics infrastructure is world-class**—The Netherlands has a large logistics sector (including the port of Rotterdam), which is capable of collecting materials from across Europe, as well as transferring them throughout the continent. This should give the Netherlands premium access to streams of recycled materials, such as plastics and steel scrap, which could be used as (energy-efficient) replacements for industrial feedstocks.

**The energy system is stable and well-connected**—The Netherlands' energy infrastructure is strong, with a reliable electricity network and an extensive gas network that are among the world's most reliable transmission and distribution systems. These assets have allowed the Netherlands to become Europe's second largest importer and exporter of electric power and natural gas. In addition, the country has commissioned some of the lowest-cost offshore wind installations in the world.

# Chapter 5: Charting a way forward

As we reported last year, an accelerated transition to low-carbon technologies and behaviors across the Dutch economy could generate substantial economic benefits for the Netherlands as a whole—provided that the private and public sectors make a large-scale commitment of effort and capital investment. We also noted that each sector of the economy will need its own approach to the transition, supported by clear targets.

With this report, we assessed how the Dutch industrial sector could move towards a low-carbon model, resulting in the selection of six decarbonization solutions. As many of the underlying business cases are not positive yet, this plan will need to be articulated further to succeed. Effectively, some of these measures may require a regulatory stability and outlook that even the EU cannot provide: understanding how to mitigate potential 'diversion' is key.

The government can consider policies that would help industrial companies to carry out the changes that decarbonization will involve, both in national and international context.

In line with our findings for the Netherlands as a whole, we see three key elements of a policy program that will support industrial decarbonization:

- **Develop a master plan for decarbonization** — which serves three purposes: increase clarity around targets and goals, provide a higher level of regulatory certainty, and improve energy system design.

  Most companies of the capital intensive Dutch industrial sector operate with investment horizons of more than 30 years. Before they commit to purchasing equipment and instituting practices that will lower carbon dioxide emissions, companies will want to have some assurance that regulations will favour the necessary investments and operational changes. Companies will also likely prefer to have some clarity about the future of energy prices, since so much of their operating costs come from sourcing energy. Hence, a reliable outlook on the availability of low-carbon (renewable) energy and of power in particular, coupled with an outlook on the likely power price development for industry, would be very beneficial given the increased sector coupling between power generation and industry. The committed targets the Dutch government sets on the roll-out of renewable power is one of the instruments it has at its disposal to do so.

  This strong coupling between the energy industry and the industrial sector also puts the design of our power system under pressure. Making smart use of industry energy demand by using industry as buffer for intermittent renewables (e.g. convert excess electricity to heat that can either be stored or used) will allow integration of more intermittent renewables into the system. Through increasing collaboration of different actors in the energy system (utilities, transmission and distribution operators, energy intensive industries, and financial institutions), a more effective and economic system design may be possible. This could lead to economic benefits as well as system-level benefits (e.g. reliability and security of supply), for instance utilizing buffer capacity industrial processes can offer may be cheaper than using alternative energy storage technologies.

- **Optimize planning for long-term economic value** — Several of the decarbonization options we have recommended for Dutch industrial companies will create value for the national economy: GDP growth, greater innovation, and a more sophisticated, reliable, and cost-effective energy system, all of which will help to create a more attractive environment for domestic and foreign investment in the industrial sector. As illustrated in Box IV, industry in the Netherlands is relatively well-positioned to create value from investments in CCS/CCU, recycling, and bio-to-chemical routes, and possibly alternative steel routes (depending on the chosen decarbonization path). Likewise, creating optionality in medium temperature heat, and further innovation in hydrogen production, electric furnaces, and medium temperature heat-pumps may yield secondary benefits in the transitioning of the energy system towards incorporation of more renewables and should be valued as such (e.g. by using stacked business cases). Most efficient are focused programs that have scale or aim for scale up.

  Therefore, the capital and operational costs associated with these options should be reviewed against the additional economic value they would create for the Netherlands in the long run. Given the relatively 'untrodded territory' that these technologies entail, it seems there is a real opportunity for the Netherlands to shape a leading role in their development, deployment and global scale-up.

- **Structure public incentives to support the master plan** — As we describe above, industry is faced with uncertainty when considering the investments required to realize the low carbon targets. Public incentives can support in taking away some of this uncertainty – let us mention a few different angles. Firstly, ensuring existing industry regulation is fully aligned with targets of the energy transition (e.g. enable valorization of waste streams, favour high-value use of bio products). Secondly, ensuring incentives favour the creation of long-term economic value, as well as environmental and social benefits for the public, as per the above recommendation. Finally, calibrating the regulatory system to match the uncertainty in both the capital and operational costs. As we can see from Figure 9, operational costs (consisting of commodity costs but also $CO_2$ prices) are actually the majority of the total costs for industry – which therefore might also need to be weighted proportionally in the regulatory system. Competitively priced renewable electricity therefore also becomes an instrument that can have major impact on the (national and international) business cases underlying the majority of the options.

# Appendix

**I. Detailed alignment with previous report**

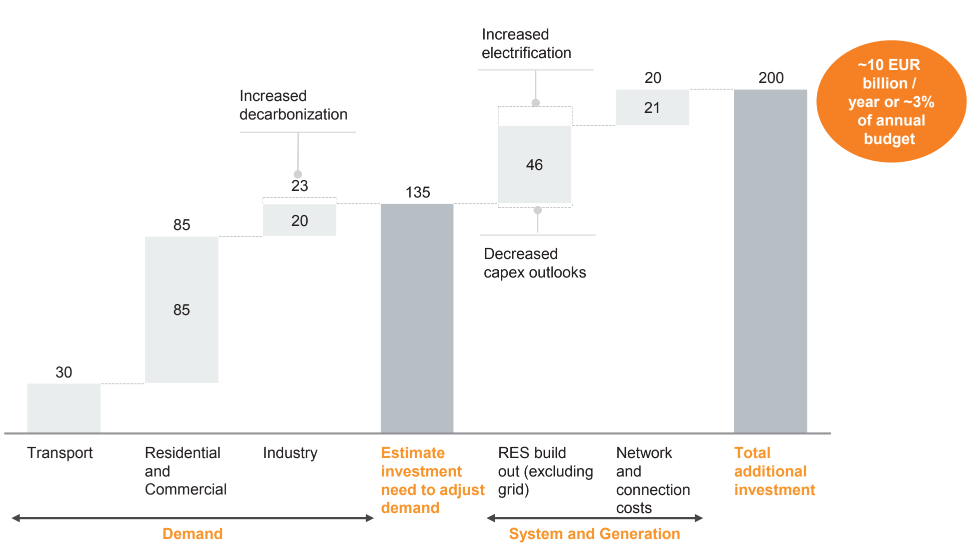
In Chapter 1 in Figure 2 we illustrated the link between the scope of carbon dioxide emissions as used in our previous report *'Accelerating the energy transition: cost or opportunity?'*, and the industrial scope as applied here.

We would also like to show how our previous investment estimates align with estimates shown here. There are two main differences: (i) previously, to ensure consistency within the report, we calculated the delta between investments needed for decarbonization and replacement investment you would have to take in any case. For instance: we would take the total cost of ownership from a fossil-fueled car and compare that to the total cost of ownership of a Battery Electric Vehicle, and would only use the delta. Here, given that industrial investment timeliness are so long and already look beyond 2040 anyway, we took the full cost into account, without adjusting for replacement capex. The main argument being that in the brownfield environment of most of our industry, limited number of required investments will take place at a natural replacement moment. (ii) in our previous report, we decarbonized the industrial sector to about 50 percent reduction instead of 60 percent. (iii) here we've taken a more granular approach, resulting in selection and calculation of a broader range of options. All in all, in our base (smart) scenario progressing all options, we arrive at a required investment of EUR 23 billion, compared to EUR 20 billion in our previous report (Figure A1).

Figure A1

An investment of ~EUR 200 billion would be needed to move towards 60% $CO_2$ reduction by 2040

**Indicative net investment need,** EUR billions, 2020 to 2040




SOURCE: McKinsey Report: *'Accelerating the energy transition: cost or opportunity?'*

In one area we do find a (major) difference: the role and impact of electricity is much greater than we anticipated. This leads to a higher increase in electricity demand of about 100 PJ (225 PJ vs 125 PJ). This in turn has implications for the roll-out (and speed thereof) of renewable power solutions, which will also require additional investments. On the bright side, since our report last year, prices for offshore wind have plummeted faster than we foresaw (Figure A1).

### II. Criteria for assessing decarbonization options

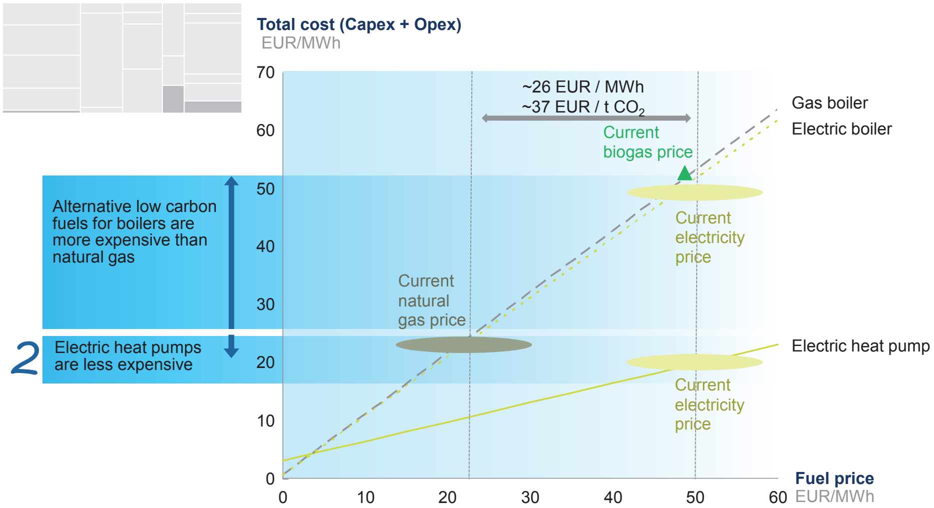
To facilitate the selection of appropriate decarbonization options for the Dutch industrial sector, we developed a set of five criteria. These criteria reflect the sources of emissions across Dutch industrial companies, the companies' competitive strengths, and the economic and financial requirements that industrial processes and technologies must meet to be viable in the long run.

- Business case—The financial requirements associated with each of the decarbonization options are largely decided by their respective investment costs and operating costs (Figures A2, A3, and A4).
  - Investment cost—Most decarbonization options will require an upfront capital investment. This investment has several major components. One is the cost of the equipment or technology. Many of the options we have identified are in use among Dutch industrial companies, but are not widely applied yet. Another component is the cost of installing the equipment and reconfiguring facilities to accommodate it. This makes it impractical to replace certain types of industrial equipment until it has reached the end of its useful life. Depending on the extent of the changes, brownfield adaptation might also be required.[12]
  - Operating cost—Operating costs have a major influence on the overall business case of decarbonization options. The cost of energy and energy-related feedstock is a significant and uncertain component of operating expenses; therefore, our analysis focuses on these costs. Decarbonization options that use less energy, or a cheaper source of energy, are therefore advantageous. For most options, we have assumed that future maintenance costs will be comparable to what they are today.
- Emissions impact—A decarbonization option must have significant potential to prevent emissions in order to be worth pursuing. The emissions impact of an option might be dispersed widely among many emissions sources, in multiple subsectors, or it might be concentrated on a large source of emissions in a single subsector. In either case, the option should reduce emissions by a large overall amount. The overall amount of

12 In our earlier report, we estimated the capital expenditure required to implement decarbonization measures by calculating the difference between the capital cost of low-carbon measures and the capital cost of conventional measures. In this report, we only accounted for the capital cost of low-carbon measures, without deducting the capital cost of more conventional measures. The main reason for the alternative approach is that we expect that assets will have to be replaced before the end of their technical lifetime, and industrial players may thus face the full investment

Figure A2

## Low temperature heat: due to the efficiency gain, heat pumps have a lower total cost than gas boilers, also at current commodity prices




NOTE: Low temperature heat: 0 - 100 ºC; Mid temperature: 100 – 500 ºC: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen, biogas assumed to be twice as expensive as natural gas

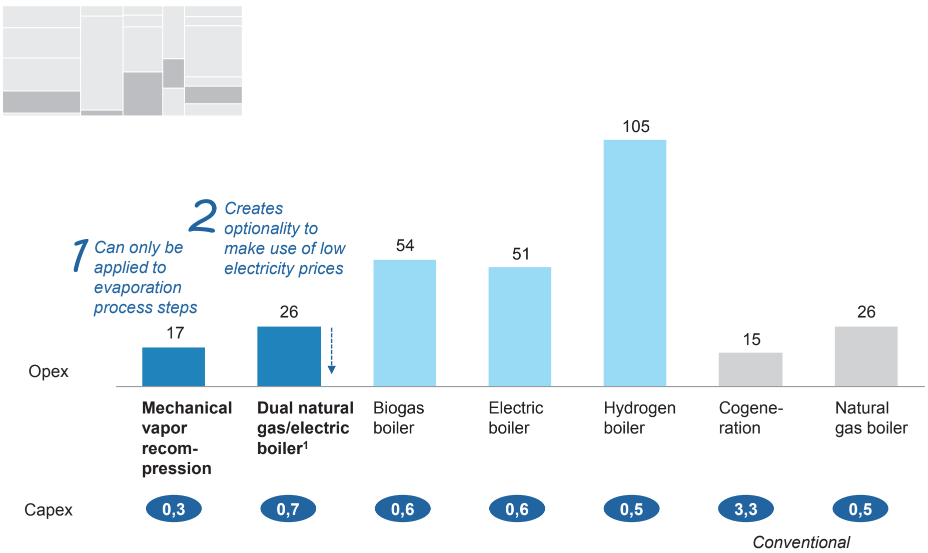
1 Only reduces carbon emissions if the renewable electricity price is below the natural gas price

SOURCE: Nottingham energy, Expert Interview, IEA Bioenergy taskforce, UK 2050 Pathway, NREL, DOE

Figure A3

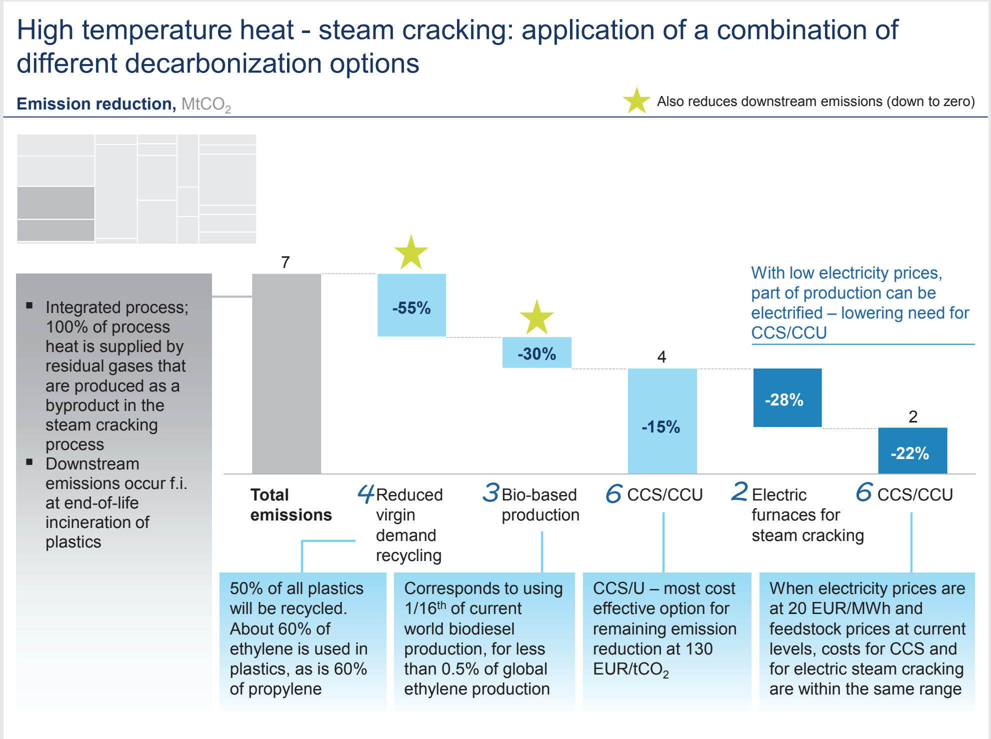
## Medium temperature heat: build in optionality to make use of low(er) electricity prices

**Cost estimate 2015,** EUR/MWh heat output




1 Hybrid boilers can switch almost instantaneously between gas to electric heating. If the hybrid boiler is only switched on if electricity prices are below 50 EUR/MWh, then the costs per MWh heat output will be lower

Figure A4




emissions prevented should also not cause emissions to shift from the industrial sector to other parts of the value chain, such as upstream sources of energy or feedstocks, or landfills, incinerators, and other end-of-life disposal sites. Ideally, the decarbonization option will lower emissions from industrial production as well as emissions across the life-span of industrial products.

- Robustness under various scenarios—As noted above, decarbonization options that require less energy are advantageous because they are less exposed to fluctuations in energy prices, which can increase operating costs. To determine how sensitive an option is to changes in energy prices, we modelled the costs of each one under three different scenarios envisioning different prices for electricity, natural gas, and hydrogen. We also explored, where possible, options that support or are more congruent with a circular economy model in the Netherlands, in line with the ambition of 'Nederland circulair in 2050'. We thus modelled the viability of each option under different scenarios for the resource productivity of the Dutch economy in the coming decades.

- Value creation for the Netherlands—Ideally, a decarbonization option will not only help to reduce emissions from the industrial sector, but also provide other economic and societal benefits. For example, decarbonization options might help make Dutch industrial companies develop new products or solutions, and thereby promote the sector's growth and its ability to provide jobs. The availability of low-carbon industrial processes and technologies could also attract more companies to the Netherlands.

### III. Sensitivity to electricity price developments

As stated numerous times throughout this report, the pricing of electricity (both base and peak pricing) will dictate (i) the relative contributions of the six different options, and (ii) heavily influence the different business cases. Here we show a sensitivity analyses illustrating how different the outcomes would be under two different pricing scenarios: at 50 EUR/MWh and at 20 EUR/MWh (both including transmission and distribution costs where applicable).

Overall, if electricity prices were to fall to average levels of 20 EUR/MWh (from 50 EUR/MWh today including transmission and distribution costs), then the entire cost of the decarbonization program would be lowered by more than 60 percent (from about EUR 23 billion to approximately EUR 8 billion in 2040 (Figures A5 and A6).

Figure A5

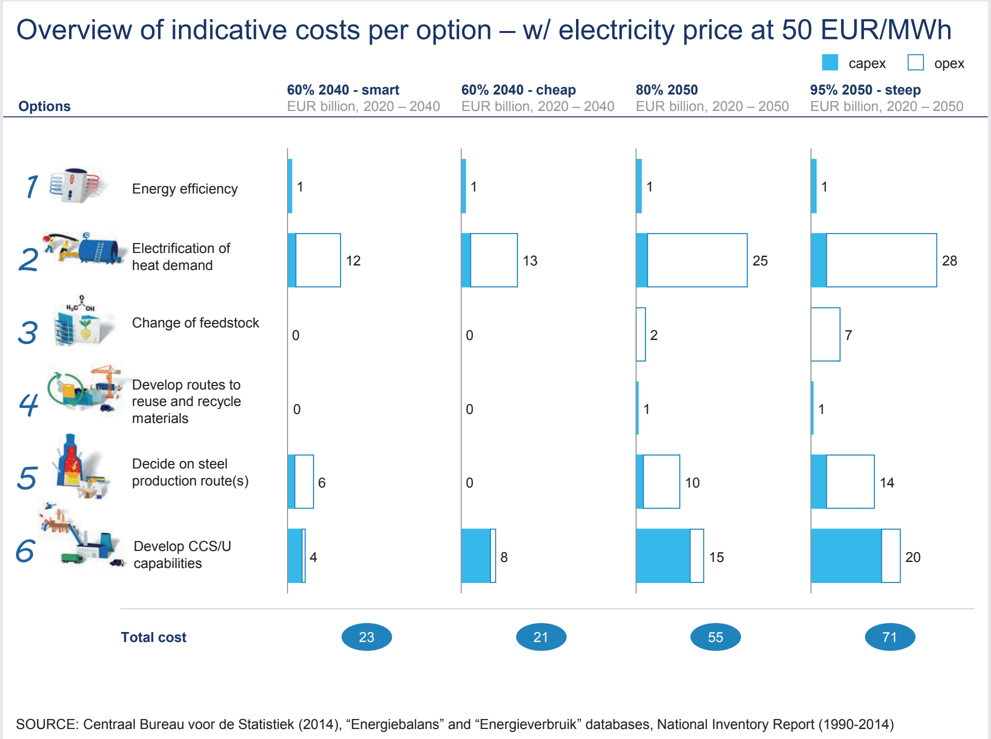
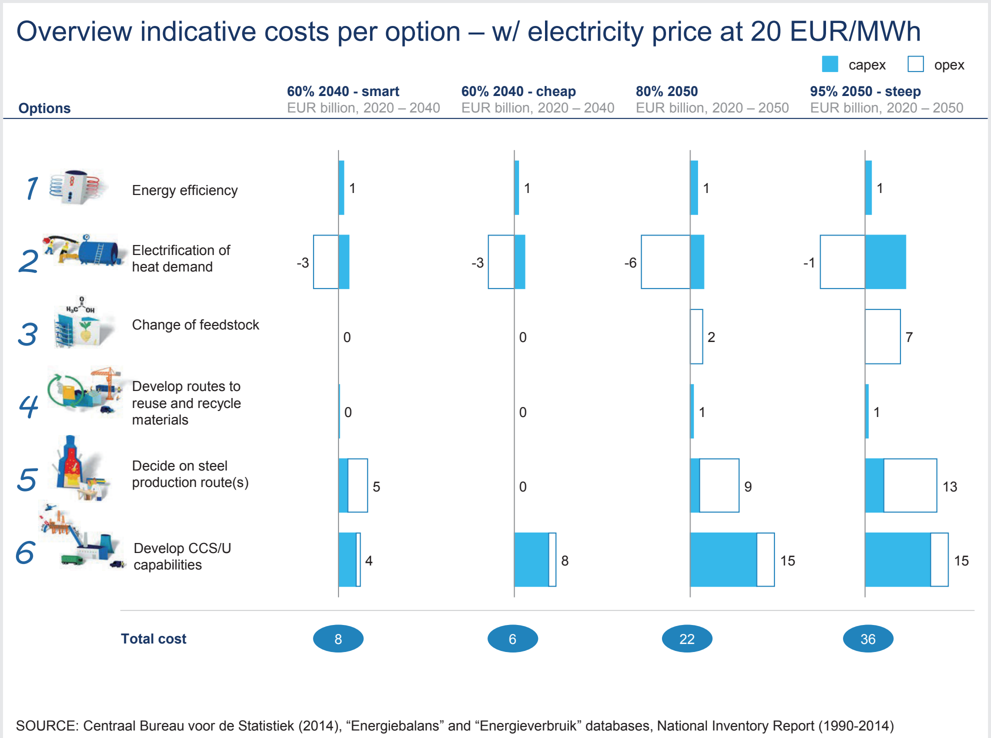



Figure A6



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