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**TNO report**

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# Review of energy transition scenario studies of the Netherlands up to 2050

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ESTRAC Energy Systems Transition Centre

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# Contents

# 1 Introduction

Following the Climate Agreement of Paris 2015, the Netherlands has set ambitious greenhouse gas (GHG) emission reduction targets of at least 49% in 2030, compared to 1990 (Rijksoverheid, 2019), and 95% reduction by 2050 (EZK, 2019). This will require a transformation of the current, predominantly fossil-based energy system towards a sustainable, climate-neutral energy system.

The transition towards a climate-neutral energy system has a large impact, not only on the energy system itself but also on society at large. The specific characteristics of this energy transition over the coming decades and the resulting outcomes of this process, however, are still highly uncertain. To some extent, this explains the large, widespread need for scenario studies in order to clarify and enhance our insights into the energy transition over a certain period and the resulting outcomes in a specific target year (e.g., 2030 or 2050).

This need has led to a large variety of scenario studies over the past years, covering different energy demand or supply sectors (or the energy system as a whole), different approaches, different issues and different geographical scopes (varying from small islands, districts or regions to countries, continents or even the world as a whole). Besides similarities in scenario outcomes, however, these studies also usually show major differences in scenario results, thereby underlining the uncertainties of the energy transition (rather than addressing these uncertainties).

The objective of this report is to review recent energy transition scenario studies of the Netherlands over the coming decades up to 2050. More specifically, this report aims to review the major findings of these scenario studies – including the major similarities (‘robust elements’) and differences (‘uncertain elements’) of these studies – in order to improve our insights and decision-making regarding the energy transition as well as to indicate (uncertain) issues that need further research and reflection.

As noted, the review is focussed on recent studies, i.e. studies over the last six years (2014-2019). Moreover, the review is predominantly focussed on the Netherlands. However, in case of lack of relevant scenario studies for a certain energy sector or transition topic (notably mobility), we include scenario studies for similar, neighbouring countries – in particular Germany – or regions (i.e. the EU). In addition the review is largely focussed on discussing and comparing the outcomes of the scenario studies rather than the methodology used by these studies (including the underlying assumptions made, data used, etc.), partly because in this report we are primarily interested in the similarities and differences across scenario outcomes and partly because in many studies the methodology applied is hardly or not explicitly mentioned and adequately explained.

The contents of the current report are structured as follows. First, we review a variety of scenario studies for the four main energy demand sectors in the Netherlands, labelled as the built environment, industry, transport and agriculture (in Chapters 2 up to 5, respectively). Subsequently, we review some scenario studies on energy supply in general and some energy supply sectors in particular, i.e.

electricity, district heating and hydrogen (Chapter 6). Next, Chapter 7 reviews some scenario studies on future energy infrastructures (electricity, gas and heat). Finally, Chapter 8 provides a summary of some general observations and main findings of the current report as well as some suggestions for further scenario research on the energy transition in the Netherlands.

# 2 Built environment

## 2.1 Introduction

The built environment consists of the residential and non-residential sector, i.e. households and services, respectively. It plays a large role in the energy transition. Table 1 provides a summary overview for the built environment regarding its realized and projected primary energy use in 2000, 2015 and 2030 as well as its direct GHG emissions in these years. For instance, in 2015 primary energy use of the built environment amounted to 681 PJ (22% of total primary energy use in the Netherlands), while its direct GHG emissions – i.e. excluding electricity use emissions – amounted to almost 25 Mt$CO_2$-eq. (about 13% of total national GHG emissions).

Table 1: Built environment: Primary energy use and greenhouse gas emissions

| **Primary energy use** | **2000** | **2015** | **2030** |
|---|---|---|---|
| ➢ Total primary energy use by the built environment (PJ) | 704 | 681 | 573 |
| ➢ As % of total national primary energy use | 22% | 22% | 20% |
| **Greenhouse gas emissions** | **2000** | **2015** | **2030** |
| ➢ Total GHG emissions by the built environment (Mt$CO_2$-eq.) | 29.7 | 24.5 | 19.0 |
| ➢ As % of total national GHG emissions | 14% | 13% | 13% |

Notes: Data for 2000 and 2015 are realizations while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called ‘Urgenda Verdict’ and the Climate Agreement of mid-2019). Primary energy use includes (non-energetic) industrial feedstocks. Sectoral GHG data do not include (indirect) emissions of sectoral electricity consumption.

Source: PBL et al. (2019b).

This chapter reviews some recent scenario studies on potential decarbonisation pathways for the Dutch built environment towards 2050. Focus is on scenarios that reach 80-95% or even higher $CO_2$ emission reductions in 2050 (compared to 1990).

## 2.2 Studies reviewed

The following studies/scenarios were reviewed:

1. CE Delft (2016), *Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – Update 2016* (A climate-neutral heat provision for the built environment – Update 2016).
2. CE Delft (2017), *Net voor de Toekomst – Achtergrondrapport* (Grid for the Future – Background report).
3. Quintel (2015), *Beelden van een $CO_2$-arme Nederlandse samenleving in 2050, Verkenning voor de Raad voor de Leefomgeving en Infrastructuur* (Images of a $CO_2$-low Dutch society in 2050, Explorations for the Council of the Living Environment and Infrastructure).
4. Ecofys (2016), *Kwantificering van toekomstscenario’s voor de gebouwde omgeving* (Quantification of future scenarios for the built environment).[1]

An overview of the reviewed studies, scenarios and their scope is given in Table 2.

[1] Since November 2016, Ecofys has joined Navigant.

Table 2: Overview of reviewed energy scenarios for built environment

| Source | Title of study | Name of scenario | Scope (demand) |
|---|---|---|---|
| CE Delft (2016) | Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – update 2016 | Available amount of green gas 1.0 bcm | Heat |
| | | Available amount of green gas 1.5 bcm | Heat |
| | | Unlimited amount of green gas available | Heat |
| CE Delft (2017) | Net voor de Toekomst | Regional Steering | Heat |
| | | National Steering | Heat |
| | | International | Heat |
| | | Generic Steering | Heat |
| Quintel (2015) | Beelden van een $CO_2$-arme Nederlandse samenleving in 2050 | 80% $CO_2$ reduction | Heat and electricity |
| | | 95% $CO_2$ reduction | Heat and electricity |
| Ecofys (2016) | Kwantificering van toekomstscenario's voor de gebouwde omgeving | Technology-adoption | Heat and electricity |
| | | Urgency | Heat and electricity |
| | | Scarcity | Heat and electricity |
| | | Gradual transition | Heat and electricity |

The mentioned studies vary in their scope. Scenarios designed by CE Delft (2016) focus on the heat demand while the Quintel and Ecofys scenarios consider the total final energy demand (both heat and electricity). CE Delft (2017) presents integral scenarios for the energy system in the Netherlands, while this chapter only considers results for the built environment.[2]

The studies provide multiple scenarios and, in some cases, include additional sensitivity analyses. For instance, CE Delft (2016) has conducted sensitivity analyses on the availability of green gas using three different scenario assumptions on the availability of green gas. CE Delft (2017) has made scenarios representing four different societal and political development pathways for the Netherlands (see Table 2, as well as Section 6.2 of the current report for more details). In both CE Delft studies, the CEGOIA model, i.e. a bottom-up scenario simulation model for the heat transition in the built environment, was used to calculate the cheapest technology options in 2050 per neighbourhood type.

On behalf of the Dutch *Raad voor de Leefomgeving en Infrastructuur* (Rli), Quintel (2015) has constructed and analysed two example scenarios of 80% and 95% emission reduction, respectively, using the Energy Transition Model (ETM). ETM, developed by Quintel, is an energy system simulation model by which the user can design a future energy scenario by choosing own input parameter values (mostly within given ranges).

[2] For findings of CE Delft (2017) regarding the energy supply sectors and energy infrastructures, see Chapters 6 and 7 of the current report, respectively.

Ecofys (2016) has made four scenarios representing possible developments that could change the social and economic dynamics in the built environment and accelerate the transition to energy neutrality by 2050 (Table 2). The focus of the Ecofys study is on a comparison of total energy system costs under different scenarios. The quantitative scenarios were developed by Ecofys and analysed by means of a system integration model. This model has been developed by Ecofys and ECN in collaboration with Alliander, Gasunie and TenneT. It is a model used for analysing system costs of heating homes in order to have a consistent overview of the costs and effects in the entire energy supply chain including energy consumption, transport, distribution and generation of energy.

For the CE Delft scenarios (2016 and 2017) the $CO_2$ emission reduction percentages are not explicitly mentioned in the report but can be assumed to be near 100% as the study focuses on achieving a climate neutral built environment. In the study by Ecofys (2016) the $CO_2$ reduction percentages in 2050 are lower than 80% in three of the four scenarios even though the study focusses on reaching an energy neutral built environment in 2050. Nevertheless, for comparative reasons, we will still include the findings of these scenario studies in the sections below.

## 2.3 Major findings of studies reviewed

### *2.3.1 Comparison final energy demand and $CO_2$ reduction*

At present, the largest share of final energy demand in the built environment is for heating purposes (space heating and to a lesser extent hot tap water). The following main decarbonization technologies for the heat demand are used in the scenarios:

- Electric heat pumps in combination with (adjusted) heating systems in (existing) buildings;
- Boilers fired with renewable gas (e.g. green gas);
- Hybrid heating systems, consisting of a gas boiler and a heat pump, using electricity and renewable gas (e.g. green gas);
- Heat networks (with heat from geothermal heat sources, residual heat sources, biomass, etc.);
- Heat/cold storage (ATES: Aquifer Thermal Energy Storage);
- Solar-thermal.

As indicated in Table 2 studies vary in their scope. Quintel (2015) and Ecofys (2016) scenarios do include electricity demand for lighting and appliances. In contrast, CE Delft (2016) and CE Delft (2017) scenarios do not include electricity demand for lighting and appliances.

Figure 1 presents the final energy demand in 2050 per scenario. It shows that the final energy demand varies significantly in the considered scenarios. The most important reasons for this variety are the scope of the study and the heating technologies used. Note that ambient heat is not included in the final energy demand. Heat pumps use electricity to upgrade ambient heat to a useful temperature for space heating and hot tap water. For example, consider a heat pump that uses 1 unit of electricity to produce 4 units of heat. This means 3 units are ambient heat. Only the electricity consumption of the heat pumps is included in Figure 1. This can be justified as ambient heat is a sustainable heat supply option available free of charge. However, ambient heat is still needed to meet the demand (and should be included to calculate final energy demand). The two Quintel scenarios and the technology-adoption scenario by Ecofys have the lowest final consumption of energy carriers in 2050, i.e. between 200 and 250 PJ. The main reason for this is a very high share of all-electric heat technologies in 2050. It is remarkable that the Quintel results in a lower demand in 2050 compared to the other scenarios since it considers both the electricity and heat demand (including lighting and household appliances) while other scenarios only consider heat demand. The combination energy savings and efficiency gains through electrification in the Quintel apparently results in a much lower final demand compared to the scenarios of CE Delft and Ecofys.

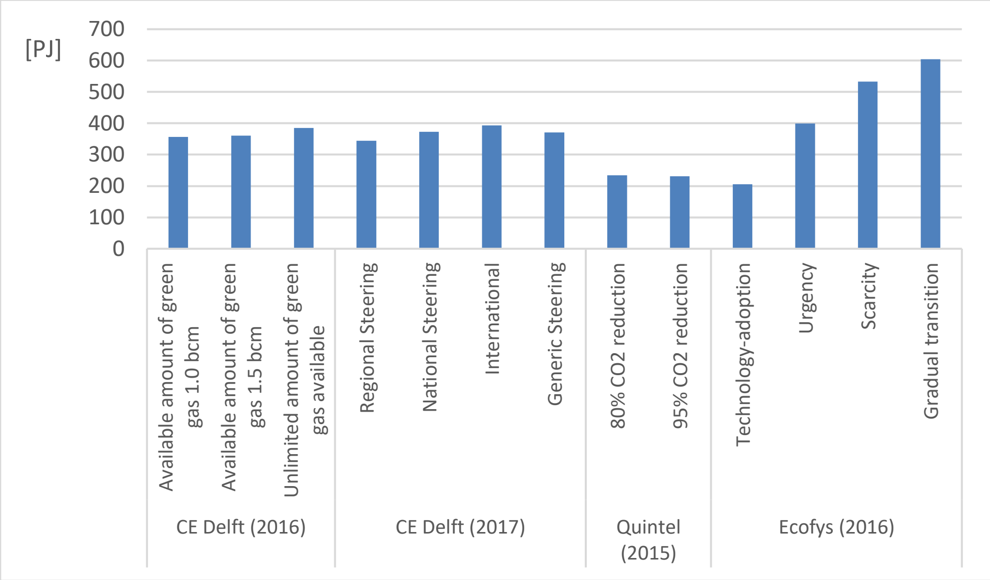



Figure 1: Final energy demand of the built environment in various 2050 scenarios, excluding ambient heat (PJ)

Note: Scenarios of Quintel (2015) and Ecofys (2016) include heat demand and electricity demand for lighting and appliances. Scenarios of CE Delft (2016 and 2017) include only final heat demand (and, hence, exclude electricity demand for lighting and appliances).

In general, a higher use of energy carriers in 2050 is seen if the share of gas or heat is higher and vice-versa. This is because less insulation measures are taken in such a scenario compared to a hybrid or all-electric scenario. High level insulation is a necessary precondition for all-electric heating concepts using heat pumps. Also, good insulation helps to increase the share of energy supplied by heat pumps in a hybrid scenario because of efficiency gains. The average final energy consumption in 2050 falls inside the range 350-400 PJ. A minimum value seems to be around 200 PJ in 2050 in the Quintel scenarios, in which case the share of heat pumps is very high. A maximum value seems to be around 600 PJ in 2050 in the gradual transition scenario of Ecofys (2016) in which case the share of gas fired boilers in the final heat demand of 2050 is still very high (around 80%) and the associated $CO_2$ reduction in 2050 compared to 2015 would be 48%.

The emission reductions in 2050 per scenario are shown in Table 2. The CE Delft scenarios model a carbon neutral built environment in 2050, which also means that the electricity grid mix is completely carbon neutral. The scenarios by Ecofys achieve lower emission reductions compared to the CE Delft and Quintel scenarios, because in the Ecofys scenarios both the gas and electricity mix are not completely renewable in 2050.

Table 3: $CO_2$ reduction percentage of the built environment in various 2050 scenarios

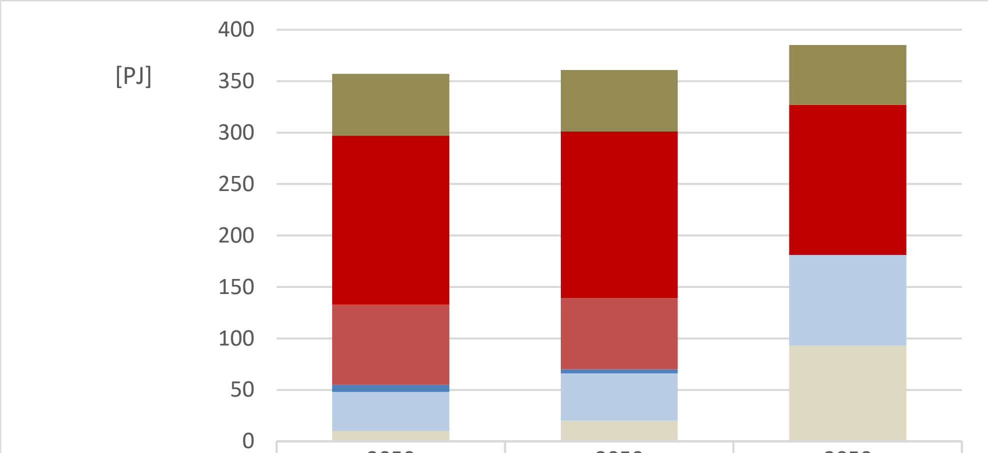
| Source | Name of scenario | $CO_2$ emission reductions in 2050 compared to 1990 | $CO_2$ emission reductions in 2050 compared to 2015 |
|---|---|---|---|
| CE Delft (2016) | Available amount of green gas 1.0 bcm | Near 100% | |
| | Available amount of green gas 1.5 bcm | Near 100% | |
| | Unlimited amount of green gas available | Near 100% | |
| CE Delft (2017) | Regional Steering | Near 100% | |
| | National Steering | Near 100% | |
| | International | Near 100% | |
| | Generic Steering | Near 100% | |
| Quintel (2015) | 80% $CO_2$ reduction | | 90% |
| | 95% $CO_2$ reduction | | 95% |
| Ecofys (2016) | Technology-adoption | | 81% |
| | Urgency | | 67% |
| | Scarcity | | 54% |
| | Gradual transition | | 48% |

### 2.3.2 *CE Delft (2016), Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving*

Figure 2 shows the final mix of heating technologies for dwellings in 2050 in the CE Delft (2016) scenarios. Figure 3 presents the corresponding use of energy carriers (excluding ambient heat). Condensing boilers and hybrid heat pumps use green gas or renewable gas. Gas is also used as backup at moments when other sources are not available.

Renewable gas means all gases that are produced by means of surpluses of renewable electricity and converted biomass. The amounts of green gas and renewable gas are shown in Table 4. It shows that when the availability of green gas is higher the share of condensing boilers and hybrid heat pumps will be higher accordingly.

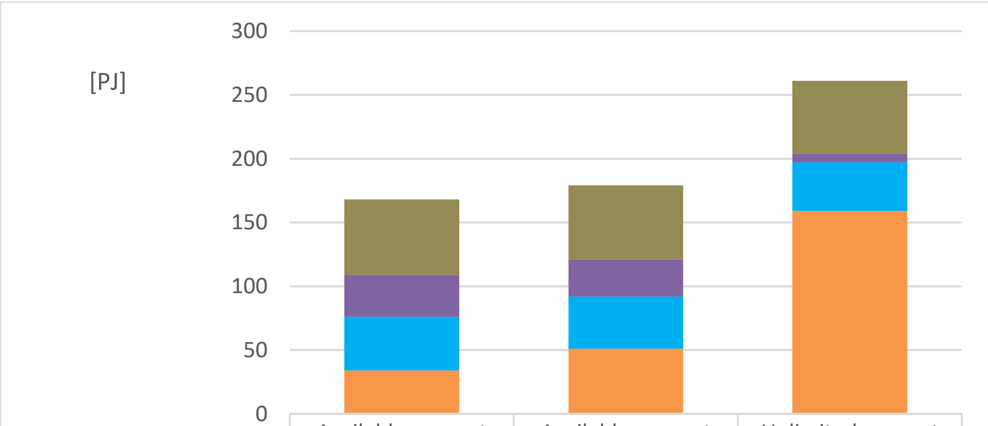
The share of geothermal and waste heat is substantial in all three scenarios: about 150 PJ of geothermal and about 60 PJ waste heat is used in 2050. The sensitivity analysis carried out for the study shows that the amount of green gas available in 2050 is decisive for its final share. Even if the price of green gas in the model doubles from 0.75 euro/m³ to 1.50 euro/m³, the maximum availability of green gas in scenarios 1 and 2 (see Table 4) will still be used in 2050. CE Delft assumes in this study that a maximum 2 billion cubic meter (bcm) green gas is available for the entire built environment and a maximum of 1.5 bcm for households.




| | 2050 Available amount of green gas 1.0 bcm | 2050 Available amount of green gas 1.5 bcm | 2050 Unlimited amount of green gas available |
|---|---|---|---|
| Residual heat | 60 | 60 | 58 |
| Geothermal | 164 | 162 | 146 |
| ATES | 78 | 69 | 0 |
| Heat pump (air/soil) | 7 | 4 | 0 |
| Heat pump (hybrid) | 38 | 46 | 88 |
| Condensing boiler | 10 | 20 | 93 |

Figure 2: Mix of heating technologies of dwellings to cover final heat demand in various 2050 scenarios (PJ)

Source: CE Delft (2016).




| | Available amount of green gas 1.0 bcm | Available amount of green gas 1.5 bcm | Unlimited amount of green gas available |
|---|---|---|---|
| Residual heat | 59 | 58 | 57 |
| Renewable electricity | 33 | 29 | 7 |
| Renewable gas | 42 | 41 | 38 |
| Green gas | 34 | 51 | 159 |

Figure 3: Mix of energy carriers to cover final heat demand for space heating and domestic hot water of dwellings in various 2050 scenarios (excluding ambient heat; in PJ)

Source: CE Delft (2016).

Table 4: Green gas and renewable gas use in 2050 per scenario (PJ)

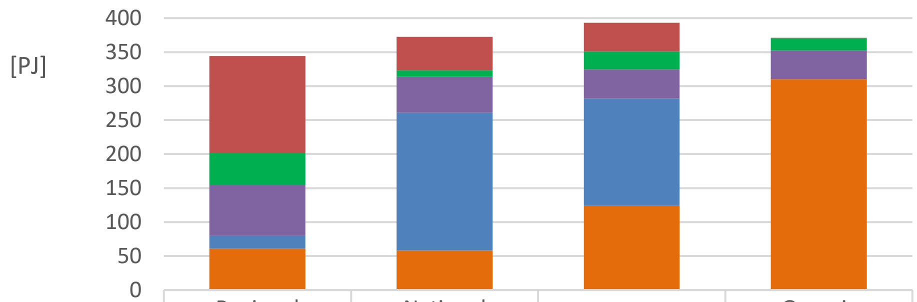
| | Scenario 1: Available amount of green gas 1.0 bcm | Scenario 2: Available amount of green gas 1.5 bcm | Scenario 3: Unlimited amount of green gas available |
|---|---|---|---|
| Green gas [PJ] | 34 | 51 | 159 |
| Renewable gas [PJ] | 42 | 41 | 38 |

Source: CE Delft (2016).

Note that the technology breakdown presented in Figure 2 is for dwellings only. The results for dwellings and non-residential buildings together are (remarkable enough) almost the same as the 1.5 bcm green gas scenario for dwellings (see Figure 54 in CE Delft, 2016). The reason for this is not explained in the report.

### 2.3.3 *CE Delft (2017), Net voor de Toekomst*

Figure 4 presents the final mix of energy carriers to meet the demand for heating (space heating and hot water) in 2050 scenarios of CE Delft (2017). Ambient heat is not included in Figure 4.




| | Regional Steerting | National Steering | International | Generic Steering |
|---|---|---|---|---|
| Heat | 143 | 49 | 42 | 00 |
| Solid biomass | 47 | 10 | 26 | 18 |
| Electricity | 74 | 52 | 43 | 42 |
| Hydrogen | 19 | 203 | 158 | 0 |
| Green gas | 61 | 58 | 124 | 310 |

Figure 4: Final mix of energy carriers for space heating and domestic hot water in the built environment in various 2050 scenarios (excluding ambient heat; in PJ)

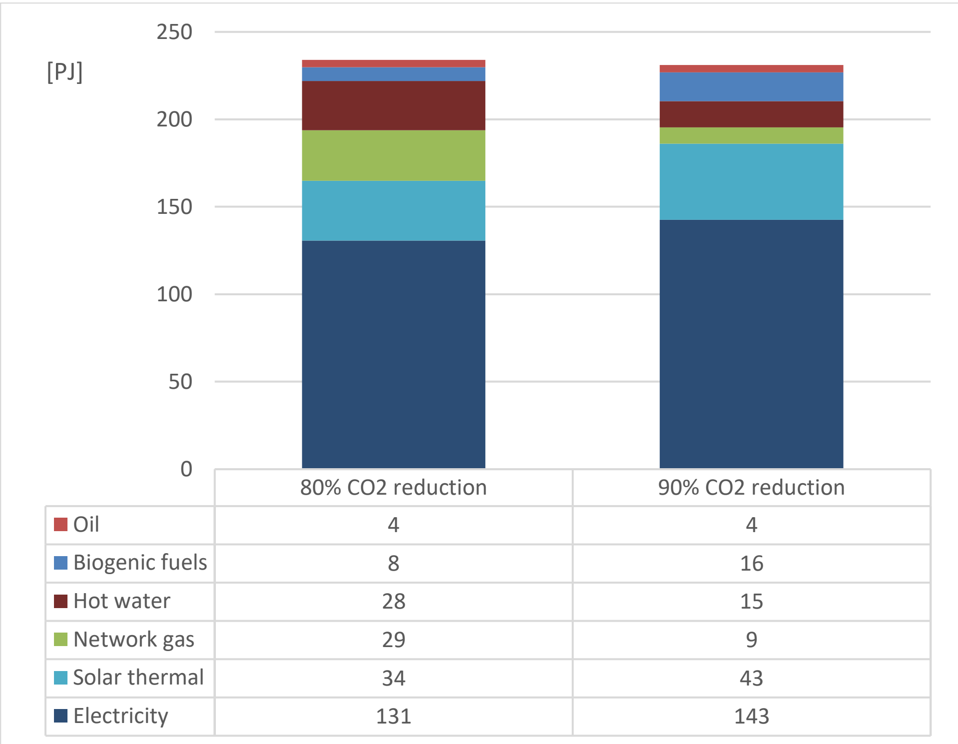
Source: CE Delft (2017).

The scenarios considered in Figure 4 show the following observations:

- The share of green gas is highly dependent of the scenario. This has to do with the demand of other sectors and the limitations set on the availability of green gas for low temperature heating in the built environment. Green gas is used in gas boilers, hybrid heat pumps and back-up boilers of heat networks. In the ‘self-sufficient’ scenarios, i.e. the ‘*Regional Steering’* and ‘*National Steering’* scenarios, the maximum availability of green gas is set at 60 PJ whereas in the ‘*International’* scenario the limit is set at 150 PJ. The production costs of green gas are assumed at 0,75 €/m3 (21 €/$GJ_{HHV}$).

- There are two scenarios in which the use of hydrogen is substantial. The production costs of hydrogen differ between scenarios due to other assumptions made. In the scenario '*Regional Steering'* the cost of electrolysis amounts to 32 €/$GJ_{HHV}$ (4,5 €/kg $H_2$); in the scenario '*National Steering'* this cost is 23 €/$GJ_{HHV}$, while in the scenarios '*International'* and '*Generic Steering'* it is 20 €/$GJ_{HHV}$. Aside from costs, limitations on hydrogen distribution possibilities influence how much hydrogen is used per scenario.
- The availability of residual heat for the realization of collective systems depends on the industry scenario. In the scenarios with a largely transformed industry this leads to a considerable decrease of residual heat as a source for heat networks. This effect is the strongest in the scenarios '*Regional Steering'* and '*National Steering'* and slightly less in the scenario '*International'*.
- The availability of large-scale collective options differs per scenario. In scenario '*Generic Steering'* it is assumed that large-scale heating networks will not scale up.
- Solid biomass plays a role in all four scenarios. In the scenarios '*Regional Steering'* and '*National Steering'* there will be no biomass imports, but in the scenarios '*International'* and '*Generic Steering'* there will be imports of biomass. Solid biomass (wood pellets) costs are assumed 20 €/$GJ_{HHV}$.

### 2.3.4 *Quintel (2015), Beelden van een $CO_2$-arme Nederlandse samenleving in 2050*




| | 80% CO2 reduction | 90% CO2 reduction |
|---|---|---|
| Oil | 4 | 4 |
| Biogenic fuels | 8 | 16 |
| Hot water | 28 | 15 |
| Network gas | 29 | 9 |
| Solar thermal | 34 | 43 |
| Electricity | 131 | 143 |

Figure 5: Final energy demand in the built environment in two 2050 scenarios

Source: Quintel (2015).

Figure 5 presents the final energy demand in the 2050 scenarios of Quintel (2015), including a fuel/heat source breakdown. It shows that the share of electrification (all-electric) is very high in both scenarios. In the 95% reduction scenario the share of electrification is even higher than in the 80% reduction scenario. Solar thermal contributes substantially in both scenarios. Hydrogen and geothermal energy are not used at all. The gas in the gas grid (i.e. distribution gas) consists of a mix of green gas and natural gas, i.e. 15% green gas in the 80% reduction scenario and 76% green gas in the 95% reduction scenario. Hot water means district heating derived for 58% and 86% from renewables in the 80% and 95% reduction scenarios, respectively. The scenarios rely on electrification and there is no use of geothermal sources for heating in the built environment. The share of renewable electricity is about 80% in both scenarios.

#### *2.3.5 Ecofys (2016), Kwantificering van toekomstscenario's voor de gebouwde omgeving*

The shares of energy carriers in 2030 and 2050 in the Ecofys (2016) scenarios are shown in Figure 6. Gas is a mixture of natural gas and green gas. We will not look into detail to the energy technologies/source breakdown for the Ecofys (2016) scenarios as the emission reductions are less than 80% in 3 of the 4 scenarios. One of the results of this study is that in a more gradual transition, the share of gas use will remain higher and the emission reductions will be lower. In a more innovation driven or urgent transition scenario, the final energy demand will decrease faster along with deeper emission reductions (Ecofys, 2016).

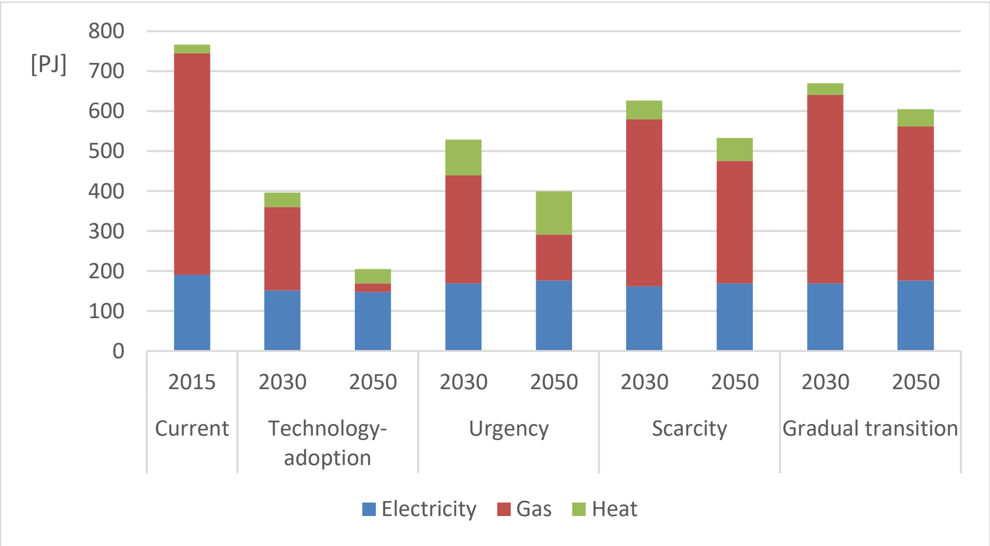



Figure 6: Final energy demand in the built environment in various 2030 and 2050 scenarios

Source: Ecofys (2016).

### 2.4 Summary of main findings

#### *2.4.1 Main similarities between scenarios*

In brief, the main similarities between the scenarios of the studied reviewed above include:

- Green gas (e.g. produced from biogas or thermal gasification of biomass) plays an important role in most scenarios (although the amount of green gas varies greatly between scenarios). Green gas is a renewable energy source and is net $CO_2$ neutral over its production-and-use cycle. It can replace fossil based

natural gas in condensing boilers and hybrid heat pumps. This way it contributes to lower net $CO_2$ emissions of the energy system. The share of green gas in total final energy use of the built environment in 2050 depends on the (domestic) availability and price of green gas (versus other, alternative renewable fuels).
- Electrification is substantial in all scenarios. Most scenarios rely for an important part on electrification of heat demand via heat pumps, both in the residential and non-residential sector. The share of heat pumps in 2050 depends on, among others, the competitiveness of alternatives such as sustainable heat networks and renewable gasses, notably green gas and hydrogen.
- Geothermal and residual heat (or one of the two) are the dominant heat sources used for heat networks (district heating) in almost all 2050 scenarios considered. Fossil energy power plants, which are currently used to supply heat to the existing networks, are projected to be substituted by geothermal and/or waste heat sources over time. Present heat networks will be expanded, and new ones will be built.
- Solid biomass is deemed to have a small role or no role at all by 2050. Solid biomass can be used for individual heating as well as for collective heating using heat networks.

### *2.4.2 Main differences between scenarios*

In brief, the main differences between the scenarios of the studied reviewed above include:
- The final energy demand of the built environment in 2050 varies considerably between scenarios. This can be attributed to differences in energy savings as well as to differences in rates of electrification of heat demand via electric heat pumps. In an all-electric scenario, final heat demand (excluding ambient heat) is lower compared to a ‘gas’ or ‘heat network’ based scenario since (i) high level insulation (deep renovation) is a necessary precondition in order to apply heat pumps in all-electric concepts and (ii) efficiency gains of a heat pump (i.e., ambient heat used by heat pumps) are not included in final heat demand. In a heat network or green gas-based scenario less insulation measures are taken. The reason for this is that (deep renovation) costs are higher than energy savings making these measures financially unattractive (CE Delft, 2016 and 2017). Depending on the case, deep renovation can be more expensive compared to realising sustainable heat sources or sustainable heat technologies (CE Delft, 2017).
- Hydrogen is used in some scenarios in 2050 while in other scenarios it is not used at all. Only some scenarios are optimistic about technology development for hydrogen and consider it an option to provide amongst others flexibility and storage options for electricity.

### *2.4.3 Key factor: The potential availability of renewables gasses*

The potential availability of renewable gasses (e.g. green gas) is one of the key determinants for how the energy system in the built environment will look like in 2050. CE Delft (2016) assumed in their scenarios a potential availability of 1.5 bcm (about 50 PJ) green gas for dwellings in 2050 and 2 bcm (about 60 PJ) for the entire built environment in 2050. This is indicated as the total domestic availability of green gas. To decarbonise the household sector, about 10 bcm of green gas would be needed at present. This means that, without energy savings, about 8 bcm of green gas would need to come from other sources such as imports and renewable gas production, e.g. hydrogen or syngas (CE Delft, 2016). According to CE Delft (2016) Gasunie indicated the following: '*In the future, we may be able to use larger quantities of renewable gas. This can be hydrogen, produced from surplus renewable electricity, or converted biomass. In a sustainable energy supply in 2050, we estimate that renewable gas can replace 5 to 10 billion m$^3$ of natural gas.*' Of this total potential 2 bcm is green gas and 3-8 bcm is renewable gas. According to KIWA, renewable gas (e.g. hydrogen mixtures) is more expensive than fossil based natural gas and there are also additional costs and challenges associated with producing, transporting and consuming this gas in case the hydrogen percentage is higher than 20% (CE Delft, 2016). Green gas (e.g. biogas upgraded to natural gas quality) is also more expensive than fossil based natural gas but can be injected directly into the gas grid (CE Delft, 2016).

In the CE Delft (2017) study other total potentials for green gas are presented for use in the built environment. The potential of green gas is dependent of the scenario. This has to do with the demand of other sectors and the limitations set on the availability of green gas for low temperature heating in the built environment. Green gas is used in gas boilers, hybrid heat pumps and back up boilers of heat networks. In the 'self-sufficient' scenarios '*Regional Steering'* and '*National Steering'* the maximum availability is set at 60 PJ whereas in the scenario '*International'* the limit is set at 150 PJ.

Ecofys (2016) does not indicate a green gas potential. Scenarios realise less $CO_2$ emission reduction compared to the CE Delft studies because use of fossil based natural gas is still high.

In both Quintel (2015) scenarios the demand for green gas is too small to exceed the potential.

### *2.4.4 Conclusions*

The final energy demand of the built environment in 2050 varies considerably depending on the scenario. Important differences between scenarios are in energy savings as well as in electrification of the heat demand via heat pumps. There are significant differences in final energy demand between the scenarios due to the efficiency gains by applying heat pumps and the fact that ambient heat is not considered in the heat demand. In a scenario that relies strongly on heat pumps (all-electric scenario), the final heat demand (excluding ambient heat) is lower compared to a 'gas' or 'heat network' based scenario since (i) high level insulation is a necessary precondition in order to apply heat pumps in all-electric heating concepts and (ii) the efficiency gains of the heat pump (i.e., ambient heat used by heat pumps) are not included in final energy demand. In a scenario that relies strongly on heat networks or gas boilers less insulation measures are taken. The reason is that (deep renovation) costs are higher than energy savings making this financially unattractive. The final energy demand for heating in the built environment (excluding ambient heat) in 2050 appears to be between 200 and 600 PJ, with 350-400 PJ as an average.

Green gas becomes an important future energy carrier in the built environment in most of the scenarios. It could replace fossil based natural gas in gas-fired condensing boilers and hybrid heating systems. This way it contributes to lower the net $CO_2$ emissions of the energy system. The share of green gas in total final energy use of the built environment in 2050 depends highly on the (domestic) availability and price of green gas (versus other, alternative renewable fuels). The domestic availability is however limited, estimated by CE Delft (2016) at 1.5 bcm (about 50 PJ) of green gas available for dwellings and 2 bcm (about 60 PJ) for the entire built environment. This implies either large imports of green gas or biomass to produce green gas are needed and/or other heating options such as heat pumps and sustainable heat networks are needed to reach deep emission reduction targets in the built environment. CE Delft (2017) indicates potentials of 60 PJ and 150 PJ depending on the scenario. Ecofys (2016) and Quintel scenarios do not specify a potential or rely less on green gas.

Considering expected sources for the energy carrier ‘heat’ in 2050: geothermal and residual heat (or one of the two) are the dominant heat sources used for heat networks (district heating) in 2050. Present heat networks will be expanded, and new ones will be built. Fossil energy power plants, which are mainly used to supply heat to the existing networks at present, will be replaced by geothermal and/or waste heat sources over time.

About the future role of hydrogen in the built environment the scenarios differ greatly. Hydrogen is used in some scenarios in 2050 while in other scenarios it is not used at all. Only some scenarios are optimistic about technology development for hydrogen and consider it an option to provide amongst others flexibility and storage options for electricity. There is still R&D and innovation needed to achieve this.

# 3 Industry

## 3.1 Introduction

Industry is the main sector in terms of both energy use and GHG emissions in the Netherlands. In 2015, primary energy use of industry amounted to 1423 PJ (46% of total primary energy use in the Netherlands), while its direct GHG emissions – i.e. excluding electricity use emissions – amounted to more than $MtCO_2$-eq. (about 29% of total national GHG emissions), as indicated in Table 5. In this table, industry includes both manufacturing industries (metal, chemical, paper, etc.) and industrial activities in the energy sector (such as refineries or coke factories), while primary energy use by industry covers both energetic use (919 PJ in 2015) and non-energetic use, i.e. industrial feedstocks (504 PJ in 2015).

Table 5: Industry: Primary energy use and greenhouse gas emissions

| **Primary energy use** | **2000** | **2015** | **2030** |
|---|---|---|---|
| ➢ Total primary energy use by industry (PJ) | 1442 | 1423 | 1461 |
| ➢ As % of total national primary energy use | 46% | 46% | 52% |
| **Greenhouse gas emissions** | **2000** | **2015** | **2030** |
| ➢ Total GHG emissions by industry ($MtCO_2$-eq.) | 75.3 | 56.4 | 54.2 |
| ➢ As % of total national GHG emissions | 34% | 29% | 38% |

Notes: Data for 2000 and 2015 are realizations while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called 'Urgenda Verdict' and the Climate Agreement of mid-2019). Primary energy use includes (non-energetic) industrial feedstocks. Sectoral GHG data do not include (indirect) emissions of sectoral electricity consumption.

Source: PBL et al. (2019b).

The aim of this chapter is to conduct a review of recent scenario studies on industrial decarbonization up to 2050 in order to identify both robust elements ('similarities') across these studies as well as uncertain elements ('differences') that require further research and explanation. Section 3.2 provides, first, a brief description of the studies and scenarios reviewed in the current chapter. Subsequently, Section 3.3 discusses the major findings of the individual studies reviewed, while Section 3.4 presents a comparative review across these studies on specific (industrial abatement) topics such as energy efficiency, electrification, CCS/CCS, etc. Finally, Section 3.5 provides a summary of the main findings of this chapter.

## 3.2 Studies reviewed

As part of the current chapter, the six following studies on decarbonization scenarios for the Dutch industry up to 2050 have been reviewed:

- McKinsey (2014), *Energy transition - Mission (im)possible for industry*;
- VEMW (2017), *Decisions on the industrial energy transition*;
- Berenschot et al. (2017), *Electrification in the Dutch process industry*;
- PBL (2017a), *Verkenning van klimaatdoelen* (Exploration of climate targets);
- SER (2018), *Transitiepad Hoge Temperatuurwarmte* (Transition pathway High Temperature Heat);
- VNCI (2018), *Chemistry for climate - acting on the need for speed - Roadmap for the Dutch chemical industry towards 2050*.

Table 6 provides the main objective of each of the six industrial scenario studies reviewed.

Table 6: Main goal of used literature sources

| Study | Objective |
|---|---|
| McKinsey (2014) | Assess decarbonization options in industry considering technical feasibility, effectiveness, costs, and benefits, including impacts further up and down the value chains. |
| VEMW (2017) | Based on McKinsey (2014). Elaborates further on impact for industry and required policy support to enable industrial transition. |
| Berenschot et al. (2017) | The purpose of this study is therefore to explore the opportunities and barriers of electrification in the Dutch process industry, and to provide perspectives on how the Netherlands might obtain a distinctive international innovation position in this area. |
| PBL (2017a) | Analyses which cost optimal set of technologies would reduce GHG emissions in the Netherlands with 80-95% by 2050, including the industrial sector |
| SER (2018) | Overview of potential options for high temperature processes in industry |
| VNCI (2018) | Analyse potential pathways towards 80-95 percent reduction of greenhouse gas emissions by 2050. |

Table 7 provides an overview of the scope of each study (decarbonization target, sectors, scope of energy use, and timeframe).

Table 7: Overview of decarbonisation targets

| Study | Decarbonisation target (compared to 1990) | Sectors | Scope energy use | Time frame |
|---|---|---|---|---|
| McKinsey (2014) | Reduction of industrial emissions by 80% or 95% in 2050. | Chemicals, steel, petroleum refining and food processing/beverages/tobacco. | Includes use of energy carriers for energy purposes and feedstock. | Up to 2050. |
| VEMW (2017) | Reduction of 95% of industrial GHG emissions (63 $MtCO_2$). | Chemicals, iron and steel, food processing, beverages and tobacco, other industries. | Includes use of energy carriers for energy purposes and feedstock. | Up to 2050. |
| Berenschot et al. (2017) | Not specified. | All energy intensive industry sectors | Only includes use of energy carriers for energy purposes. | Up to 2050. |
| PBL (2017a) | GHG emission reduction of 80% or 95% in the Netherlands. | Industry. | Only includes use of energy carriers for energy purposes. | Up to 2050. |

| Study | Decarbonisation target (compared to 1990) | Sectors | Scope energy use | Time frame |
|---|---|---|---|---|
| SER (2018) | 8 to 12 $MtCO_2$ maximum allowed GHG emissions in industry for the 80% reduction scenario, and 3 to -16 (negative emissions) $MtCO_2$ GHG emissions for the 95% reduction scenario. | Refinery, chemistry, basic metals, building materials, paper, food. | Only includes use of energy carriers for energy purposes. | Up to 2050. |
| VNCI (2018) | An 80% GHG emission reduction (at least) in the chemical sector by 2050 compared to 1990 levels, including both energy as well as end-of-life related emissions. | Chemical sector. | Includes use of energy carriers for energy purposes and feedstock. | Up to 2050. |

Each of the reviewed studies has defined its own scenarios. Table 8 provides a brief description of each scenario.

Table 8: Description of scenarios

| Study | Scenario | Description |
|---|---|---|
| McKinsey (2014) | Cheaper route: 60% reduction | Focus of achieving 60% GHG emission reduction by 2040 and 80% GHG emission reduction by 2050, compared to 1990 levels. |
| | Steeper route: 80% reduction | Focus of achieving 80% GHG emission reduction by 2040 and 95% GHG emission reduction by 2050, compared to 1990 levels. |
| VEMW (2017) | 95% reduction | Focus of achieving 95% GHG emission reduction by 2050 compared to 1990 levels. |
| Berenschot et al. (2017) | No scenario | |
| PBL (2017a) | 80% beelden | Focus of achieving 80% GHG emission reduction by 2050, compared to 1990 levels. |
| | 95% beelden | Focus of achieving 95% GHG emission reduction by 2050, compared to 1990 levels. |
| SER (2018) | No scenario | |
| VNCI (2018) | 2030 compliance at least cost | Scenario builds the potential for decarbonisation options based on the most cost-effective measures, given energy prices in 2017. |
| | Direct action and high-value application | Scenario optimises the system to the highest value by using energy and feedstock resources, whilst considering external constraints. |

### 3.3 Major findings of studies reviewed

By means of bullet points, this section summarizes the major findings of the individual studies, as outlined below.

*McKinsey (2014), Energy transition - Mission (im)possible for industry*
- Decarbonizing industry by 60 percent in 2040 will cost approximately € 23 billion between now and 2040;
- Decarbonizing industry by 95 percent is also possible but more costly, up to € 71 billion between now and 2050;
- A portfolio of different decarbonization measures will be needed: 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;
- A shift from fossil-based electricity generation to renewables is needed. The electricity price will have a major influence on cost effectiveness and feasibility;
- Many business cases hinge on the 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 use of hydrogen can play a role here (through use in gas boilers or for back-up power generation).

*VEMW (2017) Decisions on the industrial energy transition*
- Dutch industry needs to remain competitive in an international market place. Many products produced by Dutch industrial players are sold on the European or global market, often at slim margins between global suppliers. The cost structure of Dutch industrial players needs to be competitive to keep market share. Investments that therefore 'disproportionally' penalize profitability can quickly lead to loss of position and production in the Netherlands;
- Uncertainty in operational costs, mainly energy and feedstock. The biggest driver of the business cases for decarbonization concerns the expectation of future OPEX, rather than the investment itself. The relatively higher cost of renewable energy carriers, such as renewable electricity and hydrogen, versus conventional energy carriers, such as natural gas and coal, quickly become prohibitive to invest in absence of a $CO_2$ price. This not only applies to the current higher cost, but also to the uncertainty in the (relative) prices between energy carriers;
- Large prior investments mean choices have often been locked in. Industrial assets have long lifetimes and require brownfield adaptation rather than the 'simplicity' of new build. For example, an ammonia plant has a lifetime of over 50 years, during which the gas consumption for the steam reforming process is more or less locked in. A change in process setup, feedstock or energy carrier is therefore a costly cash-out;
- Utility type investments versus business investments. The investments in utility infrastructure such as heat and waste streams typically yield a utility return: longer payback times with relatively stable returns. These types of investments are typically not part of the 'core business' of industrial players and are therefore not able to attract the capital and attention required. In many greenfield industrial clusters this is solved by creating a separate utility company that provides infrastructure and utilities to the resident assets. USG in Chemelot has created such a utility in a brownfield site;

- Every solution needs to be tailored to the specifics of a single case. Every industrial site is different and requires a tailored decarbonization approach. For example, the costs and the percentage of carbon that can be captured out of a residual stream depend to a large extent on the specifics of the emitter, such as size and $CO_2$ concentration. Furthermore, in an existing site (brownfield), changes in equipment necessary for decarbonization need to be embedded in an existing process setup. This leads to additional complexity and costs. Also, many of the feedstock and heat/energy uses are intertwined within and between industrial users. As a result, decarbonization often needs to go hand in hand with process changes. In sugar beet processing, for example, heat is cascaded through the different process steps. Therefore, a change in heat demand of a single step necessitates changes in many of the other steps.
- Industry asks from the government:
  - Develop policy instruments comparable to the SDE+ that includes a wide range of $CO_2$ emission reduction measures;
  - Tailor existing industry regulation to align with the targets of the energy transition;
  - Streamline and optimize innovation budget both for development as well as scale-up;
  - Develop, together with industry, a long-term vision for competitively priced renewable electricity;
  - Take a coordinating role of the government in infrastructure rollout (e.g., waste heat networks, $CO_2$ networks).

*Berenschot et al. (2017) Electrification in the Dutch process industry*

- In general, it is expected that industrial energy demand – for the majority consisting of heat – can be reduced to a certain extent by energy efficiency measures and industrial symbiosis. For the remaining heat demand, four transition pathways are foreseen: geothermal energy, bioenergy (predominantly for niche applications), Carbon Capture Utilization and Storage (CCUS) and electrification;
- Electrification strategies: flexible electrification or baseload electrification;
- Power to Heat shows a high potential and a wide range of technologies, applications (sectors, processes, utilities) and parties involved, both in the Netherlands and abroad;
- Power to Hydrogen has high potential, but is not economically feasible for large-scale application in the current situation, due to the high CAPEX;
- Power to Gas options have a more limited potential than Power to Hydrogen, although both categories might become interesting in the long term;
- Power to Chemicals is regarded as high potential, showing a wide variety of initiatives; some of them commercial (chlorine production), but to a large extent in the starting phase (ammonia, formic acid);
- Electrification for Mechanical drive shows a limited potential, but the unit power levels can be very high;
- Power for Separation will have a limited potential and is mainly focused on the food industry;
- Focus areas:
  - Development for application-ready concepts of high temperature heat pumps;
  - Establishment of new business models and market roles (ESCOs);
  - Concepts for intermittent electrification;

   - Focus on the implementation of technologies with a high energy efficiency Coefficient of Performance (COP).

*PBL (2017a), Verkenning van klimaatdoelen*

- For 80% GHG reduction by 2050, additional cost in 2050 varies from ~7 to ~12 billion € per year;
- For 95% GHG reduction by 2050, additional costs in 2050 varies from ~15 to ~50 billion 5 per year;
- Lack of biomass or CCS availability increases the costs of $CO_2$ reduction;
- CCS (with or without biomass) forms an essential part of emission reduction;
- Other robust options are electrification and large-scale wind energy (especially offshore);
- Important support actions to be taken are: preparing infrastructure for transport and storage of $CO_2$, ensuring timely availability of steel, concrete R&D projects;
- Also important: first phase of electrification (including hybrid options with demand-response); demo-projects, first phase of CCS (also for municipality waste incineration plants);
- In addition, energy savings by means of process optimisation is important.

*SER (2018), Transitiepad Hoge Temperatuurwarmte (industrie)*

- Options up to 2030:
   - CCS for processes with high $CO_2$ concentration waste streams;
   - Valorising waste streams;
   - New steel production processes (HIsarna);
   - Development of deep geothermal projects.
- Options 2030-2050:
   - Continuous process improvements;
   - Electrification of heat processes or use of electrolysis based $H_2$ to replace blue $H_2$;
   - CCS and CCU;
   - Innovative steel processes.

*VNCI (2018) Chemistry for climate - acting on the need for speed - Roadmap 2050*

- 90% emission reduction by 2050 in Dutch chemical industry requires:
   - The investment required for this pathway is expected to be around EUR 63 billion, which is comprised of around EUR 26 billion to be invested in the chemical industry, and around EUR 37 billion in the energy system;
   - In addition, annual fuel and feedstock cost for the industry would increase by approximately EUR 3 billion (around 50%), at present prices;
   - Average abatement costs for this pathway are approximately 140 €/t$CO_2$eq (excluding the energy system). While the abatement costs of several measures are significantly lower than many in other Dutch sectors, many of the associated abatement measures are not profitable at a company level.
   - Some of the abatement options are currently profitable. They can be accelerated through regional development and investment plans. Many of the abatement options in the chemical industry are however under current circumstances uneconomic, with the increase in fuel and feedstock cost being of the same order of magnitude as the industry's overall current profit;
   - Large-scale access to affordable and reliable renewable energy carriers will be key for a lasting competitive position;

  - As hydrocarbons will remain the main building block for many chemical products, carbon loops need to be closed (amongst others CCU), and renewable sources of carbon will be introduced. CCS would be applied for fossil carbon streams;
  - Infrastructure will be a key factor, including an electricity grid for transportation of large amounts of renewable energy, as well as pipelines for hydrogen, $CO_2$ and heat, plus adequate waste handling and recycling infrastructure. This illustrates that the chemical industry transition will go hand in hand with the energy transition; leveraging the synergies requires close co-operation with the energy sector.
- The study (conducted by Ecofys and Berenschot on behalf of VNCI) recommends:
  - A joint industry/government far-reaching innovation program aiming to develop the necessary technologies to the point that they can be deployed reliably at full scale. Such a program would reduce the required investments as well as the cost of fuel and feedstock, thus enabling the Dutch chemical industry to accelerate implementation once the more favourable market conditions materialize;
  - Government ensuring that the energy system and the associated infrastructure are developed timely alongside the industry transition.

## 3.4 Comparison of reviewed studies and scenarios on specific topics

The industrial abatement scenarios have been compared regarding the following topics:

- Economic development;
- Energy efficiency;
- Biomass and geothermal energy;
- Hydrogen;
- Electrification;
- Steel production;
- Reuse and recycling;
- CCU/CCS.

By means of bullet points, the major findings of the scenarios reviewed regarding the topics mentioned above are outlined briefly below. It should be stressed, however, that the different scenario studies are characterized by differences in decarbonization targets, industrial sector coverage as well as in scope of energy use (see Table 7 and Table 8 in Section 3.2 above). This complicates an adequate comparison of the studies reviewed in the sections and figures below.

### *3.4.1 Economic development*

- PBL (2017a) sets the growth of production value at 1.6% per annum over the years 2016-2050. It is unclear what the industrial energy demand is in 2050;
- McKinsey (2014) uses ‘current’ (2014) output levels (McKinsey, 2014) as base for the economic development and energy demand in 2050;
- Berenschot et al. (2017) does not specify the assumed industrial economic developments, but does mention the National Energy Outlook (ECN, et al.) as well as the ‘Welvaart en Leefomgeving’ (WLO) scenarios created by CPB and PBL (2016) to provide context;

- The chemical sector expects an increase in added value of 1% per year (VNCI, 2018);
- The other reviewed studies do not specify their assumptions regarding the future economic development of the Dutch industry.

*Summary economic development*
A comparison of the scenario studies reviewed regarding the economic and structural development of the Dutch industry up to 2050 is hardly possible, as the studies provide only limited information regarding this topic, especially for the period of 2030-2050.

### 3.4.2 *Energy efficiency options*

- McKinsey (2014) expects only a modest decrease in energy demand in the industrial sector, i.e. from 840 PJ in 2014 to 740 PJ in 2050.[3] The modest energy efficiency gains are explained by the fact most the $CO_2$ emissions are abated using electrification options, which often do not use less energy than their fossil fuel counterparts (except for heat pumps). Also, most quick wins of energy efficiency options have already been implemented. Upgrading energy efficiency equipment has an expected impact of 3 to 12 Mt $CO_2$ reduction;
- VEMW (2017) advocates the implementation of efficiency measures and options that are close to a positive business case in the low- and medium-temperature heat range, such as heat pumps, heat networks, and mechanical vapor recompression. The impact of these technologies for 2050 is around 6 Mt $CO_2$ reduction;
- Berenschot et al. (2017) only provides information regarding the expected energy demand of the industry according to the WLO scenarios, which estimate a 525 PJ (low scenario) to 725 PJ (high scenario) energy demand by industry in 2050;
- In the PBL study (2017), energy efficiency is already partly covered by the business-as-usual scenario (based on NEV 2016), but additional efficiency measures are also included (although it is noted explicitly that only part of the full potential of energy efficiency is utilised as some options are considered too costly). According to PBL, industrial reuse of waste heat has a potential of 70 PJ (80% scenario) to 120 PJ (95% scenario).
- VNCI assumes a 1% efficiency improvement per year in industry, which corresponds to about 5 Mt $CO_2$ reduction in 2050 (VNCI, 2018);

*Summary energy efficiency options*
The studies agree that the total energy consumption in 2050 will be lower than its energy demand level around 2014-2017 due to the use of energy efficiency options. Technologies related to reusing heat are often mentioned, such as heat pumps, heat networks, and mechanical vapour recompression.

Figure 7 shows the potential impact of the energy efficiency technologies expressed to reduce fossil fuel use per study.

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[3] Note that when taking feedstock into account, McKinsey (2014) expects the total energy demand to decrease from 1,407 PJ to 1,166 PJ.

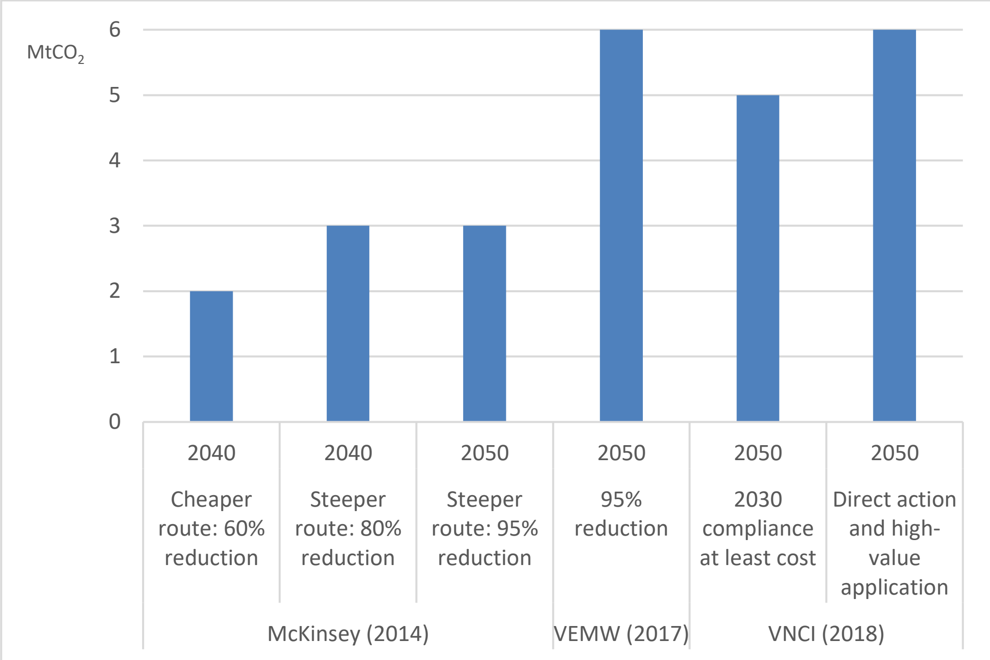


Figure 7: Potential impact of energy saving options on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

### *3.4.3 Biomass and geothermal energy*

- Biomass for feedstock purposes is considered by McKinsey and VEMW to play an important role (McKinsey, 2014);
- In their ‘2030 compliance at least cost’ scenario, VNCI expects about 60 PJ of biomass use for energy. In the *'Direct action and high-value applications'* scenario of the VNCI study, the use of biomass is restricted, and used as feedstock instead of energy purposes. Renewable heat is provided by geothermal energy as much as possible (VNCI, 2018);
- PBL expects bio-energy in combination with carbon capture and storage (BECCS) to play an important role in the decarbonisation of the industry (PBL, 2017a);
- SER (2018) expects, on the medium term, green fuels for feedstock (lignocellulose) and the use of ultra-deep geothermal for heating to become important. In the long term, CCS in combination with green fuels will play a large role (negative emissions).

*Summary of renewable energy*
There are large differences between the studies regarding the expected role of renewable energy, especially biomass, as can be seen in Figure 8.

The studies by VNCI (2014) and SER (2018) studies include geothermal energy as a key decarbonisation option.[4]

[4] SER (2018) does not quantify the potential for geothermal energy and, therefore, is not included in Figure 8.

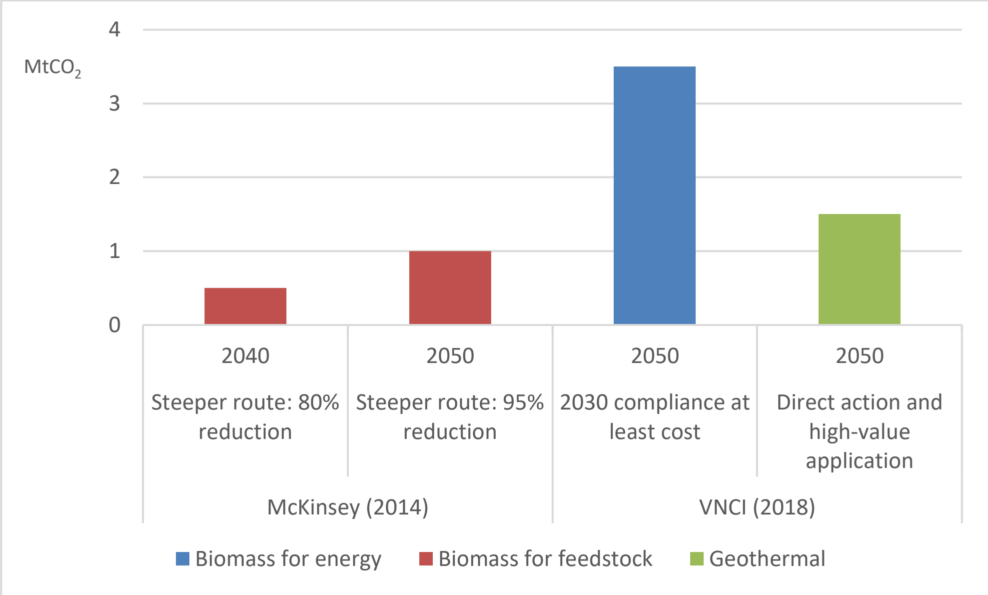


Figure 8: Potential impact of biomass and geothermal energy options on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

### 3.4.4 *Hydrogen*

- McKinsey (2014) expects ‘green’ hydrogen (via electrolysis) to play an important role by having industry switch to hybrid systems based on electricity and hydrogen instead of electricity and natural gas. The potential impact is 4 $MtCO_2$ reduction.
- According to VEMW (2017) the abatement potential for green hydrogen is much larger but hydrogen will not become feasible under the current energy prices;
- The '*Direct action and high-value applications*' scenario of VNCI (2018) expects hydrogen, in combination with CCU for production of methanol and (part of) C2/C3, to have an impact of 72 PJ fossil energy reduction in 2050;
- The use of electrolyses for $H_2$ production is considered by SER (2018) to be an important decarbonisation option in the long-term.

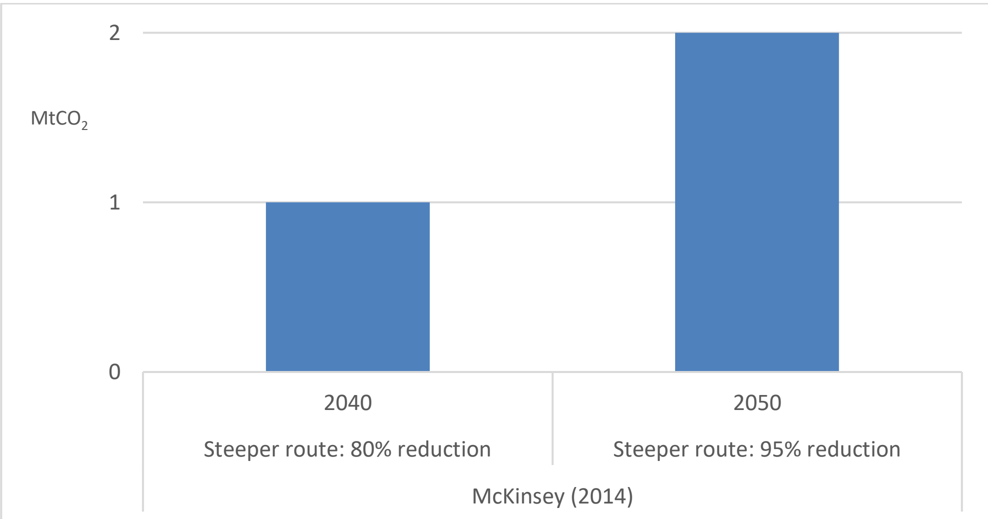


Figure 9: Potential impact of hydrogen on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

*Summary hydrogen*
The studies foresee an important role for hydrogen (see Figure 9). However, McKinsey foresees a role for hydrogen as a replacement of gas, while the VNCI study foresees a role for hydrogen, in combination with CCU, as feedstock for the chemistry sector. The VEMW study indicates that hydrogen has significant potential, but that it will not be applied under current energy prices.

### 3.4.5 *Electrification*

- Electrification is expected by McKinsey to play a major role in decarbonising the Dutch industry in any scenario. Therefore, research and development are needed to speed up the commercialisation of heat-pumps for medium temperature heat and electric furnaces for high temperature heat (400+ degrees Celsius) for e.g. refineries and ethylene production (impact of 11 Mt $CO_2$ reduction). Note that this results in an electricity demand by the Dutch industry of (340-560 PJ in 2040, i.e. three times higher than the demand in 2014 (McKinsey, 2014);
- VEMW expects hybrid or dual electricity/gas systems to play an important role in the short term, as boilers reach the end of their lifetime and need to be replaced (impact 10 Mt $CO_2$ reduction). Such dual systems can also help balance the grid. For the long-term, electrolysis for hydrogen production (zero impact, but technical potential impact 5 Mt$CO_2$ reduction) and heat pumps and electric furnaces (impact 5 Mt$CO_2$ reduction) will play an important role (VEMW, 2017);
- In the *'Direct action and high-value applications'* scenario of the VNCI study, the remainder of the heat demand, after use of the full potential of geothermal heating, is met by electric boilers (VNCI, 2018);
- According to Berenschot, for the short term, promising decarbonisation options are: electric boilers, steam recompression, mechanical vapour recompression, electromagnetic radiation and heat pumps. For the medium to long term, electrolysis for production of chlorine, ammonia and hydrogen are considered to have high impact potential (Berenschot, 2017);
- PBL analyses two scenarios: 80% GHG emission reduction and a 95% GHG emission reduction compared to 1990 levels. In both scenarios, electricity production increases due to the electrification of industry and transport. The application potential of electrification in industry is 0-25% in the 80% reduction scenario and 25-30% in the 95% reduction scenario (PBL, 2017a);[5]
- According to the SER report on high temperature heat, in the short-term decarbonisation is expected to be achieved by using electrification options such as hybrid boilers, heat pumps or mechanical vapour recompression (SER, 2018).

*Summary electrification*
The studies, in general, agree that electrification will play a major role in the decarbonisation of the industry (see Figure 10). In the short term, electrification of the steam production is mentioned by several studies to show potential (heat pumps, vapour recompression, hybrid boilers), whereas in the long-term electrification of high temperature processes (electric furnaces) are considered to play an important role.

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[5] It is not specified to which energy consumption the electrification percentage refers, but it can be assumed that it refers to the total industrial high temperature heat consumption.

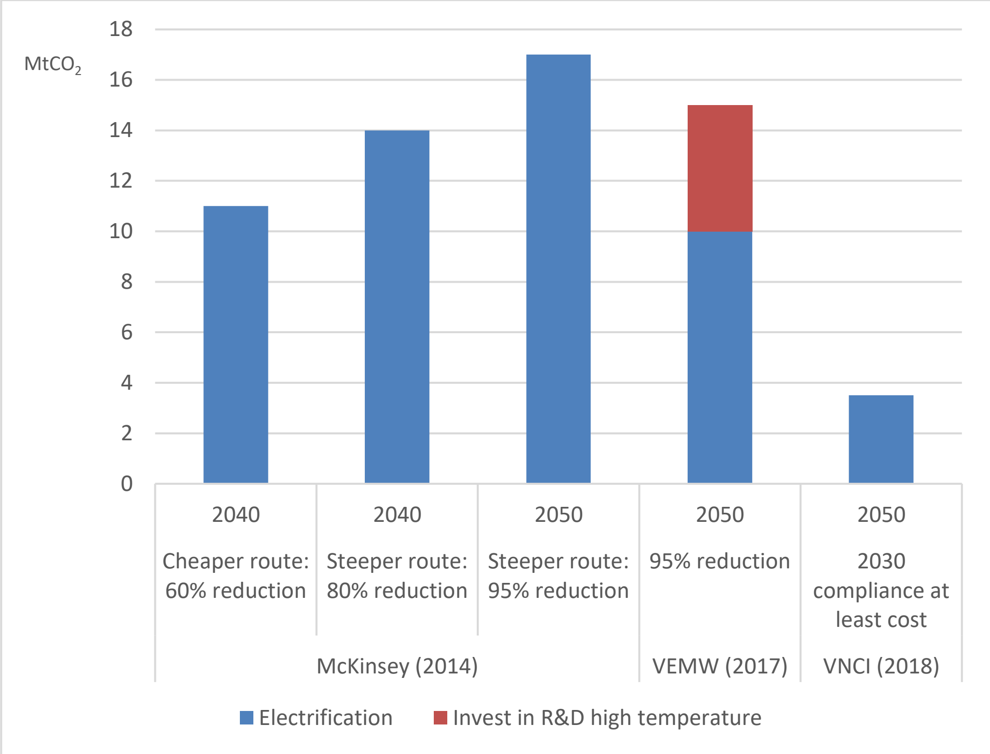


Figure 10: Potential impact of electrification on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

### 3.4.6 *Steel production*

- According to McKinsey, alternative steel production routes (HIsarna[6] and CCS) can contribute to abate 6 Mt $CO_2$ (McKinsey, 2014);
- Changing steel production is considered by VEMW to be of major importance for the decarbonisation of the industry. Reducing emissions using HIsarna or CCS/CCU can have an impact of 12 Mt $CO_2$ (VEMW, 2017);
- PBL expects steel production to use either CCS, HIsarna with CCS or the ULCOLYSIS/ULCOWIN[7] process using electricity. The potential impact is not specified (PBL, 2017a);
- According to the SER (2018), new steel making processes (HIsarna) will become important in the medium term. In the long term the focus will be on further innovative processes for steel production. The potential impact is not specified (SER, 2018).

*Summary steel production*
Potential alternative steel production routes mentioned in the studies are CCS (either with current processes or in combination with HIsarna) or the ULCOLYSIS/ULCOWIN process using electricity (see Figure 11).

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[6] The HIsarna ironmaking process is a direct reduced iron process for iron making in which iron ore is processed almost directly into liquid iron or hot metal.

[7] ULCOWIN operates slightly above 100 degrees C in a water alkaline solution populated by small grains of ore (electro-winning process). ULCOLYSIS operates at steelmaking temperature with a molten salt electrolyte made of a slag (pyro-electrolysis).

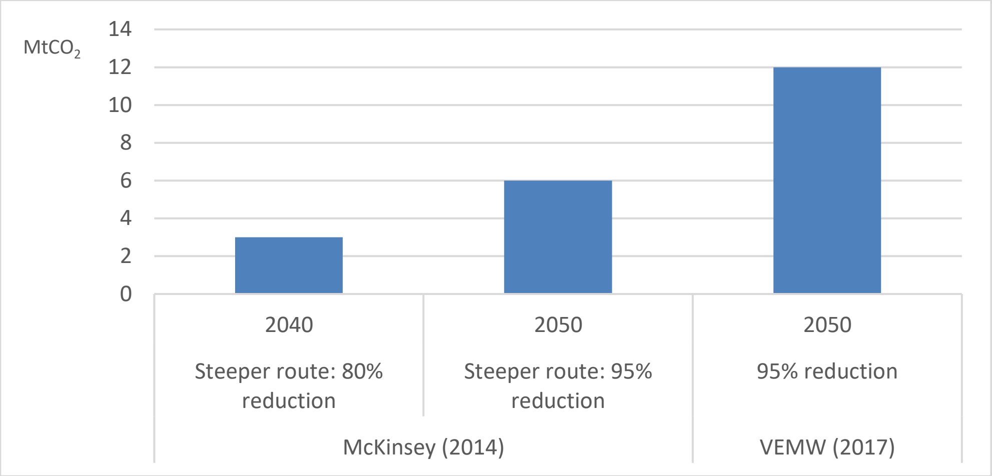


Figure 11: Potential impact of alternative steel production routes on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

### 3.4.7 Reuse and recycling

- According to McKinsey (2014), recycling of plastic, steel and biomass waste can help reduce emissions by 2 $MtCO_2$;
- VEMW (2017) expects recycling of waste streams (steel, plastic, biomass) to abate 2 Mt $CO_2$;
- In the *'Direct action and high-value applications'* scenario of the VNCI study, recycling is used to its full potential, with an impact of 1 $MtCO_2$ reduction (VNCI, 2018);
- SER (2018) expects recycling of plastics, biomass, and syngas to become important. The impact is not specified (SER, 2018).

*Summary reuse and recycling*
Figure 12 shows the estimated potential for reusing and recycling of material streams, based on the studies.

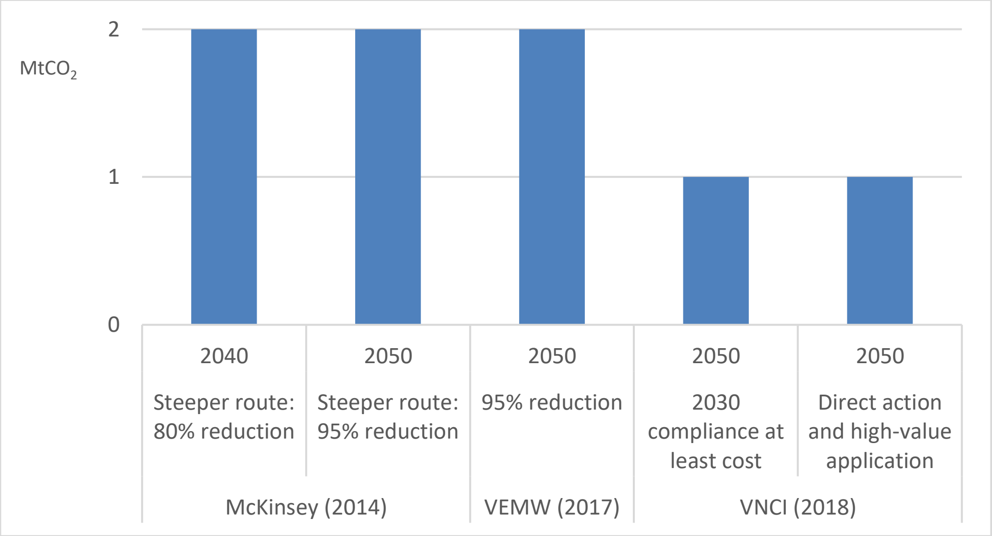


Figure 12: Potential impact of reuse and recycling on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

### *3.4.8 CCS/CCU*

- In the McKinsey study, carbon capture and storage is used to eliminate any remaining emissions after use of energy efficiency, renewable energy, hydrogen and electrification options. The potential impact is 9 $MtCO_2$ reduction (McKinsey, 2014);
- VEMW expects CCS (and CCU) to become important to decarbonise ethylene production, steel production and petroleum refining, with an impact of 11 $MtCO_2$ reduction (VEMW, 2017);
- In the *'Direct action and high-value applications'* scenario of the VNCI study, CCU is used to its full potential. CCS is applied to the remainder of the energy use and to waste incineration plants. The potential impact is 4 $MtCO_2$ reduction (VNCI, 2018);
- According to PBL, CCS is will play an important role in industrial decarbonisation, with an abatement potential of 8-29 $MtCO_2$ in the 80% reduction scenario and 6-34 $MtCO_2$ in the 95% reduction scenario (PBL, 2017a);
- In the mid-term (up to 2030), SER (2018) expects CCS for concentrated $CO_2$ streams (hydrogen production, process gasses steel production, refineries) to plan an important role. The potential impact is not specified (SER, 2018).

*Summary of CCS/CCU*
The abatement potential of CCS and CCU varies significantly per study, as shown in Figure 13. In the McKinsey and VNCI studies, CCS is used as a final option to abate $CO_2$ emissions that remain after full implementation of the other decarbonisation options. In the PBL study, on the other hand, CCS appears to play a much more prominent role (also in combination with biomass to create negative emissions), although it is difficult to compare the outcome of this study as it provides a very wide range for the impact (6 to 34 $MtCO_2$). The VNCI study specifically focuses on the potential of CCU.

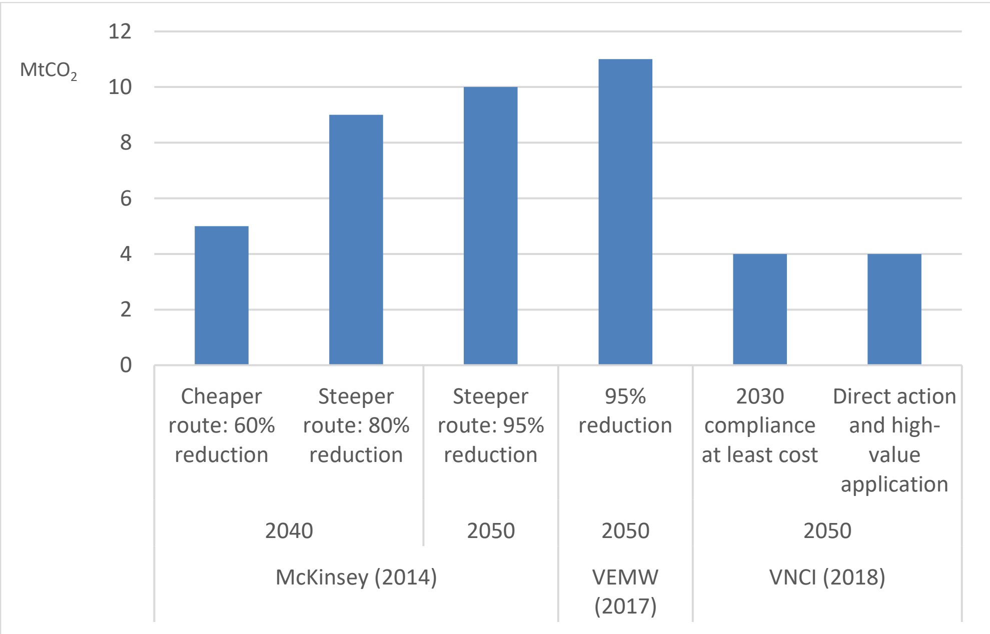


Figure 13: Potential impact of CCS/CCU on carbon abatement by the Dutch industry in various scenarios ($MtCO_2$)

## 3.5 Summary of main findings

An overview of the impact of all the decarbonisation options for energy purposes is presented in Figure 14 ($MtCO_2$) and for feedstock in Figure 15 ($MtCO_2$) and Figure 16 (PJ). As noted, however, the different scenario studies are characterized by differences in decarbonization targets, industrial sector coverage as well as in scope of energy use (see Table 7 and Table 8 in Section 3.2 above). This complicates an adequate comparison of the studies reviewed in these figures.

Note in particular that the chosen GHG emission reduction target varied per study. The differences in decarbonisation option developments have to be viewed within the context of these chosen reduction targets (see also Table 7).

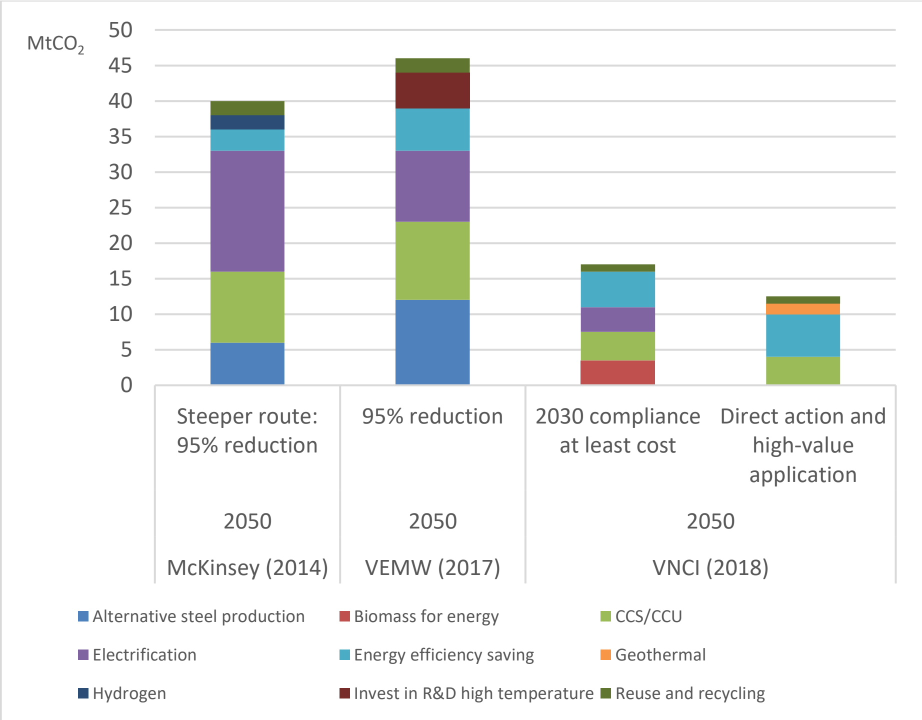


Figure 14: Potential impact of decarbonisation options for energy use by the Dutch industry in various scenarios ($MtCO_2$)

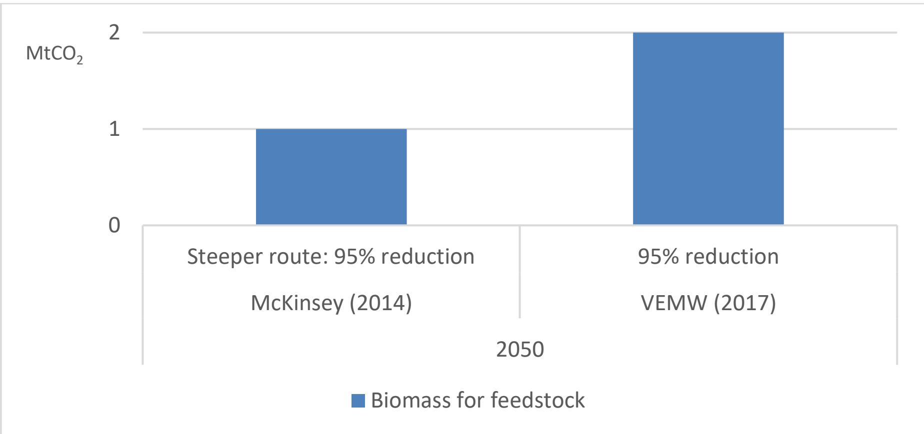


Figure 15: Potential impact of decarbonisation options for feedstock use by the Dutch industry in two 2050 scenarios ($MtCO_2$)

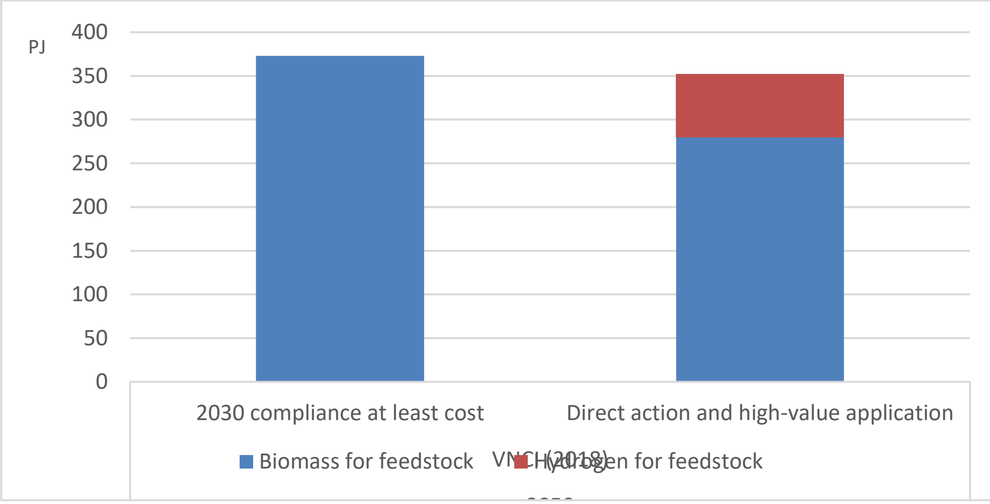


Figure 16: Potential impact of decarbonisation options for feedstock use by the Dutch industry in two 2050 scenarios (PJ)

*Robust elements*
The studies generally agree that electrification will play an important role in the decarbonisation of the industrial sector. Two other large high potential decarbonisation options are CCS/CCU and biomass for energy and feedstock purposes.

None of the studies discuss the potential of process related energy efficiency options. Instead, all studies focus on options related to reuse of heat (heat pumps, mechanical vapour recompression).

*Uncertain elements*
In general, the McKinsey study expects a larger impact from electrification, whereas the PBL study predicts a larger role for biomass and CCS (BECCS), although due to the range given for the potential impact of CCS it is hard to estimate how large the remaining role for biomass is. The application of biomass for energy purposes by PBL contrasts with the McKinsey and VNCI studies (‘*Direct action and high-value applications’* scenario), which assume biomass will only be used for feedstock.

Geothermal energy is only considered to play a role in the studies by VNCI (2018) and SER (2018).

The potential for industrial energy savings varies per study and scenario considered, but since none of the studies elaborates on the assumed economic development of the industry in their scenarios, the (estimated or assumed) impact of energy efficiency options is hard to compare.

The role for hydrogen varies per industrial scenario study but is difficult to analyse as this option is generally not discussed in detail in the studies. It does appear that its potential seems to depend strongly on the specific industrial abatement target, the energy prices (notably for gas and electricity), the $CO_2$ price, and the availability, acceptability and relative costs of alternative abatement options such as biomass or CCS/CCU.

# 4 Transport

## 4.1 Introduction

Transport is a key sector in terms of both energy use and GHG emissions in the Netherlands. Table 9 provides an overview for the transport sector regarding its realized and projected primary energy use in 2000, 2015 and 2030 as well as its direct GHG emissions in these years. For instance, in 2015 primary energy use of the transport sector amounted to 488 PJ (16% of total primary energy use in the Netherlands), while its GHG emissions – i.e. excluding electricity use emissions – amounted to almost 35 $MtCO_2$-eq. (about 18% of total national GHG emissions).

Table 9: Transport: Primary energy use and greenhouse gas emissions

| **Primary energy use** | **2000** | **2015** | **2030** |
|---|---|---|---|
| ➢ Total primary energy use by transport (PJ) | 512 | 488 | 497 |
| ➢ As % of total national primary energy use | 16% | 16% | 18% |
| **Greenhouse gas emissions** | **2000** | **2015** | **2030** |
| ➢ Total GHG emissions by transport ($MtCO_2$-eq.) | 38.0 | 34.7 | 32.9 |
| ➢ As % of total national GHG emissions | 17% | 18% | 23% |

Notes: Data for 2000 and 2015 are realizations while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called ‘Urgenda Verdict’ and the Climate Agreement of mid-2019). Total national energy use includes (non-energetic) industrial feedstocks. Sectoral GHG data do not include (indirect) emissions of sectoral electricity consumption.

Source: PBL et al. (2019b).

Until recently, the EU and national ambitions for $CO_2$ reduction in the transport sector have been relatively modest compared to other sectors. For example, the Netherlands ‘*National vision on transport fuels*’ (I&E, 2014) aims for a $CO_2$ reduction of domestic transport $CO_2$ emissions by 60% in 2050, compared to 1990, thereby (largely) excluding international aviation and shipping[8]. At that time other sectors were already expected to achieve emission reductions of 80-95%. However, following the Paris agreement (UNFCCC, 2015), it became clear that climate ambitions had to be intensified. As a result, also the ambitions for the transport sector in the Netherlands and other EU member states have been intensified to >90% $CO_2$-reduction in 2050.[9]

The purpose of this chapter is to provide an overview of some recent scenario studies on $CO_2$ emission reduction in the long term (2050) in the transport sector. The $CO_2$ emission reduction ambition of the scenarios ranges from 60 to 95%. The scenarios are analysed and compared with the aim to (i) identify the common robust elements of the scenarios; (ii) identify and explain the differences between the scenarios, and (iii) identify the key research questions that remain to be answered in order to sharpen our vision on the decarbonization path of the transport sector.

[8] Domestic transport GHG emissions of individual countries are included in their national GHG emission overviews and reported to the UNFCCC. In contrast, the GHG emissions of international aviation and shipping (i.e. ‘bunker fuels’ emissions) are currently registered as a ‘Pro Memori’ post in the UNFCCC global emission registration and are, therefore, not (yet) attributed to individual countries.

[9] Note that this target does not include international shipping and aviation.

The scope of this chapter is focussed on the transport sector of the Netherlands. However, as the number of ambitious GHG emission scenarios for the transport sector in the Netherlands is still limited, for comparative reasons we will also look to some familiar studies in neighbouring EU countries, notably Germany. Moreover, this chapter focuses on the roll-out trajectories of the low-carbon energy carriers in the transport subsectors, rather than on the expected, future developments regarding the demand for transport services. Finally, most of the scenarios reviewed in this chapter focus on domestic transport, notably on road transport. Nevertheless (international) aviation and shipping are as much as possible included, especially since these sectors are the most difficult to decarbonize and at the same time show the largest growth in future transport demand.

## 4.2 Studies reviewed

This chapter review first three Dutch studies of different scenarios and visions on the decarbonisation of the transport sector in the Netherlands. These studies are:
- ECN et al. (2014), *Scenarios for energy carriers in the transport sector*;
- I&E (2014), *A vision on sustainable fuels for transport*;
- EZ (2016), *Energy Agenda – Towards a low-carbon energy supply*.[10]

Subsequently, as indicated above, for comparative reasons this chapter also reviews briefly four German studies on transport decarbonisation in Germany. These studies have all been commissioned or released by the '*Umweltbundesamt'* (UBA), i.e. the German Environmental Agency.

These four studies include:
- UBA (2016a), *Klimaschutzbeitrag des Verkehrs bis 2050* (Contribution of the transport sector to climate protection up to 2050);
- UBA, (2016b), *Erarbeitung einer fachlichen Strategie zur Energieversorgung des Verkehrs bis zum Jahr 2050* (Development of a professional strategy on energy supply for transport up to 2050);
- UBA (2017a), *A resource efficient pathway towards a greenhouse gas neutral Germany*;
- UBA (2017b), *Climate Protection in Transport: Need for Action in the Wake of the Paris Climate Agreement*.

Finally, this chapter reviews briefly a major study by LBST and Dena (2017) on decarbonization of the transport sector in the EU as a whole, notably by means of electricity-based fuels (the so-called 'E-fuels' study).

The main findings of the studies mentioned above are discussed in the next section.

## 4.3 Major findings of studies reviewed

### *4.3.1 Dutch studies on transport decarbonization in the Netherlands*

*ECN et al. (2014), Scenarios for energy carriers in the transport sector*
This study by the 'Knowledge consortium' (ECN, CE Delft and TNO), was commissioned by the Dutch government as a starting point for the '*National vision*

[10] Actually, this is not a scenario study but rather a long-term policy document.

*on sustainable fuels for transport*' (see below). The study has developed and analyzed four different scenarios, all aiming at 60% $CO_2$ reduction by the transport sector in 2050. These scenarios were based on four possible combinations for high/low assumptions regarding the future development of two key parameters: (i) the shares of renewable energy in the total energy supply, and (ii) the penetration of new electric drivetrains in the transport sector. The resulting four scenarios are described briefly below along with a visual projection of the roll-out of energy carriers over time (see Figure 17).

1) '*Biofuels & Efficiency'*: assuming no breakthrough of transport electrification and limited availability of renewable energy sources. The focus in this scenario is on the use of biofuels and strong improvement of powertrain efficiencies.
2) '*New & All-Renewable*': assuming a breakthrough in electromobility in combination with abundant availability of renewable energy. Both electricity and hydrogen have significant shares in road transport.
3) '*Efficient Fossil Energy*': the assumed absence of breakthroughs in both transport electrification and in availability of renewable energy leads to the focus on increase of powertrain efficiency. In addition, a significant decrease in transport volume growth is required.
4) '*Fossil Electricity/Hydrogen*': a fast roll-out of electrification is assumed, though with electricity and hydrogen distributed from centralized production facilities using fossil energy. $CO_2$ reduction is realized through CCS and other technologies.

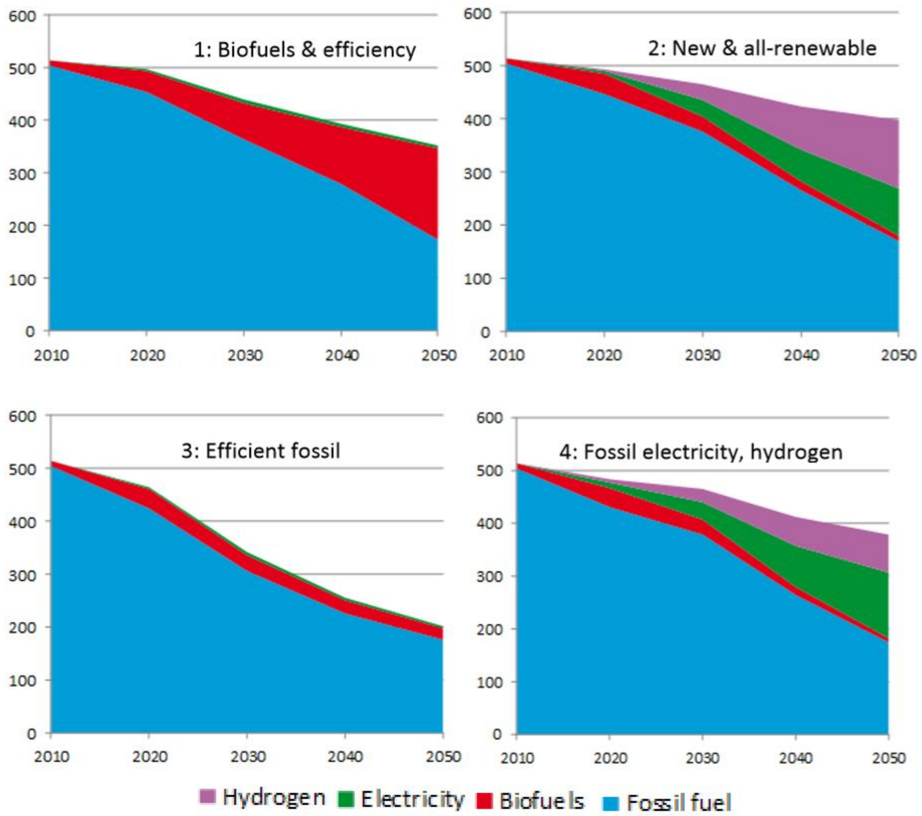


Figure 17: Development of the final energy mix (PJ) in the Dutch transport sector over the years 2010-2050 in four different scenarios (all meeting 60% $CO_2$ abatement by 2050).

Source: ECN et al. (2014).

*I&E (2014), A vision on sustainable fuels for transport*
In 2014, the Dutch Ministry of Infrastructure and Environment (I&E) issued a report called ‘A vision on sustainable fuels for transport’, including analytical support from the ‘knowledge consortium’ (ECN, CE Delft and TNO). In support of the national ‘Energy Agreement for Sustainable Growth’ (SER, 2013), this report provides a vision on the roll-out of alternative fuels over the different transport modes, thereby considering the following starting points for the transport sector:

- Transport $CO_2$ emissions to be reduced to a maximum of 25 $MtCO_2$ in 2030, i.e. a reduction of 17% compared to 1990.
- The Dutch transport sector will contribute 15-20 Petajoule (PJ) in 2020 to the overall energy savings in the agreement.
- In 2035 all newly sold passenger cars need to be “capable to drive without emissions”.
- In 2050 all passenger cars (i.e. the actual fleet) need to be “capable to drive without emissions”.
- All stakeholders involved embrace the EU ambition of 60% $CO_2$ reduction in mobility by 2050 as compared to 1990.

In 2014, the official target of the Dutch government (and the EU as a whole) for the transport sector was still 60% $CO_2$ reduction in 2050. Nevertheless, the ‘*National vision on sustainable fuels for transport*’ also included a ‘maximum’ scenario’, by then already aiming for >90% $CO_2$ reduction in 2050. Figure 18 shows that the 2050 low carbon fuel mix of this scenario is dominated by electrification and hydrogen.

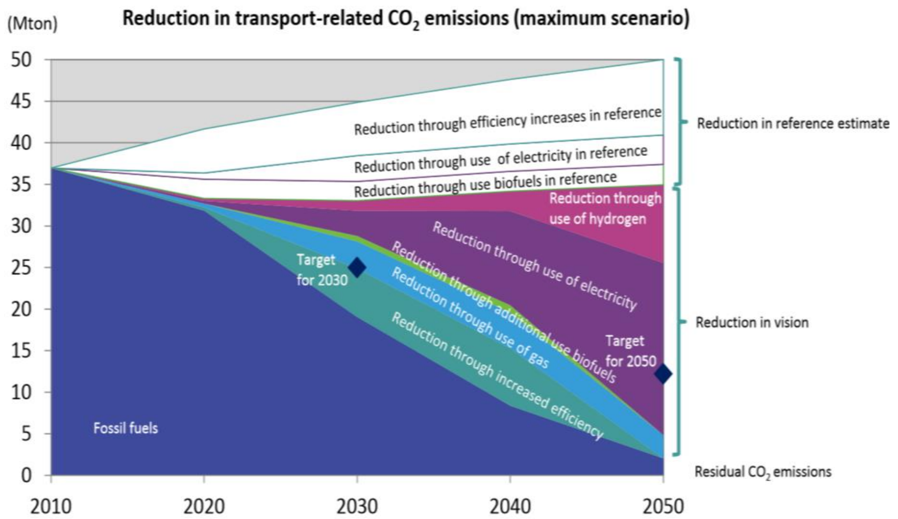


Figure 18: Reduction in transport-related $CO_2$ emissions according to the ‘maximum scenario’ (i.e. >90% $CO_2$ reduction in 2050)

Source: I&E (2014).

*EZ (2016), Energy Agenda - Towards a low-carbon energy supply*
In 2016, the Dutch Ministry of Economic Affairs (EZ, 2016) published the *Energy Agenda*, including Chapter 6 on the ‘Functionality Transport’. This document, issued one year after the Paris agreement, aims for a 2050 $CO_2$ emission reduction in the transport sector of 80%, i.e. substantially more ambitious than the 2014 ‘*sustainable energy vision’* as described in the previous section. The energy agenda takes the implementation of the 2014 ‘*sustainable energy vision*’ as a starting point, but it is

complemented with ‘additional efforts’. However, these additional efforts to enhance the $CO_2$ emission reduction from 60% to 80% are not quantitatively specified in terms of additional low carbon energy carriers. The document stresses that the extra reduction needs to be cost effective, innovative and aiming for new economic opportunities.

### *4.3.2 German studies on transport decarbonization in Germany*

As the scenario studies and visions on the transport sector for the Netherlands are (largely) limited to the ones described in the previous section, we also looked at similar studies for other (neighboring) EU countries, notably Germany. These German studies are also relevant for the Netherlands as the climate goals and the structure of the transport sector of these countries are relatively comparable. Notably in 2016-2017, the German ‘*Umweltbundesamt’* (UBA) published a range of studies (partly commissioned to other parties) on transport decarbonization (as mentioned in Section 4.2 above).

In brief, the major characteristics and findings of these UBA studies are:

- An ambitious $CO_2$ emission reduction for the transport sector by 2050 (80-95%), including an ambitious roadmap that would make transport in Germany almost greenhouse gas-neutral by 2050 (UBA, 2016b and 2017b).
- Detailed technological underpinning. The conclusions are mostly supported by rather detailed technical analyses of the future fleet development and its energy carriers.
- The key decarbonization options include:
    - Maximizing the energy efficiency of all internal combustion engine powered vehicles in all segments.
    - Largest $CO_2$-reduction impact stems from electrification. Depending on the scenario, up to an almost complete electrification for passenger cars and a substantial part of the (shorter distance) truck segment.
    - Small or no role for biofuels.
    - Relatively large role for E-fuels (liquid fuels produced from renewable electricity).
    - Role of hydrogen remains unclear. UBA concludes this, despite the favorable energy efficiency of hydrogen compared to E-fuels, because switching to hydrogen involves (i) technical barriers for several transport modes, and (ii) the large costs for $H_2$ fueling infrastructure.
- In addition to $CO_2$ reduction, UBA (2017a) also addresses optimization of resource efficiency. This includes the energy consumption and environmental impacts of the production of materials and components for vehicles as well as their decommissioning and the recycling (including life-cycle assessments).
- An overarching publication (2017b), building on the other UBA publications, describes three scenarios (See also Figure 19):
    1) *The Reference Scenario*: continuation of current policies, focusing on efficiency-enhancing measures and the use of electromobility in cars and light commercial vehicles.
    2) *The Climate Protection Scenario*: additional measures for transport avoidance and modal shift. Complemented by a transformation of the transport sector (‘Verkehrswende’) involving a complete switch to electromobility and power-to-liquid (P2L) and power-to-gas (P2G) fuels. No biofuels in 2050.

3) *The Climate Protection E+ Scenario* is similar to the previous scenario, but with hybrid trolley trucks alongside HD trucks using P2L/P2G fuels. In addition, the proportion of electromobility and light commercial vehicles is higher.

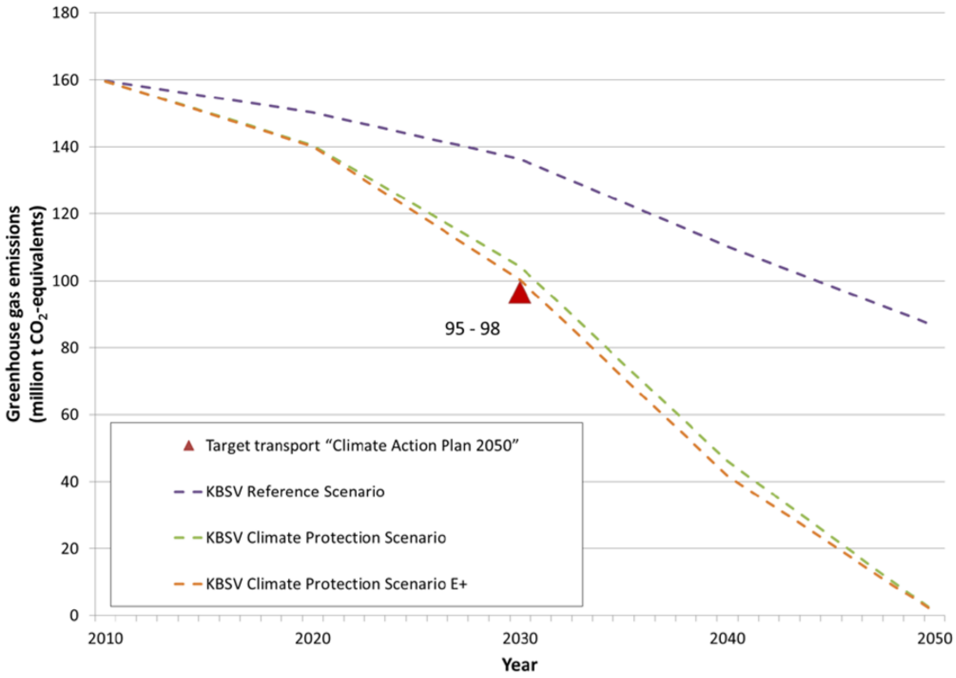


Figure 19: Target values for national transport and the trajectory of direct GHG emissions in the UBA-scenarios (national transport) from 2010 to 2050

Source: UBA (2017b).

### 4.3.3 *The 'E-Fuels study' on transport decarbonization in the EU*

In 2017, LBST and Dena published a study on 'The potential of electricity-based fuels for low emission transport in the EU', i.e. the so-called 'E-fuels study'.[11] This study analyses the future energy demand of the EU transport sector, along with the required build-up of renewable energy capacities investments, to achieve an 80-95% reduction in GHG emissions by the transport sector in 2050. More specifically, the study projects the development of the share of powertrains and fuels for all transport modes in the EU until 2050 based on four scenarios:

1) The *PtL/High/-80%GHG* scenario, i.e. a liquid-fuel-dominated scenario with a considerable increase in transport volume and a GHG reduction of 80% compared to 1990;
2) The *PtL/Low/-95%GHG* scenario, i.e. a liquid-fuel-dominated scenario with a moderate increase in transport volume and a GHG reduction of 95% compared to 1990;
3) The *PtG/Low/-95%GHG* scenario, i.e. a gaseous-fuel-dominated scenario with growing hydrogen use in electric power trains, a moderate increase in transport volume and a GHG reduction of 95% compared to 1990;

[11] E-fuels are defined as '*gaseous and liquid fuels such as hydrogen, methane, synthetic petrol, and diesel fuels generated from renewable electricity*'.

4) The *Drives/Low/-95%GHG* scenario, i.e. an electric-powertrain scenario with growing use of fuel cells in freight traffic, a moderate increase in transport volume and a GHG reduction of 95% compared to 1990.

In contrast to the UBA studies discussed above, the ‘E-fuels’ study foresees a substantial role for hydrogen next to power-to-methane (P2$CH_4$) and power-to-liquids (P2L) such as electricity-based methanol, kerosene or diesel. In addition, the E-fuels study sets the contribution of biofuels at 600 PJ per year, i.e. about 5% of today’s road fuel consumption in the EU (LBST and Dena, 2017).

The major conclusions of the E-fuels study include:
- Reaching > 80% $CO_2$ reduction in transport in 2050 is extremely challenging and requires urgent action in terms of deploying renewable energy, improving transport efficiency, and optimizing transport demand.
- Without e-fuel imports, the EU transport energy demand for renewable electricity in 2050 may exceed current EU electricity production by a factor of between 1.7 (in the *eDrives/Low/95%GHG* scenario) and 3 (in the *PtL/High/80%GHG* scenario).
- Next to electrification of road transport, e-fuels must play a major role in reducing GHG emissions from legacy road vehicles, aircraft and maritime transport.

### 4.4 Summary of main findings

The required mix of renewable energy carriers and technologies in the transport sector, along with their roll-out trajectories until 2050, intrinsically involves large uncertainties, as all options have their specific advantages and limitations, and are dependent on (international) market and costs developments. Additional uncertainties result from the yet insufficiently quantified impact of competition (and synergy) between transport and other sectors for renewable electricity and carbon sources. For several low-carbon options there is a risk that they will not reach enough technical and economic maturity and scalability, or that they will not be accepted by the mass market. In addition, uncertainties regarding the future development of transport demand increase overall uncertainty. Finally, future ‘disruptive’ developments such as the autonomous car driving and the shift from car ownership to car rental usage (‘mobility as a service’), may have a large impact on the future of the transport sector and its energy use.

*Robust elements (similarities across reviewed studies)*
Nevertheless, there are some robust options regarding deep decarbonization of the transport sector by 2050. These options include in particular:
- Maximizing efficiency of all passenger cars, vans and heavy-duty vehicles;
- Maximizing efficiency of logistics;
- Fast electrification of all passenger cars and vans, as well as the technical possible part of the truck segment (initially short distance smaller trucks).[12]

These ‘robust’ (‘no regret’) options alone, however, are not enough to meet the 2050 ambition of 95% $CO_2$ reduction in transport. In addition to large scale electrification, the remaining emission reduction needs to be achieved by a crucial

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[12] It is possible that part of these electric vehicles, especially the bigger ones used for longer distances, will be fueled by hydrogen (to generate electricity on-board; FCEVs).

but yet to be specified mix of additional technologies and renewable energy carriers, including:

- Biofuels, notably so-called ‘advanced biofuels’;
- Hydrogen, i.e. blue/green hydrogen;
- Electricity-based fuels (‘E-fuels’), notably power-to methane (P2$CH_4$) and power-to-liquids (P2L).

As explained above, it is not yet possible to define (precisely) how each of these energy carriers will enter segments of the mobility sector. Nevertheless, the following remarks can be made.

*Biofuels*
Despite the large bandwidth in estimates of biomass potentials, it is clear that the availability of sustainably produced biomass has its limitations. Also demand for biomass by other sectors is important, notably the demand for renewable carbon by the chemical industry (Usmani and De Wilde, 2018). As a consequence, the future supply of advanced biofuels for transport is difficult to project. Therefore, the most robust strategy is to reserve biofuels for those transport applications where electricity and hydrogen cannot be applied because of power and/or range requirements: long-haul trucking, aviation and shipping. In addition, it is important to note that renewable biofuels could also be provided on the longer term by the P2L technology. See for example the UBA and LBST/Dena scenario studies that project an ambitious roll-out scenario for this technology and recommend kick-starting large scale technology development and commercialization as of today.

*Hydrogen*
The market penetration trajectory of hydrogen is difficult to project. Currently the first vehicles are on the market (Toyota, Hyundai, Honda) though in limited numbers. In addition, a basic hydrogen refueling infrastructure is being rolled-out in the Netherlands and other EU countries, notably in Germany. The roll-out trajectory of hydrogen lags behind by about 10 years as compared to electromobility. Therefore, an important question is to what extent developments in battery technology and costs will enable electromobility to outcompete hydrogen in its key passenger cars market segment: larger vehicles for longer distances. At the same time, it is plausible that hydrogen will fulfill a crucial role in long haul trucking after 2030, especially when P2L developments will be moderate.

According to the UBA studies (2016-2017), the role of hydrogen remains unclear. UBA concludes this, despite the favorable energy efficiency of hydrogen compared to E-fuels, because switching to hydrogen involves (i) technical barriers for several transport modes, and (ii) the large costs for $H_2$ fueling infrastructure.

*E-fuels*
The market penetration trajectory of E-fuels such as P2$CH_4$ and P2L (e.g. methanol, kerosene or diesel) is difficult to project as these technologies are still in an early, not yet commercial stage. Nevertheless, the German scenarios by UBA and LBST/Dena foresee a much more substantial role for E-fuels compared to the transport scenarios for the Netherlands discussed in Section 4.3.1. UBA and LBST/Dena recommend to kick-start and support technology development and commercialization of these fuels as soon as possible (see also Detz et al., 2018; Usmani and De Wilde, 2018).

*Uncertain elements (differences across reviewed studies)*
Some differences ('uncertainties') across the studies reviewed include:

- The German scenarios by UBA and LBST/Dena foresee a much more substantial role for $P2CH_4$ and P2L compared to the transport scenario studies for the Netherlands.
- Compared to the reviewed transport studies for the Netherlands, the UBA studies for Germany are more reluctant towards the future application of biofuels in the transport sector. UBA even foresees a decreasing role for biofuels towards zero in 2050. For the EU as a whole, LBST and Dena (2017) projects a relatively small role for biofuels. More specifically, this study sets the contribution of biofuels to the overall fuel supply at 600 PJ per year, i.e. about 5% of today's road fuel consumption in the EU.
- As said, for UBA the role of hydrogen in the transport sector remains unclear. On the other hand, LBST and Dena (2017) foresee a substantial role for hydrogen.

*Further research issues*
In order to reduce the uncertainties indicated above and improve the robustness of future scenario studies for the transport sector, the following research issues need to be further addressed:

- The future demand for and costs of renewable electricity (RES-E) by the transport sector (i.e. for electromobility, green hydrogen and $P2CH_4$/P2L combined). Note that LBST and Dena (2017) indicate that without e-fuel imports, the EU transport energy demand for renewable electricity in 2050 may exceed current EU electricity production by a factor of between 1.7 (in the *eDrives/Low/95%GHG* scenario) and 3 (in the *PtL/High/80%GHG* scenario).
- Electric vehicles as a buffer for intermittent RES-E. Or broader: the interaction or system integration ('sector coupling') between the transport sector and the power sector, including the flexibility options (demand response, storage) offered by the transport sector to the power sector.
- The roll-out speed and type of RES-E charging infrastructure (normal/fast/-urban/rural) related to the buffering role described in the previous bullet, including the role of hydrogen since hydrogen may play a role as a buffer for RES-E surpluses and deficits.
- Biomass supply versus demand. Potential mismatch between demand for predominantly diesel type fuels (including kerosene) versus supply of predominantly petrol replacing fuels (bioethanol).
- Consumer acceptance of EVs by the 'early and late majority' and 'laggards' is uncertain. Competitiveness of EVs compared to conventional (ICE) vehicles in terms of price or TCO may not be enough for a large share of consumers to accept the drawbacks of EVs in terms of range and charging.
- The future growth in mobility demand in all transport subsectors that critically determines the overall demand for low-carbon energy carriers.
- Disruptors and game changers of transport services. It is relatively unlikely that the future development of the national, European and global transport sector will be an extrapolation of the current situation. Various game-changing innovations are emerging that may drastically alter both the structure and the volume of the transport sector by 2050, including (i) autonomous driving, (ii) other ICT driven developments, (iii) high speed trains, (iv) vacuum tube transport, and (v) car sharing & 'Mobility as a Service' (MaaS), associated with consumer preferences moving from 'ownership' to 'use' of vehicles.

# 5 Agriculture

## 5.1 Introduction

Table 10 presents the primary energy use of the agricultural sector in the years 2005, 2015 and 2030, as well as its GHG emissions in the years 1990, 2015 and 2030. It shows that in terms of primary energy use the share of agriculture in total national energy use is relatively small, i.e. about 5% in 2015. In terms of GHG emissions, however, the share of agriculture in total national GHG emissions is relatively high, i.e. approximately 14% in 2015. The latter is mainly due to the relatively high emissions of methane ($CH_4$) and nitrous oxide ($N_2O$) in the agricultural sector, notably by its subsectors cattle raising and arable soil farming (see also Figure 20, presenting the mix of GHG emissions of agriculture in the Netherlands for the years 2000, 2015 and 2030).[13]

Table 10: Agriculture: Primary energy use and greenhouse gas emissions

| Primary energy use | 2000 | 2015 | 2030 |
|---|---|---|---|
| ➢ Total primary energy use by agriculture (PJ) | 157 | 140 | 150 |
| ➢ As % of total national primary energy use | 5% | 5% | 5% |
| **Greenhouse gas emissions** | **2000** | **2015** | **2030** |
| ➢ Total GHG emissions by agriculture ($MtCO_2$-eq.) | 28.5 | 27.0 | 24.5 |
| ➢ As % of total national GHG emissions | 13% | 14% | 17% |

Notes: Data for 2000 and 2015 are realizations while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called ‘Urgenda Verdict’ and the Climate Agreement of mid-2019). Total national energy use includes (non-energetic) industrial feedstocks. Sectoral GHG data do not include (indirect) emissions of sectoral electricity consumption.

Source: PBL et al. (2019b).

In terms of both primary energy use and $CO_2$ emissions, the main subsector within agriculture is the horticultural sector, i.e. about 80% of the primary energy use and $CO_2$ emissions of the agricultural sector in the Netherlands is attributable to horticulture. Since a few decades, the horticultural sector has shrunk both in number of growers and in area: from almost 5800 companies in 2010 to nearly 3200 in 2018 and from a surface of 10300 ha glass in 2010 to 9000 ha in 2018.

Not all companies within horticulture, however, are the same. A distinction can be made between energy intensive companies, requiring year-round heat supply and electricity for lighting, and more energy extensive companies which require less heat and apply no lighting.

The horticultural sector also possesses a vast amount of decentral power supply, i.e. about 2500 MWe of gas-based CHP capacity is installed, in about two thirds of the glass area. The CHP installations produce more electricity than the sector consumes on a net-net basis, so part of the electricity production is delivered to the grid.

[13] The share of agriculture in national GHG emissions in 2015 amounts to 73% for methane ($CH_4$), 72% for nitrous oxide ($N_2O$), 5% for carbon dioxide ($CO_2$) and 14% for all GHG emissions (in $CO_2$-equivalents).

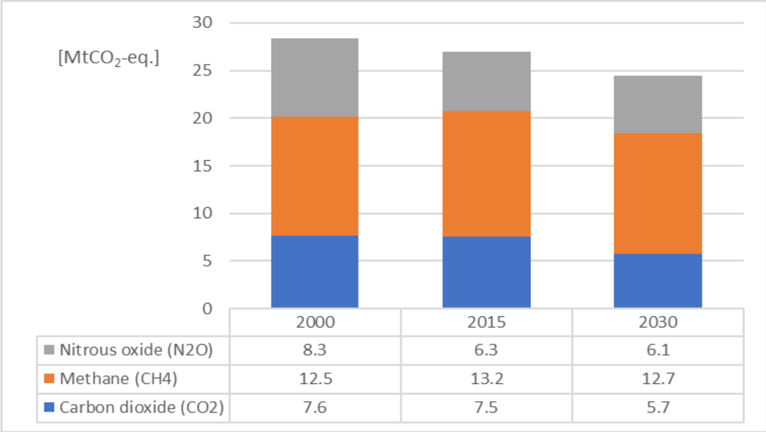


Figure 20: Mix of GHGs in the agricultural sector of the Netherlands, 2000-2030 (in $MtCO_2$-eq.)

Note: Data for 2000 and 2015 are realisations, while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called 'Urgenda Verdict' and the Climate Agreement of mid-2019).

Source: PBL et al. (2019b).

The aim of this chapter is to review some recent energy transition scenario studies of the Dutch agricultural sector in order to identify the main robust and uncertain elements of the scenarios considered. The next Section (5.2) provides first a listing of the scenario studies reviewed in the current chapter. Subsequently, Section 5.3 discusses the major findings of these studies. Finally, Section 5.4 presents a brief summary of the main findings and conclusions of this chapter.

## 5.2 Studies reviewed

As part of this chapter, the following documents and studies have been reviewed:
- LTO Glaskracht (2017a), *Voorwaarts Mars, Over de circulaire kas als kans voor de toekomst* (March Forward, On the circular greenhouse as opportunity for the future);
- LTO Glaskracht (2017b), *Energievisie en aanpak* (Energy vision and approach);
- LEI en ECN (2015), *Opties voor energieneutrale agrosectoren in 2025* (Options for energy-neutral agricultural sectors in 2050);
- WEcR (2018), *Prognoses $CO_2$-emissies glastuinbouw 2030* (Forecasts $CO_2$ emissions horticulture 2030);
- PBL (2017a), *Verkenning van Klimaatdoelen* (Exploration of climate targets);
- PBL (2018), *Kosten energie- en klimaattransitie in 2030* (Costs of energy and climate transition in 2030).

The first two publications are rather narrative in kind without concrete measures or potentials regarding energy savings or GHG emission reductions. However, they both aim at the same objective of achieving a climate neutral horticultural sector by 2040. This also formed the basis of the proposed GHG mitigation measures in the Climate Agreement of the Netherlands (Rijksoverheid, 2019). In order to achieve climate neutrality by 2050, agreed measures regarding the agricultural sector include: renewal of the greenhouses, implementing energy saving measures, decarbonise the heat supply through geothermal and external (waste) heat supply, external $CO_2$ supply for plant fertilisation and electrification.

One of the measures for the agricultural sector to become climate neutral is phasing out of gas-fired CHP as a source of electricity production, both for own consumption as for grid delivery. At the same time the sector makes its mitigation ambition dependent of several extra-sectoral conditions: there should be enough external $CO_2$ supply and heat networks available, the geothermal sector needs to develop further, electricity supply is carbon free and the restructuring of the sector succeeds. Other conditions are the continuation of the research and innovation programme *Kas als Energiebron* and the continuation of existing subsidy schemes.[14]

The major findings of the last four studies mentioned above – which are less narrative and more concrete (quantitative) in terms of energy savings and GHG mitigation potentials and measures – are discussed in the next section.

## 5.3 Major findings of studies reviewed

### *5.3.1 LEI en ECN (2015), Opties voor energieneutrale agrosectoren in 2025*

The 2015 study by LEI and ECN investigated technical options to make the different subsectors in the Dutch agricultural sector energy neutral by 2025. For this purpose, an assessment was made which technologies, including energy savings and renewables, could contribute to reducing the energy consumption by different agricultural subsectors. The study only looked at 2025 as target year for reduction of energy consumption, not to possible pathways towards 2025 (or beyond).

Being the largest energy consuming subsector in agriculture, the study found out that the horticultural sector faces the largest challenges in becoming energy neutral. The role of CHP in its energy supply and demand is crucial. The other sectors (cattle, pig and field agriculture) do have more options to become energy neutral. These options included enhanced capacity of wind on shore on agricultural soils and the use of manure digesters to produce green gas to be put in the gas grid. Three main routes towards energy neutrality were identified: (i) a reduction of own consumption, (ii) an increase of delivery of renewable energy to other sectors, and (iii) increasing the efficiency of final conversion processes in meeting final demand for heat and electricity.

Figure 21 illustrates how scenarios with increasing technology deployment towards energy neutrality in 2025 were composed in this study. A first step was to apply maximum energy saving (ES) and renewable energy (RE), indicated as scenario '*2025: Max ES + RE'* in Figure 21. A second, additional step included enhanced deployment of wind on land (WOL) and the introduction of mono-digestion of manure for green gas production (GG mono), indicated as scenario '*2025: Max ES + RE + WOL + GG mono*'. The most far going scenario towards energy neutrality in 2025 included co-digestion of manure to produce green gas (GG co), indicated as scenario '*2025: Max ES + RE + WOL + GG co*' in Figure 21. The balance for energy neutrality by the agricultural sector in 2025 could only be met by including delivery of (renewable) energy in the form of green gas and electricity to other sectors. Given the deployment of wind on land and manure digestors, the ranges for the balance of the energy neutrality in 2025 were found to be -10 to +15 PJ.

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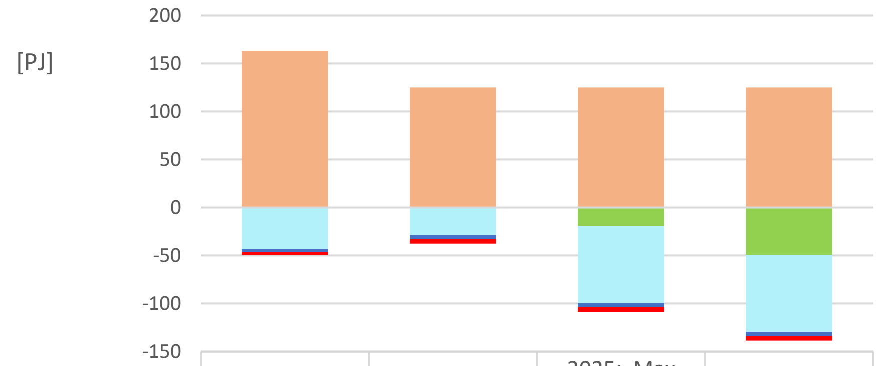
[14] These subsidy schemes include the Subsidie Duurzame Energie (SDE+), Marktintroductie Energie-Innovatie (MEI), Energie InvesteringsAftrek (EIA), Milieu-InvesteringsAftrek (MIA) and Willekeurige afschrijving milieu-investeringen (VAMIL).




| | 2013 | 2025: Max ES + RE | 2025: Max ES + RE + WOL + GG mono | 2025: Max ES + RE + WOL + GG co |
|---|---|---|---|---|
| Primary energy use | 163 | 125 | 125 | 125 |
| Energy savings | -03 | -05 | -05 | -05 |
| Production biomass | -03 | -04 | -04 | -04 |
| Production electricity | -43 | -29 | -80 | -80 |
| Production green gas | 00 | 00 | -19 | -49 |

Figure 21: Primary energy balance of the agricultural sector under different scenario assumptions, 2013-2025

Source: LEI en ECN (2015).

The 2015 study only investigated technical measures achieving a reduction of energy consumption in 2025, not in the required policies and measures to ensure the deployment of the technologies aiming for energy neutrality. Also costs aspects and who had to carry the costs were not part of this study. Nor were effects on GHG emissions estimated in the different presented scenarios.

### 5.3.2 *WEcR (2018), Prognoses $CO_2$-emissies glastuinbouw 2030*

The 2018 study by Wageningen Economic Research (WEcR), the former Landbouw Economisch Instituut (LEI), investigated three scenarios for the development of the horticultural sector in the Netherlands in 2030. Besides a '*middle*' variant (assuming average sectoral growth), a variant with less growth ('*pessimistic*') and one with more growth ('*optimistic*') were analysed. The growth variation concerned physical growth (area and production) as well as economic growth (investments) and energetical growth (energy use). The assumptions covered both external developments such as market developments, demand growth, technology development etc., as well as internal developments such as area development, rentability, energy savings, etc. (see Table 11). The study focussed primarily on the target year 2030 while neglecting possible transition pathways towards 2030 and only making some general remarks for the period beyond 2030 toward 2050.

The three scenarios show considerable changes in the energy mix of the horticultural sector (see Table 12). Compared to 2015, CHP will see its role halved – or even less – by lower heat demand and no more sales of excess electricity to the grid. Sustainable heat supply in the form of geothermal heat and external (waste) heat supply is the main contributor to a $CO_2$-neutral sector.

Table 11*: Main assumptions of three 2030 scenarios for the horticultural sector in the Netherlands*

| | | **2030 scenarios** | | |
|---|---|---|---|---|
| | **2015** | **Pessimistic** | **Middle** | **Optimistic** |
| Area (ha) | 9200 | 7000 | 8100 | 9000 |
| Lighted area (%) | 31% | 35% | 38% | 43% |
| Share of new greenhouses (>2015) | - | 22% | 46% | 66% |
| Energy saving potential ($m^3$ gas/m2) | - | 2.0 | 2.7 | 3.6 |

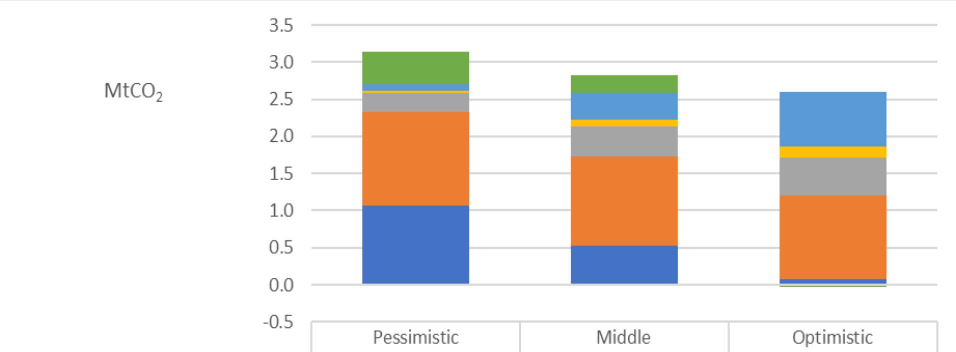
Source: WEcR (2018).

Table 12*: Main results of three 2030 scenarios for the horticultural sector in the Netherlands*

| | | 2030 scenarios | | |
|---|---|---|---|---|
| | 2015 | Pessimistic | Middle | Optimistic |
| $CO_2$ emissions (Mt) | 5.8 | 2.7 | 3.0 | 3.3 |
| Heat demand (million $m^3$ gas eq.) | 2130 | 1470 | 1660 | 1800 |
| Electricity demand (million kWh) | 6500 | 5300 | 6800 | 8700 |
| Final use of natural gas (million $m^3$ gas eq.) | 3270 | 1500 | 1690 | 1820 |
| Sustainable heat (million $m^3$ gas eq.) | 130 | 280 | 360 | 430 |
| CHP heat production (million $m^3$ gas eq.) | 1200 | 450 | 550 | 660 |
| CHP electricity production (million kWh) | 3990 | 2500 | 3000 | 3540 |

Source: WEcR (2018).

The study assumes that the horticultural sector will become $CO_2$-free by 2050 by further reducing the use of gas-fired CHP and more reliance on sustainable sources for heat and electricity. Its intermediate 2030 scenario results give a range of a possible 2.6 to 3.1 $MtCO_2$-emission reduction (see Figure 22). Consequently, an emission level of 2.7 to 3.3 $MtCO_2$ could be achieved by 2030, showing that the sector could be on a - linear - track to reach zero emissions by 2050.




| | Pessimistic | Middle | Optimistic |
|---|---|---|---|
| More energy savings | 0.44 | 0.24 | -0.03 |
| More external electricity supply | 0.09 | 0.37 | 0.73 |
| More external heat supply | 0.02 | 0.09 | 0.15 |
| More sustainable heat supply | 0.26 | 0.4 | 0.52 |
| Less electricity sales from CHP | 1.26 | 1.2 | 1.13 |
| Area effect | 1.07 | 0.53 | 0.07 |

Figure 22: Potential $CO_2$ emission reductions in the agricultural sector by 2030 ($MtCO_2$)

Note: A negative sign implies higher GHG emissions (for instance, due to less rather than more energy savings compared to the reference scenario).

Source: WEcR (2018).

### *5.3.3 PBL (2017a), Verkenning van Klimaatdoelen*

By means of the optimization model OPERA, PBL (2017a) analyses two cost-optimal scenarios to achieve, respectively, 80% and 95% GHG emissions reductions in the Netherlands by 2050. In addition, several sensitivity cases were analysed with different assumptions on the availability or deployment of biomass, CCS, nuclear or wind.

A major difference with other studies is that this study did not take a sectoral approach (e.g., analysing the agricultural sector), but one based on six functionalities, including (i) high temperature heat, (ii) low temperature heat, (iii) electric drive and lighting, (iv) mobility, (v) food and nature, and (vi) other, non-specified.

For the agricultural sector, mitigation options and impacts are related mainly to the functionalities *low temperature heat* and *food and nature*. For the functionality low temperature heat, the study presents only rather generic mitigation options, which are valid for heating demand of all buildings. Table 13 shows the generic mitigation options for the functionality low temperature heat and their potential role in achieving the GHG reduction targets for the Netherlands as a whole in 2050 (compared to 1990).

Table 13: Functionality low temperature heat: Mitigation options and potential role in achieving GHG targets in 2050

| | Potential role to achieve 2050 targets | |
|---|---|---|
| | 80% reduction | 95% reduction |
| Green gas or biomass | 5-10% | 5-30% |
| Heat networks | ~20% (or ~80 PJ) | 20-30% |
| Electrification (including heat pumps) | 40-50% | 40-80% |
| Demand reduction | 10-20 PJ | 15-65 PJ |

Source: PBL (2017a).

For the functionality food and nature, the study does not give specific results for the 80% and 95% GHG reduction scenarios but indicates the potential role of a variety of mitigation measures to achieve 2050 GHG abatement targets in 2050 as well as the cost-effectiveness of these measures (see Table 14).

Table 14: Functionality food and nature: Impact of GHG mitigation measures by 2050

| | Potential role to achieve 2050 targets | |
|---|---|---|
| | $CO_2$ reduction ($MtCO_2$-eq.) | Cost-effectiveness (€/$tCO_2$-eq.) |
| Mono digestion of manure | 3.6 | ~200 |
| *Or:* | | |
| Methane oxidation of manure | 2.5 | ~5 |
| Fodder adjustment dairy cows | 1.7 | 100-200 |
| Stable ventilation (methane oxidation) | 1 | ~700 |
| Age extension dairy cows | 0.5 | ~5 |
| Nitrification blockers | 0.4 | 50-100 |
| Optimised fertilising | 0.4 | ~100 |

Source: PBL (2017a).

### 5.3.4 *PBL (2018), Kosten energie- en klimaattransitie in 2030*

The scope and focus of the PBL (2018) study were to identify and analyse the most cost-effective options to reach 49% GHG emission reductions in the Netherlands by 2030. For the agricultural sector, including horticulture, the mitigation options are listed in Table 15, including the cost-effectiveness of these options as well as both their direct mitigation effects – i.e. GHG emission reduction in the agricultural sector itself – and their indirect effects (i.e. outside the agricultural sector, notably in the power sector). The measures are ranked according to their cost-effectiveness.

Table 15: Impact and cost-effectiveness of GHG mitigation options in the agricultural sector in order to reach 49% in the Netherlands by 2050

| | Emission reduction ($MtCO_2$-eq.) | | | Cost effectiveness (€/$tCO_2$-eq.) |
|---|---|---|---|---|
| | Total | Direct | Indirect | |
| LED lighting in horticulture | 0.3 | -0.1 | 0.4 | -200 |
| Geothermal heating in horticulture | 1.1 | 1.2 | -0.1 | -20 |
| Life extension dairy cows | 0.5 | 0.5 | 0 | 0 |
| Methane oxidation of manure[1] | 0.6 | 0.6 | 0 | 10 |
| Innovation and demonstration program 'Kas als Energiebron' in horticulture | 1.9 | 1.9 | 0 | 70 |
| Nitrification blockers | 0.4 | 0.4 | 0 | 75 |
| Optimised fertilising | 0.4 | 0.4 | 0 | 95 |
| Biomass boiler horticulture | 2.0 | 2.0 | 0 | 125 |
| Fodder adjustment dairy cows | 1.7 | 1.7 | 0 | 140 |
| Mono digestion of manure[1] | 1.0 | 1.0 | 0 | 240 |
| Stable ventilation (methane oxidation) | 0.6 | 0.8 | -0.2 | 350 |

[1] These measures are mutually excluding each other.

Source: PBL (2018).

## 5.4 Summary of main findings

A major observation of the current chapter is that a long-term (i.e. up to 2050), quantitative and comprehensive scenario study of the energy transition and full decarbonization (towards climate neutrality) of the Dutch agricultural sector as a whole is missing. Three out of the four studies reviewed in this chapter (i.e., LEI en ECN, 2015; WEcR, 2018; and PBL, 2018) analyse only options to either become (on balance) energy neutral or reduce GHG emissions up to 2025 or 2030, while focusing only or predominantly on the horticultural sector.

The fourth study reviewed (PBL, 2017a) analyses indeed the cost-optimal mix of mitigation options to reach, respectively, 80% and 95% GHG emission reductions in the Netherlands by 2050, but this study does not take a sectoral approach – e.g., analysing the agricultural sector – but one based on six functionalities. Moreover, for the functionality low temperature heat, the study presents only rather generic mitigation options (and no specific options for agriculture), while for the functionality food and nature the study does not give specific results for the 80% and 90% GHG reduction scenarios, respectively, but only indicates the potential role and cost-effectiveness of GHG mitigation options to meet abatement targets by 2050.

Across the studies reviewed, however, there is some consensus (‘robustness’) on how the agricultural sector – notably the horticultural subsector – can become climate neutral and/or, on balance, energy neutral (including energy supplies to other sectors). In brief, the major (agreed) options to achieve energy/climate neutrality by the Dutch agricultural sector include:

- Decrease energy use by implementing further energy savings;
- Phase out the use of fossil gas-fired CHP;
- Decarbonize heat supply by means of geothermal heating, external (waste) heat supply and heat pumps (‘green electrification’);
- Increase of renewable energy supplies to other sectors, in particular by wind onshore and solar parks on agricultural soils;
- Use manure digestors to produce green gas to be put in the gas grid;
- Adjust fodder for dairy cows;
- Optimize fertilisation of agricultural land.

On the other hand, there is still uncertainty and lack of knowledge with regard to the GHG abatement potential and cost-effectiveness of the above-mentioned options, notably to achieve a deep decarbonization target – including all agricultural GHG emissions – in the long run (up to 2050). Therefore, a long-term (2050), quantitative and comprehensive scenario study of the energy transition and full decarbonization of the Dutch agricultural sector as a whole seems to be highly desirable.

# 6 Energy supply sectors

## 6.1 Introduction

While the previous chapters have reviewed recent scenario studies regarding the main energy *demand* sectors individually, the current chapter reviews briefly some recent energy transition scenarios focussing on energy *supply* as a whole, including some individual energy supply sectors, notably electricity, heat (via heat networks) and hydrogen. In particular, this chapter reviews the following energy supply scenario studies:

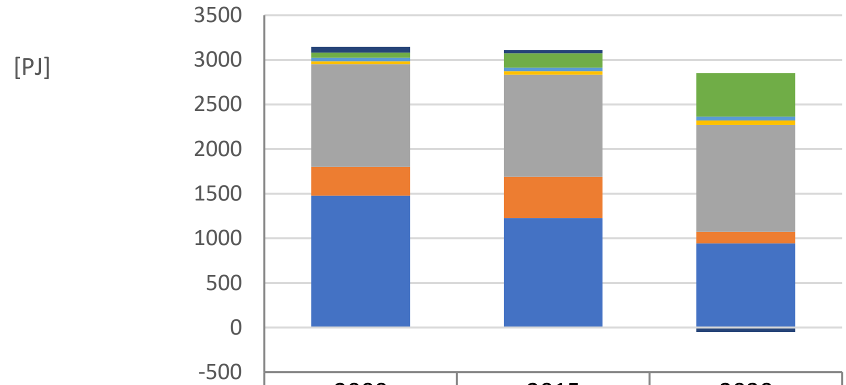
- Gasunie (2018), *Verkenning 2050* (Survey 2050).
- CE Delft (2017), *Net voor de Toekomst – Achtergrondrapport* (Grid for the Future – Background report).
- KIVI (2017), *The future Dutch full carbon-free energy system*.
- Berenschot (2018a), *Elektronen en/of Moleculen – Twee transitiepaden voor een $CO_2$-neutrale toekomst – Verkenning* (Electrons and/or Molecules – Two transition pathways for a $CO_2$-neutral future – Outlook).
- Berenschot (2018b), *Het 'warmtescenario': Beelden van een op warmte gerichte energievoorziening in 2030 en 2050, Scenariostudie ten behoeve van het Klimaatakkoord - Eindrapport* (The 'Heat scenario': Pictures of a heat focused energy supply in 2030 and 2050, Scenario study for the benefit of the Climate Agreement – Final report).

These studies and the reviewed scenarios are described briefly in Section 6.2, while the main findings of these scenarios – including their main similarities and differences – are discussed in sections 6.3 and 6.4. While some studies provide also scenario outcomes for 2030, in the current chapter we will focus on the main scenario findings for 2050 only. In order to put these 2050 in perspective, however, Figure 23 and Figure 24 provide a summary overview of total primary and final energy use in 2000, 2015 and 2030, obtained from the most recent Climate and Energy Outlook of the Netherlands (i.e. KEV 2019, see PBL et al., 2019b).

## 6.2 Studies reviewed

Table 16 provides an overview of the studies and scenarios reviewed in the current chapter. A more detailed description of these studies and scenarios is presented below.

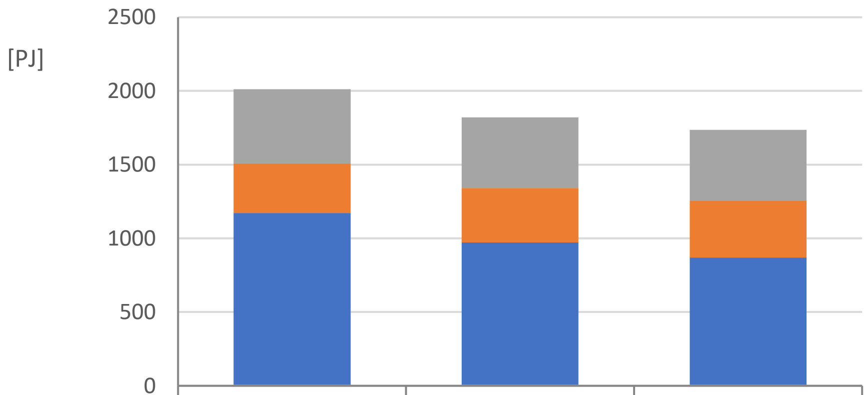
*Gasunie (2018), Verkenning 2050*
By means of the '*Verkenning 2050*' (Survey 2050), the Dutch TSO Gasunie presents its vision on the transition towards a reliable, affordable and $CO_2$-neutral energy system in the Netherlands by 2050. This scenario vision assumes further electrification, phasing out fossil energy carriers to the benefit of wind power, solar PV and hydrogen, without net import or export of electricity. Backup capacity is provided by batteries, hydrogen powered turbines, and power-to-heat technologies. Hydrogen production – including storage – is expected to become gradually more important up to 2050, partly produced from (renewable, relatively cheap) electricity during excess hours.




| | 2000 | 2015 | 2030 |
|---|---|---|---|
| Import balance electricity | 65 | 35 | -51 |
| Renewable | 57 | 160 | 490 |
| Nuclear | 41 | 39 | 41 |
| Other | 32 | 42 | 50 |
| Oil | 1151 | 1144 | 1198 |
| Coal | 325 | 461 | 129 |
| Gas | 1476 | 1227 | 944 |

Figure 23: Primary energy use in the Netherlands, 2000-2030 (PJ)

Source: PBL et al. (2019b).




| | 2000 | 2015 | 2030 |
|---|---|---|---|
| Transport fuels | 503 | 480 | 481 |
| Electricity | 336 | 368 | 385 |
| Heat | 1172 | 973 | 871 |

Figure 24: Final energy use in the Netherlands, 2000-2030 (PJ)

Source: PBL et al. (2019b).

Notes: Data for 2000 and 2015 are realisations while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called ‘Urgenda Verdict’ and the Climate Agreement of mid-2019). Primary energy use includes (non-energetic) industrial feedstocks, while final energy use excludes these feedstocks. Data for final energy use are corrected for (annual) variations in temperatures. For further details on the definitions of primary and final energy use, see PBL et al. (2019a and 2019b).

Table 16: Overview of reviewed energy supply scenarios in 2050

| Source | Title of study | Name of scenario | $CO_2$-reduction 2050 |
|---|---|---|---|
| Gasunie (2018) | Verkenning 2050 ('Survey 2050') | 2050 | 95% |
| CE Delft (2017) | Net voor de Toekomst ('Grid for the Future') | Regional Steering | 100% |
| | | National Steering | 100% |
| | | International | 100% |
| | | Generic Steering | 100% |
| KIVI (2017) | The future Dutch full carbon-free energy system | 2050 | 100% |
| Berenschot (2018a) | Elektronen en/of Moleculen ('Electrons and/or Molecules') | Electrons | 100% |
| | | Molecules | 100% |
| Berenschot (2018b) | Het 'warmtescenario' ('The heat scenario') | Heat | 100% |

*CE Delft (2017), Net voor de Toekomst*
On behalf of Netbeheer Nederland, i.e. the association of electricity and gas network operators in the Netherlands, CE Delft has conducted a study – called '*Net voor de Toekomst*' (Grid for the Future) – that defines and analyses four different visions on the future, climate-neutral energy system of the Netherlands in 2050, including the implications for the energy network infrastructure. The labels and key characteristics of these four energy scenario visions include:

- *Regional Steering ('Regie Regionaal')*: In this scenario, local and regional governments – i.e. municipalities and provinces – have a strong steering role in the energy transition, while energy is supplied as far as possible from local, small-scale sources such as sun, wind, biomass and geothermal energy. Other characteristics of this vision are: pro-active civil movement acting locally, high level of local and regional energy self-sufficiency, strong electrification, and large investments in local energy infrastructure, including energy conversion (electrolysis) and storage (batteries, hydrogen).
- *National Steering ('Regie Nationaal')*: in this vision, the national government takes strong steering control of the energy transition, while energy is supplied from a mix of particularly large-scale, centralized energy sources, notably offshore wind. Other characteristics of this vision are: high level of national energy self-sufficiency, strong electrification (including hydrogen production through electrolysis), and large investments in national energy infrastructure, including offshore electricity and gas (hydrogen) networks.
- *International ('Internationaal')*: in this vision, the national government focuses on stimulating an innovative economy and free international trade, including imports of renewable energy such as biomass and hydrogen from climate-neutral sources. Other characteristics of this vision are: less electrification (more green gases), lower level of national energy self-sufficiency (higher import dependency), and less investments in domestic electrolysis and local storage (batteries).
- *Generic Steering ('Generieke Sturing')*: in this vision, the energy transition is directed less by active government control but rather by generic policy instruments and policy-induced market forces, such as a strong $CO_2$ price incentive, while energy is supplied from a mix of local, national and international

options. Other characteristics of this vision are: less policy-coordinated, collective energy options (such as home insulation or district heating), more CCS in industry, slow but gradual penetration of market-induced, renewable energy technologies, and less policy-coordinated, harmonized investments in energy infrastructure.

*KIVI (2017) The future Dutch full carbon-free energy system*
In KIVI (2017), the authors present and discuss one single scenario for the Dutch energy system in 2050. In particular, the study aims to design a scenario of a fully carbon-fee energy system in 2050, starting from a stringent reduced energy demand scenario (through electrification and reducing conversion losses), heavily targeting wind power and solar PV, while supply security is assumed to be addressed by demand side management, electricity storage in batteries, a hydrogen-based back-up system and electricity imports as a last resort. Besides being carbon-free, this energy scenario is defined and characterised by the following elements: (i) most of the energy resources used are available in the Netherlands without relying too much on energy supplies from other countries, (ii) zero excess energy produced in the winter months or the summer months, avoiding the need of seasonal energy storage, (iii) strong electrification, and (iv) a very high penetration rate of renewable energy.

*Berenschot (2018a), Elektronen en/of Moleculen*
In order to facilitate the discussion on the energy transition, Berenschot (2018a) has designed two scenarios for the future Dutch energy system that both are characterized by the overarching aim that the $CO_2$ emissions of this system are reduced to almost zero. More specifically these scenarios include:

- *The 'electrons' scenario*: Besides becoming $CO_2$ free, this scenario is characterized by (i) a very large-scale deployment of renewable energy sources, notably sun and wind, (ii) production of hydrogen from wind and electrolysis, in particular for industry and gas (hydrogen) fired power stations, (iii) application of full electrification options in industry, including electric boilers, and (iv) deployment of all-electric heat pumps in the existing built environment.
- *The 'molecules' scenario*: In addition to becoming almost $CO_2$ free, this scenario is characterized by (i) production of hydrogen from high caloric gas or LNG with pre-combustion CCS, notably for industry and gas fired power stations, (ii) post-combustion CCS for steel and waste processing in industry, (iii) application of energy saving (high COP) electrification options in industry, and (iv) deployment of hybrid heat pumps – i.e. switching between renewable electricity and green gases – in the existing built environment.

*Berenschot (2018b), Het 'warmtescenario'*
In addition to the two scenarios mentioned above, in a separate study Berenschot has defined and analyzed a third, alternative scenario indicated as the (renewable) 'heat scenario'. This scenario also aims to achieve a carbon-neutral energy system in the Netherlands by 2050. In addition, its distinguishing features are characterized by (i) optimal use of (renewable) heat supply sources in all sectors (geothermal, solar, residual heat from industry, etc.), (ii) remaining heat demand is covered by green gases and (hybrid) heat pumps, (iii) import of renewable energy carriers, notably hydrogen and – to some extent – biomass, and (iv) substantial investments in additional (district) heat infrastructure.

The next Section (6.3) provides a comparative review of the main findings of the studies and scenarios mentioned above with regard to total energy supply as a whole (subsection 6.3.1) and some key individual energy supply sectors in particular (subsections 6.3.2 up to 6.3.4). In case certain studies or scenarios are not included in specific figures in Section 6.3 below, it is simply because adequate data on the topic concerned were not available in these studies or scenarios.

## 6.3 Major findings of studies reviewed

### *6.3.1 Total energy supply*

All studies and scenarios mentioned in Section 6.2 above provide data on total final energy use in 2020 and – except for Berenschot's *Heat* scenario – on total primary energy use (Figure 25). In addition, all studies – except CE Delft (2017) – provide data on the mix of total final energy use into major energy carriers (Figure 26).[15]

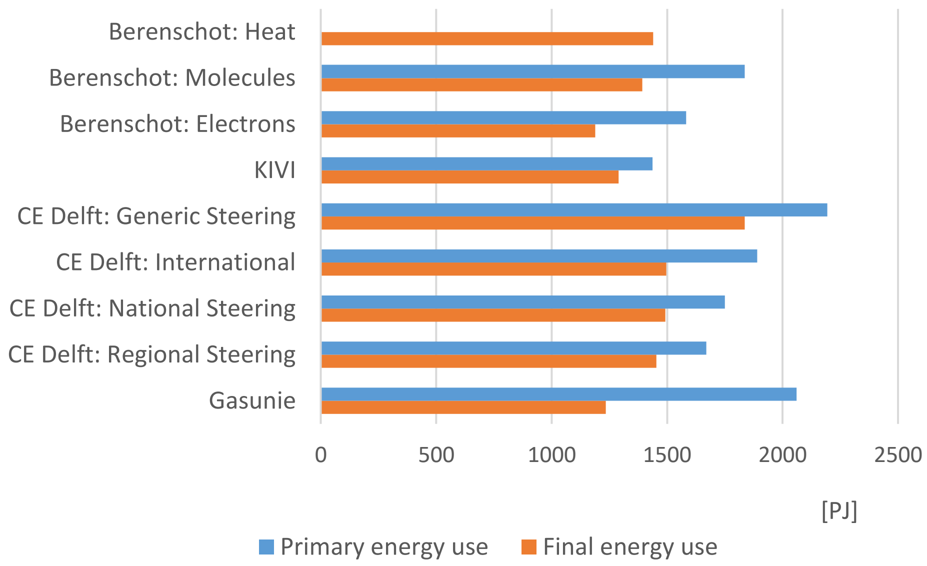



Figure 25: Total primary and final energy use in various 2050 scenarios (PJ)

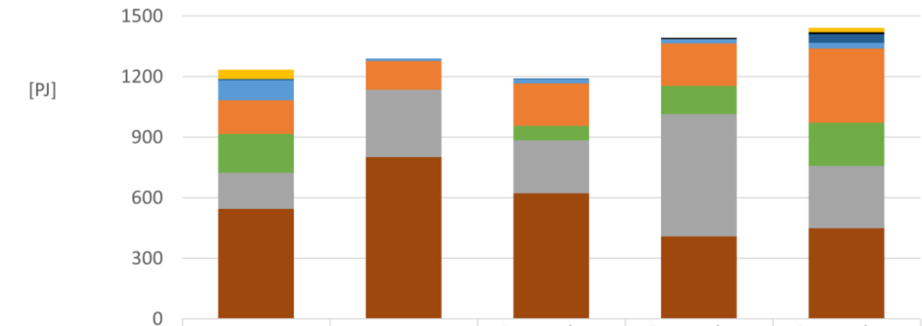
Figure 25 shows that for both total primary and final energy use the recorded scenario values for 2050 vary considerably. For instance, for total primary energy use these values range between 1436 PJ in the 2050 scenario of KIVI to almost 2200 PJ in the *Generic Steering* scenario of CE Delft.[16] For final energy use, the total amount varies between nearly 1290 PJ (Berenschot, *Electrons* scenario) to almost 1840 PJ (CE Delft, *Generic Steering* scenario).

[15] CE Delft (2017), however, does provide data for 2050 on the breakdown of total final energy use into major energy sectors/functionalities as well as of total primary energy use into major energy carriers (see Figures 21 and 22 on page 73 of CE Delft, 2017). In addition, 2050 data on the mix of primary energy carriers are also available in KIVI (2017).

[16] Note that the presented data by CE Delft on total final energy use (and likely also on total primary energy use) include non-energetic industrial feedstocks, while the final energy data of the other studies (most likely) do not include these feedstocks (or, in any case, do not record data on non-energetic feedstocks by industry). Estimates by CE Delft of energy use for industrial feedstocks in 2050 vary from nearly 270 PJ in the '*International*' scenario to approximately 450 PJ in the '*Generic Steering*' scenario.

Another striking feature of Figure 25 is that the energy conversion losses – i.e. when moving from primary to final energy use – also differ widely across the scenarios reviewed, ranging from approximately 150 PJ in KIVI's 2050 scenario (10% of primary energy use) to almost 830 PJ (40%) in the 2050 scenario of Gasunie. These differences in conversion losses are party due to differences in the (assumed) mix of primary and final energy carriers and partly to differences in (assumed) energy conversion efficiency rates.

Figure 26 shows the mix of final energy use by energy carriers across various 2050 scenarios reviewed. Due to the (assumed) further electrification of the energy system – notably of mobility and heat in industry and the built environment – electricity becomes far more important in all these scenarios (compared to recent levels). More specifically, however, electricity use across the scenarios considered in Figure 26 varies from almost 410 PJ in Berenschot's *Molecules* scenario – i.e. nearly 30% of total final energy use – to approximately 800 PJ in KIVI's 2050 scenario (i.e. about 62% if total energy use).[17] It should be noted that Figure 26 presents the values for final energy use. The primary production (and share) of electricity, however, is much higher in certain 2050 scenarios due to the intermediate conversion of power to hydrogen.




| | Gasunie | KIVI | Berenschot: Electrons | Berenschot: Molecules | Berenschot: Heat |
|---|---|---|---|---|---|
| Oil | 47 | 0 | 0 | 0 | 21 |
| Coal | 0 | 0 | 0 | 7 | 7 |
| Natural gas | 7 | 0 | 1 | 0 | 45 |
| Other renewables | 97 | 12 | 22 | 22 | 28 |
| Heat | 169 | 144 | 210 | 210 | 369 |
| Green gas | 191 | 0 | 73 | 139 | 213 |
| Hydrogen | 178 | 335 | 263 | 608 | 307 |
| Electricity | 545 | 799 | 620 | 406 | 449 |

Figure 26: Breakdown of final energy use by energy carriers in various 2050 scenarios (PJ)

All scenarios recorded in Figure 26 also show that up to 2050 hydrogen becomes more important as an energy carrier (compared to current levels), although projections of hydrogen use vary from almost 180 PJ in Gasunie's 2050 scenario – i.e. about 14 of total final energy use – to more than 600 PJ in the *Molecules* scenario of Berenschot (44%).[18]

[17] To compare: over the last five years (2015-2019), electricity use in the Netherlands amounted to some 100-110 TWh (about 360-400 PJ), i.e. less than one-fifth of total final energy use, excluding industrial feedstocks (see Figure 24 and, for more details, PBL, 2019b).

[18] Current hydrogen use in the Netherlands amounts to about 110 PJ per annum, mainly as industrial feedstock. See Detz et al. (2019), which reviews a much broader set of scenario studies on the future role of hydrogen in the Netherlands, including hydrogen demand, supply, infrastructure and wider energy system functions of hydrogen.

Finally, Figure 26 illustrates that the use of green gases and heat (from carbon-neutral resources) becomes significant in most 2050 scenarios recorded, but also here the amounts concerned (in PJ) vary substantially across these scenarios.

### 6.3.2 *Electricity supply*

Table 17 shows the primary energy use of the power sector in the Netherlands as well as its GHG emissions in 2000, 2015 and 2030. The primary energy use of the electricity sector is defined as the sum of its energy use (of gas, coal, other fossil fuels, nuclear, renewables, etc., including own use and distribution losses) minus net power production to other (demand) sectors.

Table 17: Electricity: Primary energy use and greenhouse gas emissions

| **Primary energy use** | **2000** | **2015** | **2030** |
|---|---|---|---|
| ➢ Total primary energy use by electricity (PJ) | 331 | 375 | 120 |
| ➢ As % of total national primary energy use | 11% | 12% | 4% |
| **Greenhouse gas emissions** | **2000** | **2015** | **2030** |
| ➢ Total GHG emissions by electricity ($MtCO_2$-eq.) | 48.4 | 53.3 | 13.7 |
| ➢ As % of total national GHG emissions | 22% | 27% | 9% |

Note: Data for 1990, 2005 and 2015 are realizations while data for 2030 are projections based on the policy measures determined or intended before 1 May 2019 (i.e., excluding additional policy measures following the so-called 'Urgenda Verdict' and the Climate Agreement of mid-2019). Total national energy use includes (non-energetic) industrial feedstocks. Primary energy use of the electricity sector is defined as the sum of its energy use (of gas, coal, other fossil fuels, nuclear, renewables, etc., including own use and distribution losses) minus net power production to other (demand) sectors.

Source: PBL et al. (2019b).

As indicated by Table 17, total primary energy use of the Dutch power sector increased from 331 PJ in 2000 to 375 PJ in 2015. Over the years 2015-2030, however, this use is projected to decline substantially from 375 PJ in 2015 to 120 PJ in 2050, i.e. from 11% to 4% of total national primary energy use in these years, respectively. Note that, primary energy use of the electricity sector is defined as the sum of its energy use (of gas, coal, other fossil fuels, nuclear, renewables, etc., including own use and distribution losses) minus net power production to other sectors (PBL et al., 2019b). Hence, total primary energy use by electricity is referring to own electricity use, distribution losses and conversion losses of electricity production to other sectors. Since conversion losses of variable electricity sources (sun/wind) are zero, total primary energy use by electricity declines significantly as the share of variable electricity sources increases substantially.

In addition, Table 17 shows that the GHG emissions of the Dutch power system increase from 48 $MtCO_2$ in 2000 to more than 53 $MtCO_2$ in 2015, i.e. 22% and 27% of the total Dutch GHG emissions in these years, respectively. This increase is largely due to the increase in total power production in general and the increase in the share of coal-fired electricity generation in particular (notably during the latter part of this period, i.e. 2009-2015, in which some new, large-scale coal-fired power plant were installed). Over the years, 2015-2030, however, GHG emissions of the power system are projected to fall rapidly from more than 53 $MtCO_2$ in 2015 to less than 14 $MtCO_2$ in 2030, i.e. towards 9% of total Dutch GHG emissions in 2030. This steep fall in GHG emissions is due to the large penetration of sun and wind in the Dutch power system and the full phase-out of all coal-fired power plants by 2030.

*2050 scenario projections for the Dutch power system*
Figure 27 presents the mix of installed power generation capacity in various 2050 scenarios reviewed in the current chapter. It shows that in terms of installed capacity (GWe) variable energy sources – i.e. sun and (offshore) wind – play a dominant role in almost all scenario recorded. For offshore wind, however, the projected installed capacity varies from 5 GW in the '*Generic Steering*' scenario of CE Delft to 105 GW in KIVI's 2050 scenario. For sun PV, installed capacity ranges between 16 GW in the '*International*' scenario of CE Delft to 84 GW in its '*Regional Steering*' scenario.

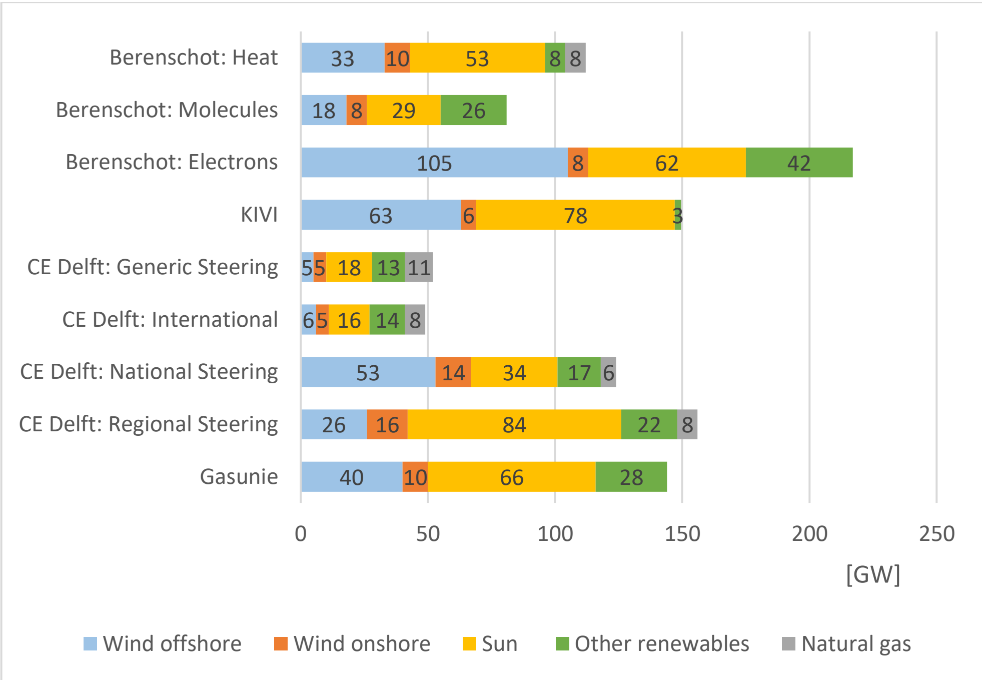



Figure 27: Mix of installed power generation capacity in various 2050 scenarios (GW)

On the other hand, in several 2050 scenarios other energy sources also play a significant role in terms of installed power generation, partly for back-up or flexibility reasons to address the intermittency of sun and wind. For instance, installed capacities of so-called 'other renewables' – including biomass (imports), hydrogen and/or green gases – vary from 13-22 GW in the four scenario visions of CE Delft to even 42 GW in the *Electrons* scenario of Berenschot. In addition, the installed capacity of natural gas (+CCS) is still significant in 2050 in the four scenarios of CE Delft (6-11 GW) as well as in the *Heat* scenario of Berenschot.

Figure 28 presents the mix of electricity *output* by energy source in various 2050 scenarios in energy terms (PJ), whereas Figure 29 provides a similar picture in percentage terms (%), i.e. as a share of total electricity output. Figure 28 is – to some extent – comparable to Figure 27, although for certain energy sources (e.g., sun PV) the number of full load hours is significantly lower than for other energy sources (e.g., wind). As a result, the share of sun PV in total electricity output is significantly lower than its share in total installed power generation capacity.

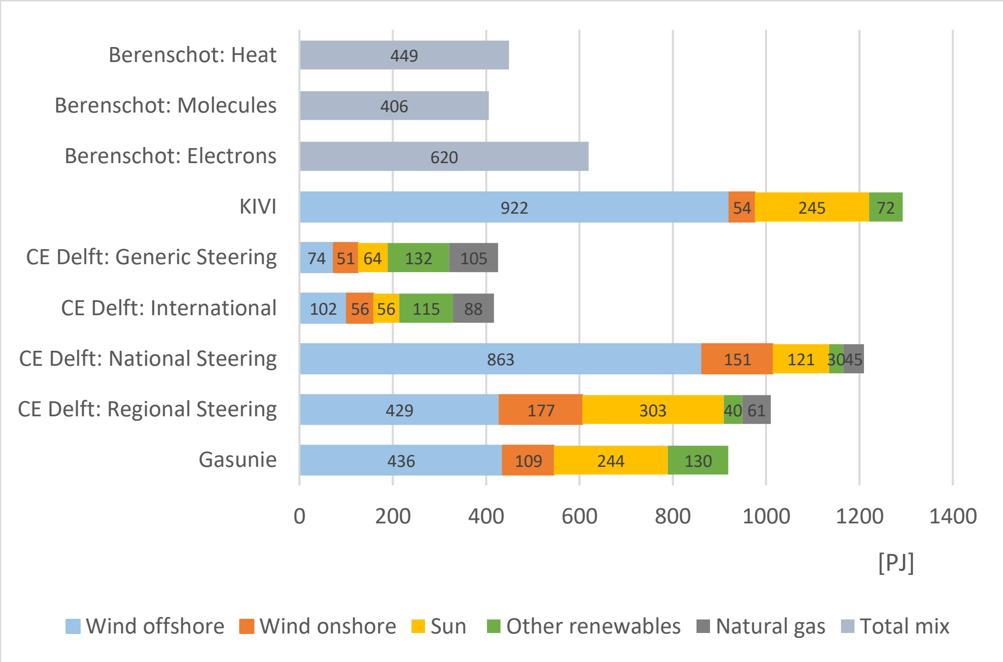



Figure 28: Mix of electricity output by energy source in various 2050 scenarios (PJ)

Note: Berenschot (2018a and 2018b) does not provide data on the mix of electricity output (only for total output as a whole).

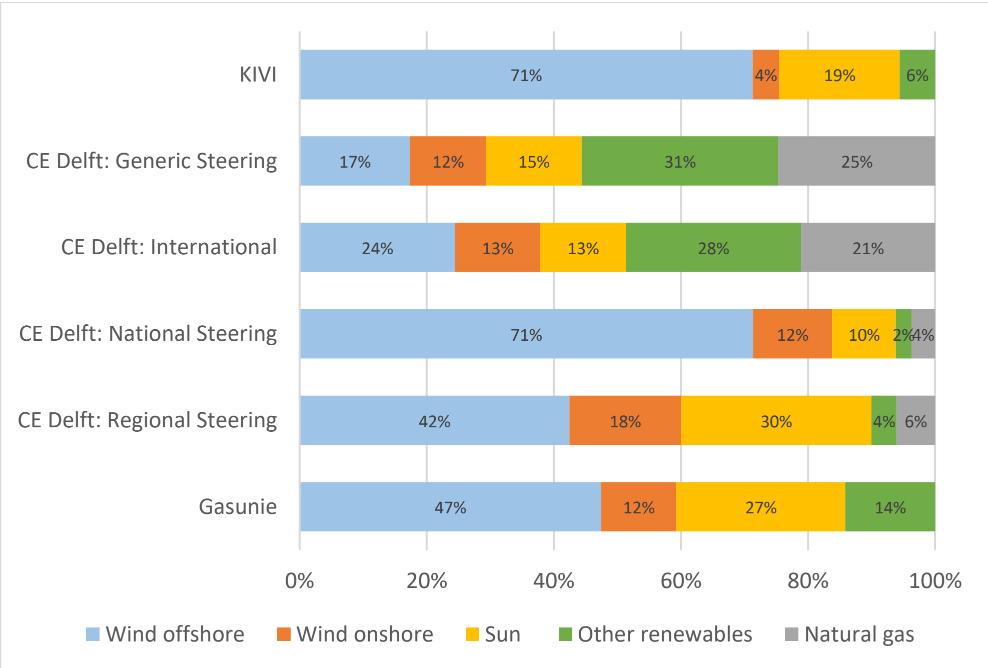



Figure 29: Mix of electricity output by energy source in various 2050 scenarios (%)

Note: Berenschot (2018a and 2018b) does not provide data on the mix of electricity output (only for total output as a whole).

Figure 28 shows first of all that the total electricity output in 2050 varies substantially across the reviewed scenarios, ranging from slightly more than 400 PJ (110 TWh) in the '*Molecules*' scenario of Berenschot and both the 'International' and '*Generic Steering*' scenario of CE Delft to more than 1200 PJ (330 TWh) in

KIVI's 2050 scenario and the '*National Steering*' scenario of CE Delft. In addition, it shows that the variation in electricity output from specific energy sources is often even more substantial. For instance, in 2050 electricity output by means of offshore wind ranges from 74 PJ (21 TWh) in the '*Generic Steering*' scenario of CE Delft to 863 PJ (240 TWh) in its '*National Steering*' scenario and even more than 920 PJ (256 TWh) in KIVI's 2050 scenario.

More specifically, Figure 29 shows that, as a percentage of total electricity output, the power generation mix in 2050 varies also significantly across the reviewed scenarios. While the share of offshore wind in 2050 is substantial in all scenarios recorded in Figure 29, it ranges from 17% in the '*Generic Steering*' scenario of CE Delft to 71% in both KIVI's 2050 scenario and the '*National Steering*' scenario of CE Delft. The share of total variable renewable energy sources – i.e. sun PV and both offshore and onshore wind – in total power generation varies from 44% to 94% in these scenarios, respectively.

In some scenarios, however, other renewable energy sources and/or natural gas (+CCS) play a significant role in generating electricity in 2050. For instance, the share of other renewable energy sources – including biomass (imports), green gases and/or hydrogen – amounts to 38% in the '*International*' scenario of CE Delft and even 31% in its '*Generic Steering*' scenario, while the share of natural gas amounts to 21 and 25% in these scenarios, respectively.

### *6.3.3 Heat supply*

Table 18 provides an overview of projections of heat supply from different (renewable) energy sources in some 2050 scenario studies. It shows that projections for geothermal heat supply in 2050 range from 115 PJ in Gasunie (2018) to 127 PJ in the heat scenario of Berenschot (2018b), while projections for residual heat supply vary from 95 PJ in Gasunie (2018) to 144 PJ in KIVI (2017). CE Delft (2017) does not provide separate figures for heat supply from geothermal and residual heat, but total heat supply from these sources varies from zero in the 'generic steering' scenario to approximately 80 PJ in the 'regional steering' scenario.

Table 18: Heat supply from different (renewable) energy sources in some 2050 scenario studies (PJ)

| | Gasunie (2018) | KIVI (2017) | Berenschot (2018b) |
|---|---|---|---|
| Geothermal energy | 115 | - | 127 |
| Residual heat | 95 | 144 | 100 |
| Solar thermal energy | - | - | 94 |
| Ambient heat | 245 | 129 | n.a. |
| Back-up boilers (biomass, hydrogen, green gas) | 15 | - | 49 |
| *Total heat supply* | *470* | *273* | *370* |

Note: n.a. = not available.

Gasunie (2018) and KIVI (2017) also provide projections for the extraction of ambient heat in 2050, i.e. 245 PJ and 129 PJ respectively (Table 18). According to Gasunie (2018), heat pumps in the built environment in 2050 will be extracting more than 190 PJ of sustainable ambient heat from indoor and outdoor air and from the earth for heating buildings (and will consume around 60 PJ of electricity for that purpose). Heat pumps are also being applied in the agricultural sector and industry, extracting a total of about 55 PJ of ambient heat (for which 18 PJ of electricity is necessary).

Projections on ambient heat are not available in Berenschot (2018b), although heat pumps are widely applied in its 2050 heat scenario. It is the only study reviewed in the current chapter, however, that includes solar thermal heat supply in its scenario, projected at 94 PJ in 2020.

In order to deal with situations of very high heat demand – 'extreme winter peaks' – or with incidences of system breakdown (notably of heat networks), some scenario studies also consider heat supply from so-called 'back-up' facilities. In Gasunie (2018), security of supply of heat provided by heat networks is guaranteed by means of auxiliary boilers running on green gas, providing some 15 PJ in 2050. In Berenschot (2018b), back-up boilers – running on biomass, hydrogen or green gas – are projected to provide even about 49 PJ of heat supply in 2050 (Table 18).[19]

*Residual heat supply*
Table 19 provides some more detail on projections of residual heat supply in some 2050 scenario studies. As already mentioned above, projections on total residual heat supply vary from 95 PJ in Gasunie (2018) to 144 PJ in KIVI (2017).[20] Table 19 shows that this supply comes from differences sources – notably industrial processes, data centres, waste incineration, electrolysers and power stations – while, on the other hand, residual heat is (re-) used by local industries, the built environment and horticulture.

Table 19: Residual heat supply in some 2050 scenario studies

| Source | Residual heat supply in 2050 |
|---|---|
| Gasunie (2018) | 95 PJ residual heat supply from industrial processes. 53 PJ of this supply is re-used by local industry, while the other 42 PJ is fed into heat networks and used by the built environment. |
| KIVI (2017) | 144 PJ of residual heat can be obtained from industry, electrolysers and fuel cell power stations. Through heat networks this residual heat supply is used to meet low temperature heat demand (in industry, horticulture and the built environment). |
| Berenschot (2018b) | 100 PJ of residual heat (from industries and data centres) of which 50 PJ is used by local industries, 35 PJ by the built environment and 15 PJ by horticulture. |

*Heat supply via heat networks*
Finally, Table 20 presents projections on different energy sources of heat supply via (district) heat networks in some 2050 scenario studies. Total heat supply via these networks varies from 92 PJ in Gasunie (2018) to 144 in KIVI (2017) and even 289

[19] Another option to deal with peaks in heat demand is heat storage but this option is hardly or not explored in the scenario studies reviewed in the current chapter.

[20] As noted, CE Delft (2017) does not provide specific data on residual heat supply in its four 2050 scenarios. It only states that the technical potential of residual heat from industry, waste incineration and energy stations is estimated at 57 PJ, but it does not mention any reference year for this estimate while the source of this estimate is relatively old, i.e. dating from 2011.

PJ in the heat scenario of Berenschot (2018b.). In Gasunie (2018), this total heat network supply comes mainly from geothermal energy (58 PJ) and residual heat (127 PJ), while in Berenschot (2018b) these sources provide 127 PJ and 100 PJ, respectively. In KIVI (2017), however, total heat network supply is assumed to derive from just one source, i.e. residual heat from industry, electrolysers and fuel cell power plants (see also Chapter 7 on energy infrastructure, notably Section 7.3.3 on heat networks).

Table 20: Energy sources of heat supply via heat networks in some 2050 scenario studies (PJ)

| | Gasunie (2018) | KIVI (2017) | Berenschot (2018b) |
|---|---|---|---|
| Geothermal | 58 | - | 127 |
| Residual | 42 | 144 | 100 |
| Back-up boilers (biomass, hydrogen, green gas) | 15 | - | 41 |
| Losses | -23 | - | - |
| Total | 92 | 144 | 268 |

### 6.3.4 *Hydrogen supply*

Figure 30 presents a summary overview of hydrogen supply by end-users' energy functions ('applications') as recorded in the scenarios reviewed in the current chapter.[21] In these studies, total domestic demand/supply of hydrogen in 2050 varies from approximately 165 PJ in the '*Generic Steering*' scenario of CE Delft to almost 600 PJ in the *Heat* scenario of Berenschot.

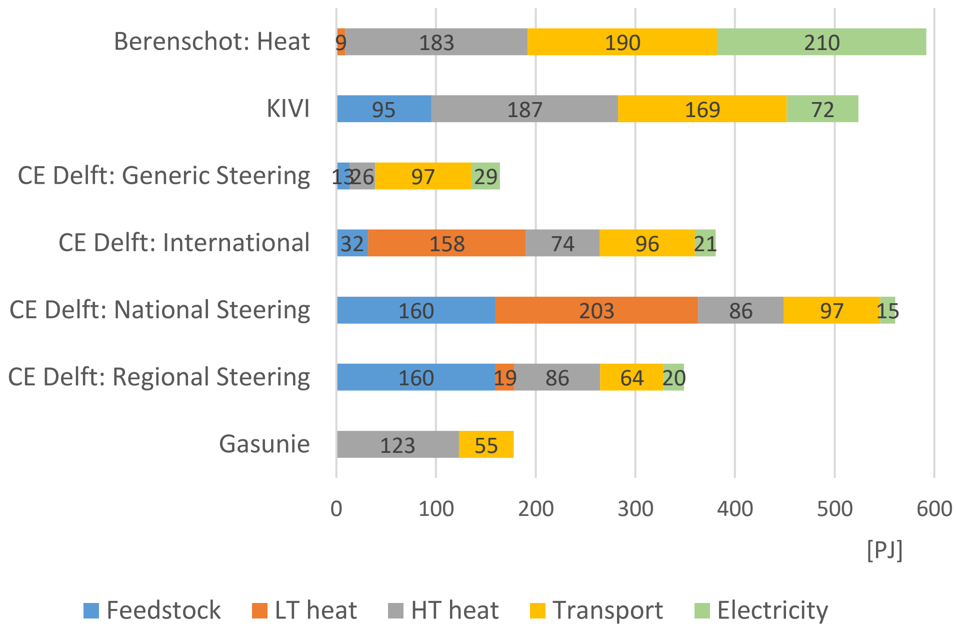



Figure 30: Hydrogen demand by end-users' energy functions in various 2050 scenarios (PJ)

[21] For another recent, more detailed (meta-)analysis of the future role of hydrogen in the Netherlands, based on a review of a much broader set of scenario studies on this specific role (including hydrogen demand, supply, infrastructure and wider energy system functions), see Detz et al. (2019).

In addition, the scenarios reviewed show a variety of outcomes in terms of both the number of hydrogen applications (end-users' energy functions) and the volume (size) of these applications. For instance, the number of hydrogen applications is restricted to only two energy functions in the 2050 scenario of Gasunie, i.e. low-temperature (LT) heat and high-temperature (HT) heat, while three out of four 2050 scenarios of CE Delft cover five hydrogen applications, i.e. including also (industrial) feedstock, transport and electricity generation besides LT and HT heat (Figure 30).

In terms of hydrogen volumes per energy function, there is also a wide variety of outcomes across the scenarios recorded in Figure 30. For instance, while Gasunie and KIVI do not include any hydrogen use for LT heat in their 2050 scenarios, it varies in the other scenarios from 19 PJ in the '*Regional Steering*' scenario of CE Delft to 203 PJ in its '*National Steering'* scenario. Similarly, while Gasunie also does not include any hydrogen use for power generation in its 2050 scenario, it ranges in the other scenarios from 20 PJ (6 TWh) in the '*Regional Steering*' scenario of CE Delft to 210 PJ (58 TWh) in the *Heat* scenario of Berenschot.[22]

## 6.4 Summary of main findings

The sections below summarize the main findings of the current chapter, notably in terms of the main similarities and differences regarding the energy supply scenarios reviewed above.

### *6.4.1 Main similarities*

The main similarities ('robust elements') observed across the energy supply scenarios reviewed in the sections above include:

- In all scenarios, the role of fossil fuels decreases to (nearly) zero in 2050, while the share of renewables increases up to 100%. Only in a few scenarios – notably in the Heat scenario of Berenschot – there is still a minor role in 2050 for fossil fuels, in particular natural gas (+CCS).
- In all scenarios, the share of electricity in total final energy use increases significantly up to 2050 (although the specific size of this share and rate of additional electrification up to 2050 varies widely across the scenarios reviewed).
- In all scenarios, the share of variable renewable energy sources in power generation – notably of offshore wind and onshore sun PV – increases substantially up to 2050 (although, once again, the specific size of this share in 2050 varies widely across the scenarios considered).
- In all scenarios, the role of (renewable) hydrogen in the Dutch energy system increases significantly (although, once again, the specific size of this share in 2050 varies widely across the scenarios considered);
- In all scenarios, neither coal nor nuclear plays any role in power generation in the Netherlands by 2050, partly because these technologies are not competitive under the (assumed) scenario conditions or because new investments in these technologies are considered (assumed) to be not socio-politically acceptable by 2050;

[22] In electricity production, hydrogen – for instance, produced and stored during periods of power surpluses from sun and wind – is mainly used as a back-up facility for balancing the electricity system during periods of power shortages.

- Across the energy supply scenario studies reviewed in this chapter, there is a high consensus (‘robustness’) on the (renewable) energy sources of heat supply in 2050. These sources include in particular geothermal energy, residual heat, solar thermal energy, ambient heat and – to address (very) high winter peaks of heat demand or system (heat network) breakdowns – heat boilers running on biomass, hydrogen or green gas. Across these studies, however, there is also a high diversity (‘uncertainty’) regarding the technical potentials or projected volumes of these heat supply sources in 2050 as well as the projected volumes or shares of heat supplied through (district) heat networks in total heat supply;
- In all scenarios, emergent technologies that are still nearly or fully absent – or not included – in the reviewed scenario studies are deep geothermal electricity generation and ocean power (tidal, wave, osmosis), partly because of ignorance or unfamiliarity with these technologies or because they are (assumed to be) less important for the Netherlands up to 2050.

### *6.4.2 Main differences*

The main differences (‘uncertain elements’) observed across the energy supply scenarios reviewed in the sections above include:

- In general, as already indicated above, there is a wide variety of scenario outcomes in terms of total energy supply and the mix of (renewable) energy supply technologies by 2050. These differences in outcomes are mainly due to underlying scenario uncertainties and resulting differences in assumptions made regarding the key determining factors of energy supply such as the domestic availability (including imports), the socio-political acceptability and the relative cost developments of compering energy sources and technologies.
- More specifically, observed values for total primary energy use in 2050 range from approximately 1400 PJ to 2200 PJ across the various scenarios reviewed, while energy conversion losses – i.e. when moving from primary to final energy use – vary between 10 and 40%. These differences in energy use are due to differences in (the definition and calculation of) the primary/final energy mix and differences in assumptions with regard to future developments in sectoral energy demand (including energy savings).
- Although offshore wind becomes a dominant power generation technology in most of the scenarios reviewed, overall installed capacity figures for offshore wind vary widely between 5 and 105 GWe across all scenarios considered.
- Some scenarios foresee a major role for renewable energy technologies such as solid biomass, deep geothermal heat or solar thermal heat, while in other scenarios these technologies play hardly or no role at all by 2050.
- Although almost all scenarios foresee a growing, significant role of hydrogen by 2050, observed values regarding this role vary widely across the scenarios reviewed. Moreover, while some scenarios foresee a significant role of hydrogen in a wide variety of end-users’ applications (including power generation by utilities and low-temperature heat production in the built environment), other scenarios show that its role focuses only on a limited set of energy functions (notably for providing high-temperature heat and transport services).

# 7 Energy infrastructure

## 7.1 Introduction

The transition to a climate-neutral energy system has a significant impact on the energy infrastructure, notably on electricity, gas, and heat networks. Both the size and type of investments as well as the operation of energy networks are likely to be affected. The extent to which the different energy grids will be influenced depends on a variety of technological, economic and social factors regarding the development of the energy system, including:

- Types and learning rates of emerging new technologies;
- Development of fuel and $CO_2$ prices;
- Public rejection of certain type of resources (nuclear, biomass, shale gas, CCS) and energy networks;
- Policies concerning market design and network regulation.

These (uncertain) factors are often analyzed by means of (modelling) scenarios. In this chapter, we will review some recent scenario studies on the implication of the energy transition for the energy infrastructure in the Netherlands in order to identify both robust and uncertain elements of these studies. First, Section 7.2 briefly lists and differentiates the studies reviewed according to the type of network considered (electricity, gas, heat, integrated energy infrastructure). Subsequently, Section 7.3 discusses the major findings of these studies. Finally, Section 7.4 provides a summary of the main findings and conclusions of the current chapter.

## 7.2 Studies reviewed

Regarding the electricity grid, the following studies have been reviewed:

- CE Delft (2017), *Net voor de Toekomst – Achtergrondrapport* (Grid for the Future – Background report);
- ECN and Alliander (2017), *Demand and supply of flexibility in the power system of the Netherlands, 2015-2050 – Summary report of the FLEXNET project*;
- Stedin (2016), *Energie-infrastructuur van de toekomst (E) – Flexibiliteit en timing succesfactoren energietransitie* (Energy infrastructure for the future (E) – Flexibility and timing success factors of the energy transition).

Concerning the gas grid, this chapter reviews the following studies:

- CE Delft (2017), *Net voor de Toekomst – Achtergrondrapport* (Grid for the Future – Background report);
- DNV GL (2017), *Verkenning waterstofinfrastructuur* (Outlook hydrogen infrastructure)
- OTE (2018), *Belemmeringen in nettarieven* (Obstructions in network tariffs);
- KIWA (2018), *Toekomstbestendige gasdistributienetten* (Future-proof gas distribution networks);
- ACM (2019), *MOet Regulering Gasnetten ANders (MORGAN*; Should regulation of gas networks be different).

For heat networks, only one study has been reviewed:

- PBL (2017b), *Toekomstbeeld klimaatneutrale warmtenetten in Nederland* (Future image of climate-neutral heat networks in the Netherlands).

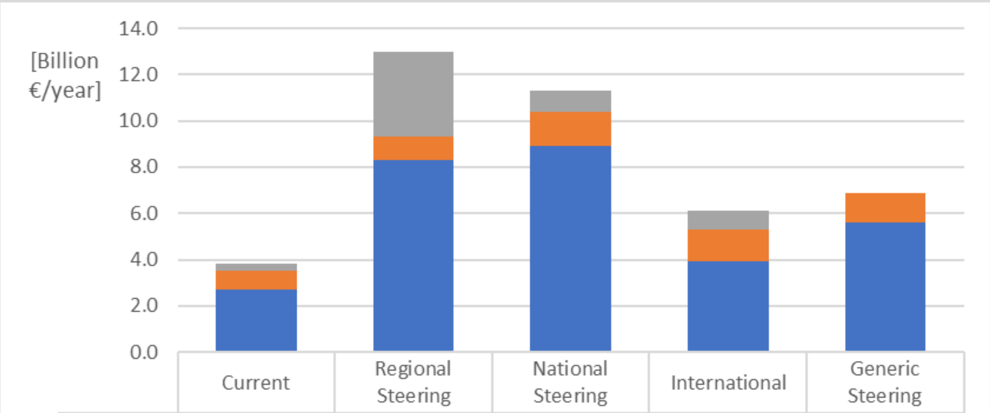
Finally, one recently released, integrated electricity and gas infrastructure study has been reviewed:
- Gasunie and TenneT (2019), Infrastructure Outlook 2050.

The major findings of the studies mentioned above are discussed in the sections below.

## 7.3 Major findings of studies reviewed

### *7.3.1 Electricity infrastructure*

*CE Delft (2017), Net voor de Toekomst*
As outlined in the previous chapter (Section 6.2), CE Delft – on behalf of Netbeheer Nederland – has defined and analyzed four scenarios on the future, carbon-free energy system as part of the study 'Net voor de Toekomst' ('Grid for the Future', see Netbeheer Nederland, 2017; and CE Delft, 2017). These scenarios result in different energy infrastructures and associated costs. Yearly costs for electricity, gas and heat infrastructures will increase by 50-300% compared to current amounts (see Figure 31). Especially the regional and national steering scenarios – with regional and national self-sufficiency, respectively – show strong increases of infrastructure costs. In the other two scenarios – international and generic steering – energy import is quite significant.

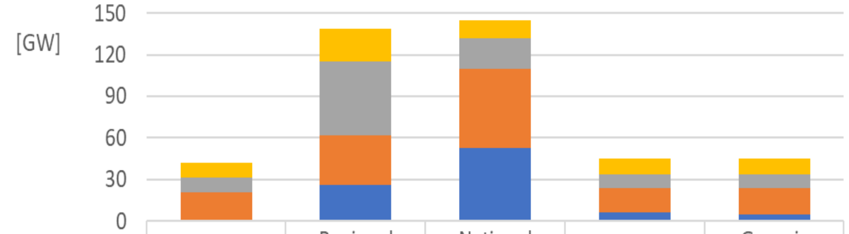



| | Current | Regional Steering | National Steering | International | Generic Steering |
|---|---|---|---|---|---|
| Heat | 0.3 | 3.7 | 0.9 | 0.8 | 0.0 |
| Gas | 0.8 | 1.0 | 1.5 | 1.4 | 1.3 |
| Electricity | 2.7 | 8.3 | 8.9 | 3.9 | 5.6 |

Figure 31: Infrastructure costs for the current situation and four 2050 scenarios (billion €/year)

Source: CE Delft (2017).

Electricity becomes more important in the energy system (see previous chapter, notably Section 6.3.2). This is reflected in the network capacity installed in the different scenarios (Figure 32). Highest network capacities are required in the scenarios regional and national steering. In the regional steering scenario, electricity from distributed generation fed in at distribution grids will be transported to the industry through the transmission grid.




| | Current | Regional Steering | National Steering | International | Generic Steering |
|---|---|---|---|---|---|
| Low voltage | 11 | 24 | 13 | 11 | 11 |
| Medium voltage | 10 | 53 | 22 | 10 | 10 |
| High voltage | 20 | 36 | 57 | 18 | 19 |
| Offshore wind connections | 1 | 26 | 53 | 6 | 5 |

Figure 32: Electric network capacity in the current situation and four 2050 scenarios (GW)

Source: CE Delft (2017).

*ECN and Alliander (2017), Demand and supply of flexibility in the power system of the Netherlands, 2015-2050*
Within the context of the FLEXNET project (2015-2017), ECN and the Dutch network operators have conducted a study on the supply and demand of flexibility of the Dutch power system over the period 2015-2050.[23] More specifically, as part of this project, Alliander – i.e. the largest DSO of the Netherlands – has analyzed the impact of the energy transition on its electricity distribution grid and the role of flexibility options to deal with congestion of this grid (and, hence, to save costs by reducing necessary reinforcements of the grid).

Starting point for the FLEXNET analysis are two nationwide scenarios, i.e. (i) *a reference scenario*, denoted with the letter R, which is based upon determined national policies as assumed in the National Energy Outlook 2015, and (ii) *an alternative scenario*, denoted with the letter A, which assumes 85% GHG emission reduction by 2050. The reference scenario is characterized by a strong growth of installed variable renewable energy (VRE) generation capacity until 2030 and a weak growth of additional electrification. The time span of this scenario is limited to 2030. The alternative scenario is equal to the reference scenario, except for the strong growth of additional electrification, and covers the time period until 2050.

Based on the assumptions of the two scenarios – notably with regard to the penetration of electric vehicles (EVs), heat pumps (HPs) and VRE technologies (wind and solar PV), the major findings of Alliander's part of the FLEXNET project include:

1. *The expected percentage of overloaded assets as a result of the adoption of EVs, HPs, and sun PV seems limited until 2030 relative to the conclusions of previous studies*

The ANDES modelling analysis of the implications of the FLEXNET scenario cases for the load profiles of the Liander distribution grid indicates that the incidence of

[23] For details on the FLEXNET project, including all its deliverables, see https://www.ecn.nl/flexnet/. For a summary of the main findings of this project, see ECN and Alliander (2017).

overloaded assets due to the increasing adoption of PV, EVs and HPs is limited, at least until 2030 (<10%). In the alternative scenario for 2030 (A2030), about 8% (±3000) of the distribution transformers and 9% (about 40) of the substation transformers will be overloaded. The percentage of overloaded cables is even lower at 2-3% (±1500 km of LV cables and ±700 km of MV cables). As a conclusion it can be said that most assets of the grid, especially cables, will have sufficient capacity to facilitate the increased loads for at least the next 15 years.

Despite a limited total number of overloaded assets, the regional distribution grids face great challenges in the form of large numbers of new connections for EV charging points, local congestion due to local concentrations of EV, PV and/or HP, a large increase of connections for medium size solar and wind farms, and the phase out of gas in the built environment that creates the need and natural moment to adapt the electricity grid.

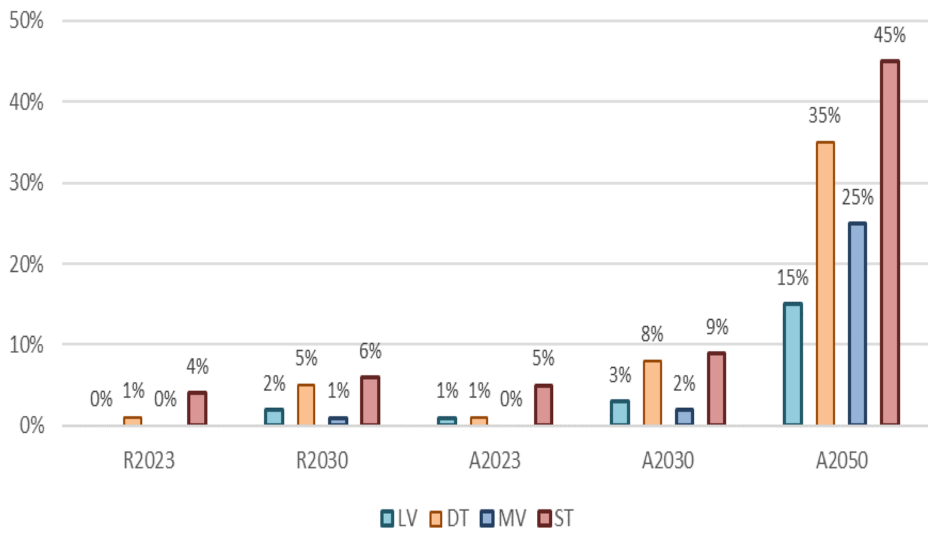



Figure 33: Percentage of overloaded assets per scenario case at different levels of the distribution grid

Note: LV = Low voltage cable; DT = Distribution transformer; MV = Medium voltage cable; ST = Substation transformer; R = Reference scenario; A = Alternative scenario

Source: ECN and Alliander (2017).

2. *Beyond 2030, the incidence of grid overloads is more significant, but most likely not alarming with the right investment strategy*

According to the result of the ANDES model, 35% of the distribution transformers and 45% of the substation transformers are expected to be overloaded in the A2050 scenario case. Although these overload percentages are significant, they are not per se alarming. Due to asset ageing, many of the assets indicated as overloaded in 2050 will most likely have been replaced with larger capacity assets before becoming overloaded. The additional costs of installing assets with larger capacities are marginal, as most of the costs are caused by the required work, not the material. The model therefore assumes the investment strategy considers future load increases. Moreover, several ‘smart solutions’ are expected to become available within this time span.

3. *In the long run, most overloads are expected to arise in city centers*

Geographically, most overloads are expected to arise in city centers, because of relatively old networks. The fact that the adoption of PV, EV and HP is lower in the city centers is offset by the density of the urban population, resulting in a larger increase of power load in urban areas than in non-urban areas.

4. *Apparent need for trade-off between grid reinforcement and deployment of flexibility*

From both a socioeconomic and a (regional) grid load perspective, there appears to be a clear need for weighing network reinforcements versus deployment of flexibility options, notably in the period beyond 2030 (when the incidence of grid overloads increases significantly). This trade-off, however, is also important in the coming years to use the efficiency potential of flexibility solutions and to deal with less predictable grid load increases where flexibility can be a good temporarily solution till grid reinforcement is carried out.

5. *The net benefits of deploying large-scale flexibility options purely for congestion management in the Liander area are, in general, limited*

In order to prevent overloads (congestion) in the Liander grid due to the increased deployment of sun PV, EVs and HPs, *additional* investments in grid reinforcements are required of 2 to 5% per year up to 2030 and about 7% per year in the period from 2030 to 2050. Given current annual grid investments in the Liander service area of, on average, € 750 million in 2012-2016, this corresponds to a cumulative grid reinforcement investment of € 1.0-1.5 billion up to 2050 in the alternative scenario. The lower value of the bandwidth results from the fact that network assets that become overloaded after they reached the life expectancy of 60-90 years could be regarded as non-energy transition investments.

In terms of capital investment savings (CAPEX), it is estimated that a mix of flexibility-based measures to mitigate grid overloads – notably deploying PV curtailment and demand response pricing mechanisms – can save up to about € 700 million (cumulative) in energy transition related grid investments up to 2050. This amount of € 700 million is an indication of the value of flexibility for network investment planning by Liander.

The amount of € 700 million mentioned above, however, does not yet include additional costs required to implement and operate the flexibility-based measures to mitigate grid overloads, such as lost PV revenues, additional grid losses, additional smart metering costs, higher risks, etc. Hence, the net benefits of deploying flexibility as an alternative for grid reinforcements are significantly lower. It should be noted though that the results have been calculated based on the current (2017) perspective on the future. Moreover, flexibility could have a higher value for purposes such as portfolio and investment planning optimization or system balancing.

In specific situations (e.g., locally and/or temporarily), the deployment of flexibility measures to prevent or mitigate grid overloads – and, hence, to avoid or reduce investment costs in grid reinforcements – may offer a significant potential and relatively high value for DSOs, resulting in a concomitant high value of flexibility and associated benefits for flexibility providers. Other applications and opportunities besides congestion management which could be a reason for a DSO to deploy flexibility options include, among others, local voltage support, system balancing, synergies groundwork with other infrastructural companies, black-out recovery. Moreover, a rough comparison of the Liander modelling results with modelling outcomes of DSO Stedin indicates more overloads in the Stedin service area and, therefore, a higher demand for flexibility in this area and, perhaps, higher values (net benefits) of deploying flexibility as an alternative for grid reinforcements.

6. *Energy storage: benefits of using battery systems purely for congestion management do not outweigh costs*

For energy storage at the regional grid level, the benefits of the use of a battery system for mitigating overloads do not outweigh the costs. Relatively large battery capacities are required to mitigate overloads of distribution transformers (DTs). Given (i) the accompanying cost of a battery system, (ii) the required operational expenditures (OPEX), (iii) the additional energy losses, and (iv) the added complexity and, therefore, the higher operational risks, it is safe to assume that the use of a battery system at the distribution transformer (DT) level in comparison to DT reinforcement purely for the purpose of mitigating an overload is only economically feasible for a very limited number of cases at most. The use of a battery system might be more profitable in case the same system could provide other services such as for instance voltage support, energy trading, frequency support, or resilience/back up power.

*Stedin (2016), Energie-infrastructuur van de toekomst (E) – Flexibiliteit en timing succesfactoren energietransitie*

Stedin is the second largest DSO in the Netherlands. The presentation by Stedin (2016) provides forecasts of costs and benefits of Stedin's infrastructure until 2050 for three scenario's and for two network investment strategies. The three scenarios (*Paces*, *Tides* and *Circles*) are characterized by different penetrations of especially solar PV, heat pumps, and electric vehicles (as well as of onshore wind and storage). Given a recession and high energy prices, *Paces* is characterized by a limited increase of solar PV, HPs and EVs, and considerable energy savings in the built environment. Instead *Circles* shows an abundant availability of renewable energy, a breakthrough of EVs, and replacement of gas boilers by electric HPs. The *Tides* scenario is in between the scenarios *Paces* and *Circles*.

Two investment strategies are distinguished, i.e. (i) regular network expansion and automation of distribution stations ('*without control*'), and (ii) more ICT, demand response by time-of-use pricing or critical peak pricing, investments in storage behind the meter, and network expansion if necessary ('*with control*').

Overloads in 2030 and 2050 are calculated with a simple, dedicated profile model (MKBINS) to calculate the network load on three voltage levels for the three different scenarios. The model is based upon capacity and load of transformers and substations, cables are not considered. Cost figures are general and not project-specific. Every scenario has four representative model districts: rural, ground-floor urban, urban, and city center. Each model district is coupled to postzip-4 areas of Stedin in order to enable coupling with Stedin network assets.

Overloads are determined for five-year periods until 2050. Table 21 shows the expected overloads of Stedin's distribution stations in the three 2050 scenarios compared to the current (2016) overloads.

Table 21: Expected overloads of Stedin's distribution stations in three 2050 scenarios

| Voltage level | Current % overloaded | Overloaded stations in 2050 scenarios (%) | | |
|---|---|---|---|---|
| | | Paces | Tides | Circles |
| HS/MS | 5 | 29 | 63 | 92 |
| TS/MS | 2 | 46 | 70 | 93 |
| MS/LS | 1 | 25 | 57 | 91 |

Source: Stedin (2016).

Active network management can substantially reduce overloads. The lower overloads in case of active network management with deployment of flexibility measures translates into a lower need for grid expansion investments. When flexibility measures such as storage and demand response are deployed this results in considerable reduction of network investments to 11 billion euro in 2050 compared to 15 billion euro of grid expansion investments when grid overloads are mitigated by network expansion investments only.[24] This means a cost saving of about 30%.

Moreover, the deployment of steering implies that bottlenecks occur later in time. In some cases, steering allows for postponement of network expansion investments for about five years. In light of the uncertainties about future developments of generation and load this indicates a significant option value for network operators.

However, once the cost of deployment of both demand response and storage for network management purposes are considered, it proves that deploying both flexibility measures is not profitable enough to reduce network costs for the network operator. But in case the investment strategy concerns only the deployment of demand response, required cashflows for Stedin are often lower compared to the case without control. It should be noted though that the cost of providing price incentives to loads may bring along additional costs for the network operator.

Some (additional) conclusions that can be drawn (Stedin, 2016)

- The development of energy demand and supply in the three different scenarios leads to strongly diverging (over)loading of the electricity grid:
  - Up to 93% overloading in the different voltage levels, i.e. more than 11 times the allowed capacity in the Circles scenario. The overloading is similar for the four model districts: rural, ground-floor urban, urban, and city center though.
  - The overloading differs per location in time and size, given the current available grid capacity and the different implications of the scenarios for different locations given technical and social-economic factors.
- Demand response and storage can lead to a lower increase of the peak, which decreases the total required grid capacity by 2050 and allows to postpone network capacity expansion.
- In the most sustainable scenario with large scale application of solar-PV and storage, transport from higher voltage levels to low voltage remains necessary in order to feed electric heating in winter periods.

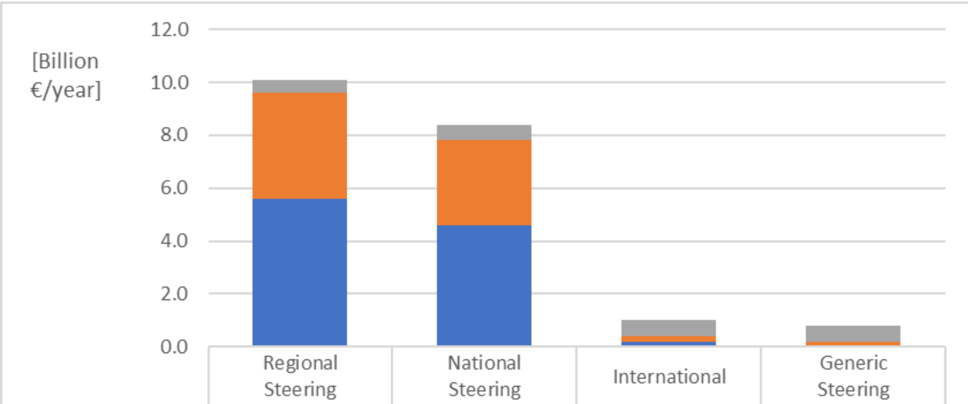
[24] Note that the investment cost data of Stedin concern total investment costs, i.e. both 'normal' or 'conventional' investment costs – including 'normal' or 'conventional' grid replacements and reinforcements – as well as 'additional' investment costs, i.e. additional due to the energy transition, while the investment cost data of Alliander mentioned before refer to the additional investment costs only.

- Without measures, 200-400M euro of yearly additional network investments is needed from 2020 to 2050 in the Circles scenario.
- Up to 30% of grid investments can be saved in the Circles scenario from 2020 to 2050, while network expansion investments can be postponed for a number of years.
- Benefits of storage and demand response accrue not only to DSOs, but also to the TSO, customers and producers. These benefits can improve the overall business case of investments by grid operators in flexibility.

### 7.3.2 *Gas infrastructure*

*CE Delft (2017), Net voor de Toekomst*
In addition to analyzing the implications of the energy transition for the electricity grid (see previous section), CE Delft has also considered these implications for the gas network. Despite the phasing out of natural gas towards 2050, gas networks – both transmission and distribution infrastructures – remain necessary for the transport of climate-sustainable gases, such as hydrogen or bio-methane, in order to fulfill the heat demand by industry and the built environment.

Moreover, as shown by Figure 34, the regional and national steering scenarios developed by CE Delft do also require substantial capacities of electrolysis for the conversion of excess electricity in gas (P2G) and subsequently seasonal storage of hydrogen (or green gas in the international and generic steering scenarios). According to CE Delft (2017), hydrogen is considered indispensable in the future energy system for transport, fulfilling the heat demand, as well as feedstock for the chemical industry.




| | Regional Steering | National Steering | International | Generic Steering |
|---|---|---|---|---|
| H2 gas buffers | 0.5 | 0.6 | 0.6 | 0.6 |
| Battery storage | 4.0 | 3.2 | 0.2 | 0.2 |
| H2 electrolysis | 5.6 | 4.6 | 0.2 | 0.0 |

Figure 34: Cost of energy storage and conversion systems in four 2050 scenarios (billion €/year)

*DNV GL (2017), Verkenning waterstofinfrastructuur*
This study, commissioned by the Ministry of Economic Affairs and Climate Policy, focused on the required measures to make (parts of) the existing gas transport grid suitable for the transport of hydrogen. It requires that compressor stations and measurement systems are adjusted to the different gas composition. Furthermore, existing gas pipelines that are no longer used for transport of Groningen gas (or high caloric gas as networks can often be used for both) need to be isolated from

the existing natural gas networks for Groningen gas. Given the timing of the expected stop of Groningen gas consumption in Germany, Belgium and France, gas pipelines to Germany could become available first for hydrogen transport. The study does not provide any (investment) cost figures.

*KIWA (2018), Toekomstbestendige gasdistributienetten*
This study, assigned by the joint grid operators, aimed to answer three questions:
- To which extent can the current gas distribution grid withstand sustainable gasses, i.e. hydrogen and biomethane?
- Which adjustments are necessary to make existing gas distribution grids suitable for sustainable gases?
- Which costs are involved with a gas switch in the built environment?

The first question is a technical question and focusses on the materials of distribution grids. It was answered positively for hydrogen as well as for biomethane, although for the latter some maximum values for gas components should remain in order to prevent degradation of metallic parts of the gas grid and the applied polyoxymethylene (POM) material.

For hydrogen it is necessary to replace the gas meter and to renew the procedure for settlement of the delivered amount of energy due to the lower energy density of hydrogen, which implies that higher amounts of gas need to be transported at peak times than can be measured by the current gas meters. For biomethane, additional costs have to be made for dealing with the varying caloric value. An important recurrent cost item is tightening control on digging activities given the potential higher risks of hydrogen transport compared to natural gas transport.

Based upon the four scenarios that are deployed by CE Delft (2017), costs involved amount up to € 700 million, which translates into 10-50% higher grid costs per dwelling per year. One-off costs for hydrogen and biomethane are highest in the international and national steering scenarios (€ 718M and € 608M respectively), while recurrent costs are highest in the generic steering, international, and national steering scenarios (€ 711M, €607M, and € 554M, respectively). It should be noted that the costs depend very much on the assumptions regarding the energy carriers for low temperature heat, i.e. hydrogen in case of the international and national steering scenarios, and biomethane for the generic steering scenario. The study’s best guess is that the additional O&M costs are about 5% of the current O&M costs of gas grids. The cost for adjusting devices of end users, such as cooking stoves and heating equipment, are deemed much higher though.

In addition, it should be noted that both the extent to which the current (fossil) gas network is suitable for transporting climate-sustainable gases, the required measures and adjustments involved, as well as the associated costs depend on a variety of technical factors. In particular, these factors include (i) the steel strength and composition of the gas pipelines, (ii) the current condition of these pipelines (e.g., do they already have initiation defects or corrosion spots), (iii) the possibilities to prevent the diffusion of the hydrogen molecules to the metal via oxide layer or coating, and (iv) the incidence of accelerated fatigue of current gas pipelines due to the transport of hydrogen (and possible measures to prevent or reduce this accelerated fatigue).

As a result, the factors mentioned above are also relevant to (and qualify) recent analyses and discussions on the relative infrastructure costs of transporting (green) hydrogen versus electricity and, hence, the best geographical location of P2G electrolysers (see also the review of the recent Infrastructure Outlook 2050 by Gasunie and TenneT below). Since there is some uncertainty and controversy on these (technical) factors and the associated costs of transporting green hydrogen versus electricity, additional research on this topic seems desirable and legitimate.[25]

*OTE (2018), Belemmeringen in nettarieven*
Amongst the regulatory barriers identified for the (near) future, is the increase of the natural gas transport tariffs when the use of natural gas is phased out. This tariff increase for those who stay behind occurs for two reasons. First, the gas infrastructure costs will not proportionally decrease with the lower number of gas network connections. Second, given the network costs are depreciated over time periods up to 50 years, part of the costs cannot be recovered from those who caused these costs as they left the system.

The joint network operators have made an estimation of the effects given current regulation. They estimate that in 2050 a regulated asset base of DSOs of about 5 billion euro is not yet recovered by the gas transport tariffs. This figure does not include the additional O&M costs as well as the gas grid removal costs.

In order to avoid rising network tariffs in case of phasing out natural gas, OTE (2018) assesses five alternative solutions to recover the residual gas network costs:
- Gas grid phasing out contribution;
- Complete socialization of network costs;
- Degressive depreciation of capital investment costs (rather than the current linear depreciation)
- Fund (financed by taxes to cover the residual gas network costs);
- Stakeholder pays (residual gas network costs are paid by the stakeholders of the network operator, i.e. they receive less dividends).

The alternative solutions are assessed qualitatively on the merits regarding costs, feasibility and robustness, summarized roughly in Table 12. Solution 2 (complete socialization of network costs) falls off because of inconsistency with existing EU legislation. With regard to the other four solutions, the member of the OTE (2018) workgroup have different thoughts and preferences, and do not come to the choice or recommendation of a single preferred solution or mix of solutions.

Table 22: Assessment of alternative solutions to address residual gas network costs

| Solution | Costs | Feasibility | Robustness |
|---|---|---|---|
| Gas grid phasing out contribution | + | + | - |
| Complete socialization | - | - | 0 |
| Degressive depreciation | 0 | + | 0 |
| Fund | - | 0 | + |
| Stakeholders pays | - | 0 | 0 |

Source: OTE (2018).

[25] In addition to DNV GL (2018) and KIWA (2018) – addressing this topic for the Netherlands – , see also the journal paper by Saadi et al. (2018) – focussing on the UK – as well as recent e-mail discussions by Maarten Meijburg (eRiskGroup) and Néstor Gonzalez Diez (TNO).

*ACM (2019), MOet Regulering Gasnetten ANders (MORGAN)*
In 2018, the Dutch market regulator ACM launched the project '*MO*et *R*egulering *G*asnetten *AN*ders' (MORGAN). The cause for this project was the possible significant decrease of using the gas net in the Netherlands due to the transition towards a climate-neutral energy system by 2050 and the resulting implications for the development of the gas network tariffs. Hence, the central aim of MORGAN was to determine whether and, if yes, how the ACM should adjust its gas tariff regulation in order to deal with the possible significant decrease of using the gas net (ACM, 2018).

In order to assess the future use of the gas net (including the implications for network costs and tariffs), ACM developed three scenarios to determine the demand for three gaseous energy carriers (natural gas, green gas and hydrogen) in 2050 in three sectors (industry, built environment and electricity generation). These three scenarios included:

- *'Sun, Wind & Heat'*, characterized by (i) rapid reduction of natural gas, (ii) phasing out of regional gas distribution infrastructure, and (iii) CCS for industry and electricity infrastructure;
- *'Green Gas'*, characterized by (i) reduction of natural gas, and (ii) re-use of gas infrastructure due to large role of green gas;
- *'Hydrogen'*, characterized by (i) reduction of natural gas, and (ii) large-scale re-use of gas infrastructure due to large role of hydrogen.

The major results of the scenario analyses include (ACM, 2019):

- In all scenarios, the demand for gaseous energy carriers declines substantially towards 2050 – ranging from -36% in the scenario 'Hydrogen' to -49% in the scenario 'Sun, Wind & Heat' – although the mix of this demand (per gas and/or demand sector) varies significantly across the scenarios;
- As a result, in all scenarios the needed capacity of the gas network decreases significantly up to 2050. Only in the 'Hydrogen' scenario the needed capacity stabilizes from 2030, although at a lower level than in 2018;
- For the national (TSO) and regional network operators (DSOs), both total costs (CAPEX/OPEX) and allowed (regulated) revenues show a declining trend up to 2050 (minus 10-50%);
- For the connected gas users, the network tariff increases up to 2050 because the capacity used declines steeper than the total network costs. More specifically, the TSO tariff increases with a factor 1.9-2.4 in 2050 (compared to 2018), while the average DSO tariff increases with a factor 1.3-2.7, depending on the specific scenario (see Table 23);
- For the Dutch TSO Gasunie Transport Services (GTS), the predicted (contracted) network capacity declines most in the 'Green Gas' scenario. As a result, this scenario shows a higher increase of the TSO gas network tariff than in the other two scenarios. For the DSOs, the network capacity declines most strongly in the scenario 'Sun, Wind & Heat' because the regionally distributed volumes of gas are lowest in this scenario. For both the TSO and DSOs, the capacity use of the gas network is in the long run the highest in the scenario 'Hydrogen'. As a result, the network tariffs in 2050 are relatively lowest in this scenario, in particular for the average DSO tariff (see Table 23).

Table 23: Assessed increase of gas network tariff in 2050 in three scenarios (2018=100)

| Scenario | TSO (GTS) tariff | Average DSO tariff |
|---|---|---|
| Sun, Wind & Heat | 194 | 267 |
| Green Gas | 238 | 211 |
| Hydrogen | 198 | 127 |

Source: ACM (2019).

### *7.3.3 Heat infrastructure*

*CE Delft (2017), Net voor de toekomst*
Compared to the current situation, CE Delft (2017) projects that heat supply through district networks in 2050 will be far more important in the (self-sufficiency) scenario ‘regional steering’, only slightly more important in the scenarios ‘international’ and ‘national steering’ and hardly or not important at all in the scenario ‘generic steering’. As a result, costs of heat networks increase from € 0.3 billion in the current situation (2016-2017) to about € 3.7 billion in 2050 in the ‘regional steering’ scenario, to approximately € 0.8-0.9 billion in the ‘international’ or ‘national steering’ scenarios, while decreasing towards zero in the ‘generic steering’ scenario (see Figure 31 in Section 7.3.1 above). The future role of (district) heating networks, however, depends its future costs – relative to the costs of competing, renewable heat options in the built environment, industry and horticulture – as well as on the regulatory framework to provide clarity, including the right incentives, to heat network investors and operators.

*PBL (2017b) Toekomstbeeld klimaatneutrale warmtenetten in Nederland*
The study by PBL estimates that, in the long run, the potential demand for low temperature heat supplied through (district) heat networks amounts to about 350 PJ, against a current demand for low temperature heat of about 50 PJ (see also Section 6.3.3, discussing sources of heat supply via heat networks. The amount of 350 PJ is the sum of estimates for low temperature heat demand of dwellings (165 PJ), utility buildings (105 PJ), industry (50 PJ) and horticulture (12-40 PJ).

Heat grids are considered as indispensable to fulfill low temperature heat demand as cost efficient as possible. In line with the development of demand, this requires an expansion of the distribution heat grid with a factor 7. Whether or not also the transmission grid expansion needs to be expanded depends on the locations of producers and consumers, demand profiles, and temperature regimes.

PBL (2017b) does not provide cost figures concerning the development of grid infrastructure. Instead, it tries to answer two questions: Who will realize the grid expansion and which barriers must be overcome to this aim?

Current heat grids have been established by firms seeking a market for their own residual heat. Since climate neutral heat sources are smaller sized than existing heat sources, future heat networks will be fed by a higher number of heat sources and need to be open to new heat producers. The study points to the lack of coordination between future supply and demand and pleas for a role of the national government to establish coordination and a sound business case since a larger role for heating grids would be cheaper than pursuing alternatives at certain locations.

### 7.3.4 *Integrated electricity and gas infrastructure*

*Gasunie and TenneT (2019), Infrastructure Outlook 2050*
Early 2019, the Dutch TSOs Gasunie Transport Services (GTS) and TenneT (electricity) presented their first Infrastructure Outlook 2050. This outlook is the result of a joint study by these TSOs on the development of an integrated energy infrastructure in the Netherlands and Germany (i.e. the two countries in which both TSOs operate). The outlook takes the target of the Paris Agreement (COP21, 2015), to achieve a 95% GHG emission reduction by 2050, as its starting point and analyses, subsequently, the implications for the gas and electricity transport network by means of an integrated infrastructure model. For the Netherlands, the outlook uses three (out of four) scenarios developed as part of the study 'Grid for the Future' (Netbeheer Nederland, 2017; and CE Delft, 2017), labelled as 'Regional', 'National', and 'International' (as defined and analysed in the previous chapter, notably sections 6.2 and 6.3).[26]

Figure 35 presents the resulting outlook outcomes in terms of final energy demand (in TWh) for the Netherlands in 2017 and in the three selected 2050 scenarios. It shows that the total final energy demand decreases from almost 670 TWh in 2017 to approximately 410 TWh in the three 2050 scenarios. It should be noted that Figure 35 presents the value for *final* energy demand. The primary production of electricity, however, is much higher in 2050 due to the intermediate conversion of power to gas (Gasunie and TenneT, 2019).


Figure 35: Final energy demand (TWh) for the Netherlands (2017 and three 2050 scenarios)

Source: Gasunie and TenneT (2019).

Although the volume of the final energy demand in 2050 is more or less the same in all three 2050 scenarios (about 410 TWh), the mix of this demand varies across these scenarios and is also quite different from the final energy demand mix in 2017 (Figure 35). By 2050, the dominant role of liquid fuels (i.e. fossil oil) in 2017 will be replaced largely by electricity and (renewable) gaseous energy carriers such as hydrogen or synthetic methane. The 2050 scenarios with a high share of domestic renewable energy production from sun and wind ('Local' and 'National') show an increase of 30% in the total amount of electricity that will need to be transported. For the scenario 'International', this amount of electricity transport is comparable to

[26] Since the 'Grid for the Future' study did not include neighboring countries, the authors of the infrastructure outlook selected some specific studies for Germany in line with the general story lines definition of this outlook. As such, the German scenarios are not identical to the Dutch ones. For details on the selected German studies as well as on the German and Dutch scenarios, see Gasunie and TenneT (2019).

today's transport volumes. On the other hand, in all three 2050 scenarios, the total annual volume of (renewable) gaseous energy carriers is either comparable or even higher than today's volume (Gasunie and TenneT, 2019).

Figure 36 presents the Dutch national peak demand and supply (in GW) of electricity and gas in the three selected 2050 scenarios, together with the current (2017) peak demand. It shows that the peak supply of electricity in 2050 (from sun and wind) may increase by a factor 5 compared to 2017. This considerable increase in electricity peak supply/demand indicates that reinforcement of the transmission grid will become necessary (Gasunie and TenneT, 2019).

Figure 36 also shows that the transport needs in 2050 for both total gas demand and total gas supply are lower that the currently observed level. This implies that no severe problems are foreseen if the locations for P2G (i.e. hydrogen electrolysers) are properly selected. Moreover, the total gas system has enough capacity for hydrogen and methane transport to handle the volatilities in electricity supply from sun and wind if enough storage for hydrogen – both in terms of capacity and volume – is made available (Gasunie and TenneT, 2019).

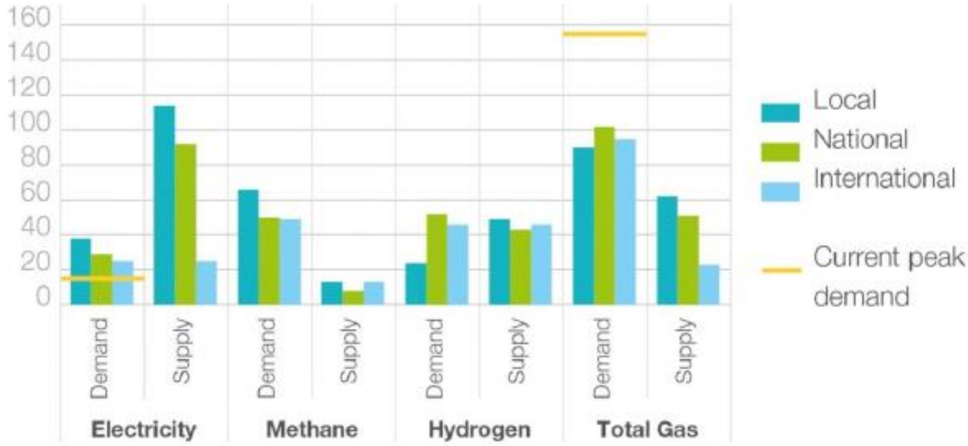



Figure 36: Dutch national peak demand and supply of electricity and gas (GW) for three 2050 scenarios

Source: Gasunie and TenneT (2019).

Figure 37 presents the required storage volumes in the Netherlands for the three selected 2050 scenarios. The total need for (seasonal) gas storage in all scenario amounts to about 35 TWh in 2050, which is divided more or less equally between the demand for hydrogen storage and for methane storage, depending on the specific scenario. The outlook results show that there are currently enough pore and aquifer storages (depleted gas fields) available to store methane in all considered scenarios. For hydrogen – assuming storage in salt caverns to be the preferred option – the available capacity, however, has to be up to 20 times higher than current capacity in order to meet storage needs in 2050, in particular in the 'National' scenario (Gasunie and TenneT, 2019).

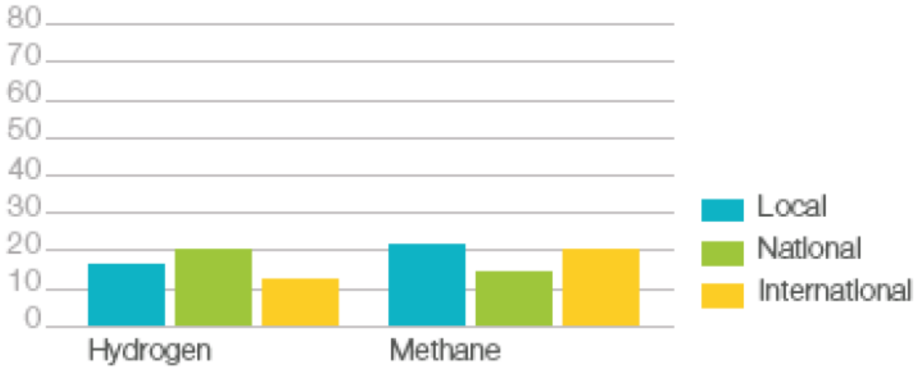



Figure 37: Required hydrogen and methane gas storage volumes in the Netherlands (TWh) for three 2050 scenarios

Source: Gasunie and TenneT (2019).

Overall, the main findings and conclusions of the 2050 Infrastructure Outlook by Gasunie and TenneT (2019) include:

- In all scenarios, both the existing electricity and gas infrastructure will play a crucial role in (the transition to) the energy system of the future.
- The energy infrastructures (electricity, hydrogen and methane) need to be further integrated. The existing gas network has enough capacity up to 2050 and can be split into a network for hydrogen and for methane.
- Although additional electricity storage will be available by 2050, only gas storage provides a solution for seasonable storage in a climate-neutral energy system based on wind and solar power.
- Location, capacity and operation of P2G installations are decisive factors for investments in electricity grids and, hence, have to be aligned with both electricity and gas TSOs. More specifically, converting renewable electricity to hydrogen at locations close to the renewable generation facilities (rather than near industrial areas with hydrogen demand) will reduce the total transport demand for electricity and, hence, will relieve bottlenecks in the electricity grid without causing congestion problems for the gas infrastructure.
- Also, beyond 2030, electricity grids need to be further reinforced in order to meet the growing demand for electricity due to the increasing penetration of Power2Gas, Power2Heat, Power2Mobility (EVs) and other Power2X technologies in all sectors of the energy system.
- Import of renewable energy (notably of ‘green molecules’) can reduce the need to reinforce electricity grids.
- Socially acceptable solutions for an integrated energy infrastructure require a new level of public and political support. More specifically, the Infrastructure Outlook 2050 identifies two crucial aspects for the realisation and success of the energy transition, i.e. (i) political willingness to construct new electricity transmission lines to accommodate the predicted demand growth by end-users, and (ii) the creation of a clear supportive regulatory framework for the integration of P2G plants in the system in order to minimise the total number of grid expansions (Gasunie and TenneT, 2019).

## 7.4 Summary of main findings

This chapter has reviewed a number of scenario studies focusing on the implications of the energy transition for the energy infrastructure in the Netherlands. Although almost all studies have analyzed the effects of the energy transition on (des)investments in energy grids, not all of them provide quantitative insights on grid capacity needs, energy transport volumes and associated costs, including both investment and operational costs (see Table 24 for a summary overview – notably of infrastructure investments – of the studies reviewed in the current chapter). Furthermore, most studies focus on the implications for either electricity or gas grids, while they pay little attention towards heat grids or the integration of energy infrastructures, notably of electricity and gas networks.

In general, almost all studies reviewed in the chapter report project that – as part of the energy transition – yearly costs for energy infrastructure (electricity, gas, heat) increase significantly up to 2050 (+50-300%), although most of these studies do not make an adequate distinction between ‘conventional’ infrastructure investment and operational costs (including conventional replacements and reinforcements) versus ‘additional’ infrastructure costs (i.e. additional costs due to the energy transition).

In particular, both investment and operational costs of the *electricity* network are projected to increase substantially over the coming decades due to the further electrification of energy system – i.e. the further penetration of emerging P2X technologies across all energy demand sectors – as well as the growing share of variable energy sources (sun/wind) in total power generation, resulting in higher electricity transport flows, higher volatility of these flows and, notably, higher peaks in electricity demand/supply (requiring reinforcement and expansion of power grid capacities).

Estimates of future power grid capacities and associated costs, however, vary widely across the scenarios and studies reviewed depending on a variety of factors, in particular (i) the assumed timing, speed and (ultimate) share of the penetration of P2X technologies, notably of (variable) power demand/supply technologies such as electric vehicles (EVs), heat pumps (HPs), sun PV, electrolysers (P2G), etc., (ii) the realizable potential and associated costs and benefits of (local) flexibility options – such as electricity storage or demand response – in order to reduce power peaks and the resulting electricity grid capacity needs, and (iii), the location of P2G electrolysers, i.e. converting (renewable) electricity to hydrogen at locations close to the power generation facilities or near industrial areas with hydrogen demand, including the total (domestic) demand for green hydrogen and the extent to which it will be produced/consumed at home or imported/exported abroad.

More specifically, scenario studies of regional DSOs in the Netherlands (Alliander, Stedin) on the impact of the energy transition on their regional electricity distribution network show that this impact – notably in terms of the incidence or risk of overloaded (congested) grid assets, the need for additional grid reinforcements, as well as the opportunities, costs and benefits of reducing these reinforcements by deploying (local) flexibility options – varies significantly across the studies and scenarios considered, depending on the current (existing) capacities of their distribution networks and the assumptions made with regard to the first two factors mentioned above.

With regard to the future *gas* infrastructure, the major issues concern the implications of the transition from fossil gas to renewable, climate-sustainable gases – such as green/blue hydrogen, biomethane or other green gases – for the existing gas network, including the extent to which this network can be used for the emerging, climate-sustainable gases, the grid adjustments and capacities needed, the costs involved and the resulting networks tariffs. In general, there is some consensus ('robustness') that – to some extent – the existing gas infrastructure can be used for the transport of climate-sustainable gases, that the existing gas capacities are usually sufficient to do so and, hence, that the additional capacity investment costs are limited (or even zero).

On the other hand, however, there is uncertainty – or even controversy – with regard to the necessary adjustments to the existing gas infrastructure for the transition toward climate-sustainable gases, the available and required gas storage capacities, and the resulting, related costs involved – including the costs of well-integrated electricity and gas networks – depending on assumptions made with regard to (i) the technical characteristics and current conditions of the existing gas infrastructure, (ii) the volume levels and time profiles of future demand and supply – including trade – of the climate-sustainable gases, and – as mentioned before – (iii) the location of P2G electrolysers.

Finally, with regard to the future (district) *heat* networks, (limited) available scenario studies seem to agree that, in principle, there is a substantial potential to increase the role of district heating significantly in the coming decades (up to a factor 7 in 2050, compared to the current situation). The actual future role of (district) heat networks, however, depends in particular on (i) the specific scenario assumed, notably the assumed level of local/regional/national energy self-sufficiency, (ii) the (assumed) future cost developments of these networks relative to the cost developments of alternative, renewable heat options in the built environment, industry and horticulture, as well as (iii) the regulatory framework to provide clarity – including the right incentives – to heat network investors and operators.

Table 24: Key characteristics of studies reviewed, focusing on energy infrastructure investments

| Study | Scope | Geographical area | Method | Scenarios | Energy infrastructure investments |
|---|---|---|---|---|---|
| CE (2017) | Electricity, gas, heat | NL | Electricity: Feed-in and consumption at three voltage levels (LS, MS, HS). Calculation of peak load based upon profiles of demand and supply, and translation towards expected grid investment costs with cost figures.<br><br>Gas: assumptions for cost of compression and measurements with feeding in of green gasses, mid value of 10 million euro/PJ. | Regional steering, national steering, international, generic steering | Depends on the scenario; cost figures are available for four 2050 scenarios.<br><br>Cost figures below include expansion as well as replacement investments. The latter are strictly taken no additional costs of the energy transition. No figures disaggregating expansion and replacement investments are available.<br><br>Electricity: 3.9-8.9 billion euro per year (international vs. national steering scenario) including O&M costs. Excluding O&M costs: 3.2-7.2 billion euro per year.<br><br>Gas: 1.0-1.5 billion euro per year, for the transport of $CO_2$ free gasses (regional vs national steering scenario).<br>Excluding O&M costs: 0.3-0.8 billion euro per year.<br><br>Heat: 0-3.7 billion euro per year (generic steering vs regional steering scenario). |
| ECN and Alliander (2017) | Electricity | Areas with Liander as DSO | Overloads are calculated with the bottom-up ANDES model. It determines the local adoption of technologies such as solar PV, heat pumps and EVs based upon prediction of customer behavior, projects the local adoption on the grid topology, calculates load profiles per asset, and determines the overloads per asset type. | Reference scenario (based upon existing policy plus strong growth of installed VRE capacity) and alternative scenario (85% GHG emission reduction and strong growth of installed VRE capacity as well as additional electrification). | Additional distribution network reinforcements of 1-1.5 billion euro until 2050 in the alternative scenario.<br><br>With the deployment of flexibility measures, i.e. demand response and PV curtailment, maximum gross savings of about 700 million euro can be achieved by 2050. After deduction of deployment costs of flexibility measures such as ICT costs, additional network losses due to a higher utilization of network assets, and compensation of PV owners, net savings of about 350 million euro remain for the alternative scenario. |

| Study | Scope | Geographical area | Method | Scenarios | Energy infrastructure investments |
|---|---|---|---|---|---|
| Stedin (2016) | Electricity | Areas with Stedin as DSO | Overloads in 2030 and 2050 are calculated with a simple, dedicated profile model (MKBINS) to calculate the network load on three voltage levels for the three different scenarios. The model is based upon capacity and load of transformers and substations, cables are not considered. Cost figures are general and not project-specific. Every scenario has four representative model districts; rural, ground-floor urban, urban, and city centre; each model district is coupled to postzip-4 areas of Stedin in order to enable coupling with Stedin network assets. | Paces, Tides, and Circles, with increasing amounts of solar PV, electric vehicles and heat pumps. | Additional distribution network investments for the period 2020-2050 amount to 1.8 billion euro for the Paces scenario, 4 billion for the Tides scenario, and ca 15 billion euro for the Circles scenario. |
| OTE (2018) | Gas | NL | Analysis of depreciation of gas assets on network tariffs in case of large changes in customer base. | A phase out scenario assuming (i) the use of the low-pressure gas grid of the DSOs is discontinued, while the high-pressure grid of the DSOs remains in service for the current large gas consumers; (ii) replacement investments in the low-pressure grid decrease with the decline of the number of small consumers. | 5 billion euro of network investments is not recovered by network tariffs in 2050. |

| Study | Scope | Geographical area | Method | Scenarios | Energy infrastructure investments |
|---|---|---|---|---|---|
| ACM (2019) | Gas | NL | Demand for natural gas, green gas and hydrogen; translation to need for network capacity, impacts on network tariffs | Three scenarios: (i) Sun, Wind & Heat, (ii) Green Gas, and (iii) Hydrogen | No data available on investments, but total annual costs of the national gas TSO (GTS) decline from almost 1 billion euro in 2018-2020 to about 500-800 million euro by 2050, while total annual costs of the regional DSOs decline from almost 1400 million euro in 2018-2020 to 900-1000 million euro by 2050 |
| DNV GL (2017) | Gas | NL | Technical analysis | None | N/A |
| KIWA (2018) | Gas | NL | Technical and safety analysis | Four scenarios of CE Delft (2017): regional steering, national steering, international, generic steering | Recurring grid costs for hydrogen and biomethane together are lowest in the regional scenario (€ 161M/year) and highest in the generic steering scenario (€ 711M/year). The latter reflects the large role of biomethane in the generic steering scenario. Hydrogen has the most prominent role in the national and international steering scenarios |
| Gasunie and TenneT (2019) | Integrated electricity and gas | NL (and Germany) | Scenario analysis by means of an integrated infrastructure model for Germany and the Netherlands | Three scenarios of CE Delft (2017): regional, national and international steering | N/A |
| PBL (2017b) | Heat | NL | Socio-economic analysis | One scenario with maximum economic potential for heat | Current distribution low temperature heat grids should be expanded by a factor 7. No cost figures are provided. |

# 8 Summary of general observations, main findings and suggestions for further research

In the previous chapters, we have reviewed a large variety of scenario studies on the transition and deep decarbonisation of the energy system in the Netherlands up to 2050. In this chapter, we will summarize some main observations, findings and suggestions for further research based on the review of these studies. First, Section 8.1 outlines some general observations regarding the studies considered. Subsequently, Section 8.2 presents the main findings of the current report, in particular the main similarities ('robust elements') and differences ('uncertain elements') of the reviewed scenarios studies. Finally, Section 8.3 provides some suggestions for further scenario research.

## 8.1 General observations

Regarding the energy transition scenario studies reviewed in the previous chapters, we have made the following general observations.

*High diversity of scenario studies*
The scenario studies reviewed in the current report show a wide diversity in terms of the general character and approach of these studies, their scope and focus, as well as the underlying assumptions of these studies. While some studies have a rather generic, qualitative or highly 'visionary' character, other studies follow a more specific, detailed, quantitative modelling approach. Moreover, whereas most (modelling) studies seem to use a kind of simulation approach (based on a certain societal vision or assumed future scenario), only a few studies apply an optimization – i.e., cost minimization – approach.

In addition, most scenario studies reviewed in the current report focus only on a single energy demand or supply sector (such as industry, transport or electricity generation), while a few studies focus on a variety of sectors or even the energy system as a whole. Moreover, whereas some studies focus mainly on the GHG emissions or abatement options of a certain sector and largely ignore the underlying (changes in) energy use (or vice versa), only a few studies pay adequate attention to both sides of the energy transition, i.e. changes in both energy use and resulting GHG emissions (see also below for other differences in scope and focus of the scenario studies reviewed).

Last, but not least, the studies reviewed show a wide diversity in terms of underlying assumptions made with regard to future parameters of key variables such as sectoral (energy) demand levels, fuel prices, the availability and acceptability of certain technologies (e.g., biomass or CCS), the costs of certain climate-sustainable technologies (versus other, competing technologies), etc. In many cases, however, some – or even most – of these assumptions are not explicitly mentioned, clarified and/or tested regarding their sensitivities.

*High diversity of scenario outcomes*
Even if scenario studies focus more or less on the same energy sector and the same GHG abatement technologies, they usually show a wide diversity of scenario outcomes in terms of energy use, GHG emission reductions, the penetration of new

emerging technologies, the primary or final energy mix, the need for energy infrastructures, energy system costs, etc. This diversity of scenario outcomes is mainly due to the above-mentioned differences in scenario approach and underlying assumptions, notably with regard to the key determinants of these outcomes (see also below).

In many cases, however, it is hard – or even impossible – to compare and explain the differences in scenario outcomes, not only due to the differences in scenario approach and underlying assumptions but largely because, as mentioned above, these differences are often not explicitly mentioned, clarified or tested regarding their sensitivities. Moreover, in some cases, it is even not clear whether certain scenario 'outcomes' – e.g., the installed capacity or output of certain renewable energy sources – are indeed the result of a (simulation or optimization) model calculation or rather an assumed input parameter of the scenario study concerned.

*Additional differences in scope and focus of the scenario studies*
In addition to the differences mentioned above, there are some other striking differences with regard to the scope and focus of the scenario studies reviewed in the current report. First, while the built environment and some industrial sectors have been analysed in recent years by several energy transition or deep decarbonization scenario studies up to 2050 (see chapters 2 and 3), similar recent studies are lacking for other energy demand sectors, notably transport and agriculture (see chapters 4 and 5)

Moreover, almost all energy transition scenario studies – even for the above-mentioned, so-called 'energy demand' sectors – focus predominantly on the supply side of these sectors, i.e. how can the (assumed, given) energy demand of these sectors be met in a more climate-sustainable way, while paying far less attention to – or even ignoring or neglecting – the demand side of the energy transition in these sectors, i.e. in particular the determinants – such as the underlying needs for products and services – and the expected future developments and changes in the level, structure and profiles of the sectoral energy demand categories (including the options for – and rate – of energy savings of these categories).

Finally, while some (renewable) energy supply technologies or GHG abatement options are covered by almost all scenario studies and receive much, sufficient attention – notably sun PV, wind energy, hydrogen, some P2X technologies, etc. – other technologies are covered less or receive hardly or no attention at all, in particular deep geothermal electricity generation, ocean power (tidal, wave, osmosis) or abatement options with negative emissions – such as biomass energy use with CCS – partly because of ignorance or unfamiliarity with these technology options or because these options are (assumed or appear to be) less important for the Netherlands up to 2050.

*Key scenario determinants*
The overarching factor which determines the (differences in) outcomes of the scenario studies reviewed in the current report is the GHG reduction target in a certain year for a specific sector or the energy system as a whole. However, even if these studies assume a deep decarbonisation target, e.g., for 2050 – it usually makes quite a difference in scenario outcomes whether this target is set at 80%, 90%, 95% or even higher (up to 100% or even negative emissions).

Other key scenario determinants generally seem to be the (implicit) assumptions regarding the domestic availability – including imports – and socio-political acceptability of major GHG abatement technologies, notably biomass energy (including bio-gases), nuclear energy, CCS, etc. As already mentioned, however, in many studies these assumptions are often not explicitly mentioned, clarified or tested with regard to their sensitivities.

*High techno-economic and planning character of scenario studies*
Most of the scenario studies reviewed have a high 'techno-economic' character in the sense that they largely focus on the techno-economic characteristics of the GHG abatement options concerned – potentials, costs, technical constraints, etc. – while hardly or not considering the socio-political aspects of these options and the required or resulting implications for (changes in) human behaviour and socio-economic systems.

In addition, most of the studies seem to have a high 'planning' character in the sense that system changes and (other) scenario outcomes seem to result largely from (centrally) planned decisions rather than through market forces, price incentives or (local) people's initiatives. Moreover, most studies pay hardly or no attention to the policy measures and instruments required to implement these decisions and to realise the projected scenario outcomes.

## 8.2 Main similarities and differences across scenario studies

This section provides a summary of the main similarities ('robust elements') and differences ('uncertain elements') of the scenario studies per energy sector – including infrastructure – as reviewed and discussed in the previous chapters 2 up to 7.

*Built environment*
In most scenario studies, there is some consensus that the (renewable, climate-sustainable) energy use by the built environment in 2050 will consist of a mixture of the following options: (i) electrification of heat demand by means of heat pumps (based on renewable electricity sources), (ii) district heating (based largely on geothermal and residual heat sources), and (iii) green gases (e.g., produced from biogas or thermal gasification of biomass), while solid biomass is deemed to have a small or no role at all by 2050. The mix (amounts/shares) of these options in total energy use of the built environment, however, usually varies heavily across the studies reviewed depending on the (assumed) domestic availability, acceptability and relative costs of the resource options considered. In addition, in some 2050 scenarios also hydrogen is used to some extent by the built environment, while in other scenarios it is not used at all.

Overall, total final energy demand of the built environment in 2050 varies widely between the scenarios considered. This can be attributed to differences in energy savings as well as to differences in rates of electrification of heat demand via electric heat pumps. In an all-electric scenario, final heat demand (excluding ambient heat) is lower compared to a 'gas' or 'heat network' based scenario since (i) high level insulation (deep renovation) is a necessary precondition in order to apply heat pumps in all-electric concepts and (ii) efficiency gains of a heat pump (i.e., ambient heat used by heat pumps) are not included in final heat demand.

*Industry*
Most scenario studies generally agree that electrification will play an important role in the decarbonisation of the industrial sector. Two other high potential decarbonisation options are CCS/CCU and biomass for energy and feedstock purposes. The specific role and importance of these abatement options, however, vary significantly across the scenarios reviewed depending on the specific industrial abatement target, the underlying scenario assumptions and the specific industrial sector considered.

The potential for industrial energy savings varies per study and scenario considered, but since none of the studies elaborates on the assumed economic development of the industry in their scenarios, the (estimated or assumed) impact of energy efficiency options is hard to compare.

The role for hydrogen varies per industrial scenario study but is difficult to analyse as this option is generally not discussed in detail in the studies. It does appear that its potential seems to depend strongly on the specific industrial abatement target, the energy prices (notably for gas and electricity), the $CO_2$ price, and the availability, acceptability and relative costs of alternative abatement options such as biomass or CCS/CCU.

*Transport*
Recent, comprehensive scenario studies on the deep decarbonization (e.g., 95% in 2050) of the transport sector in the Netherlands – including all major transport subsectors – are missing. Nevertheless, available transport studies either for the Netherlands (focussing on less ambitious abatement targets and/or certain subsectors, notably passenger cars), Germany or the EU as a whole (including more ambitious abatement targets and/or other subsectors as well) show that there are some robust options with regard to the (deep) decarbonization of the transport sector by 2050. In addition to maximizing efficiency of logistics and all transport vehicles, the major option concerns the (fast) electrification of all appropriate transport means, notably passenger cars, vans, buses, short-distance smaller trucks, etc.

Besides large-scale electrification, however, a crucial but yet to be identified mix of other abatement options is needed to achieve deep decarbonization targets by the Dutch transport sector as a whole in 2050. In particular, these options include:
- Biofuels, notably so-called ‘advanced biofuels’;
- Hydrogen, i.e. blue/green hydrogen;
- Electricity-based fuels (‘E-fuels’), notably power-to methane ($P2CH_4$) and power-to-liquids (P2L).

The specific mix of these options, however, depends not only on the specific abatement target for a specific subsector (or the transport sector as a whole) but also on a variety of (uncertain) factors such as the domestic availability, acceptability and relative costs developments of these options (including the fueling infrastructure costs) as well as on developments in EV charging infrastructure, battery technology and total EV costs (affecting the competition of the alternative fuel options with electromobility).

In addition to the uncertain factors mentioned above with regard to the fuel supply mix, the transport sector is characterized by uncertainties regarding future developments of transport demand, including possible ‘disruptive’ developments such as autonomous car driving, the shift from car ownership to car rental usage (‘mobility as a service’), the transport and delivery of online ordered purchases and packages, vacuum tube transport, high-speed trains, etc. These developments may not only have a significant impact on the level, structure and time profiles of transport demand but also on the fuel supply mix to meet this demand and the flexibility or other services of the transport sector offered to or required from the energy system (notably the power system).

*Agriculture*

Similar to transport, there is also a lack of long-term (i.e., up to 2050), quantitative and comprehensive scenario studies of the energy transition and deep decarbonization of the Dutch agricultural sector as a whole (including all subsectors). However, across the available scenario studies reviewed in the current report – usually mid-term, less ambitious abatement studies focusing particularly on the horticultural subsector - there is some consensus (‘robustness’) on how the agricultural sector – notably the horticultural subsector – can become climate neutral and/or, on balance, energy neutral (including energy supplies to other sectors). In brief, the major (agreed) options to achieve energy/climate neutrality by the Dutch agricultural sector include:

- Decrease energy use by implementing further energy savings;
- Phase out the use of fossil gas-fired CHP;
- Decarbonize heat supply by means of geothermal heating, external (waste) heat supply and heat pumps (‘green electrification’);
- Increase of renewable energy supplies to other sectors, in particular by wind onshore and solar parks on agricultural soils;
- Use manure digestors to produce green gas to be put in the gas grid;
- Adjust fodder for dairy cows;
- Optimize fertilisation of agricultural land.

On the other hand, there is still uncertainty and lack of knowledge regarding the GHG abatement potential and cost-effectiveness of the above-mentioned options, notably to achieve a deep decarbonization target – including all agricultural GHG emissions – in the long run (up to 2050). Therefore, a long-term (2050), quantitative and comprehensive scenario study of the energy transition and full decarbonization of the Dutch agricultural sector as a whole seems to be highly desirable.

*Energy supply*

Across the energy supply sector scenarios reviewed in the current report (notably Chapter 6), the main similarities – ‘robust elements’ – include:

- In all scenarios, the role of fossil fuels decreases to (nearly) zero in 2050, while the share of renewables increases up to 100%. Only in a few scenarios, there is still a minor role in 2050 for fossil fuels, in particular natural gas (+CCS).
- In all scenarios, the share of electricity in total final energy use increases significantly up to 2050 (although the specific size of this share and rate of additional electrification up to 2050 varies widely across the scenarios reviewed).
- In all scenarios, the share of variable renewable energy sources in power generation – notably of offshore wind and onshore sun PV – increases

substantially up to 2050 (although, once again, the specific size of this share in 2050 varies widely across the scenarios considered).

- In all scenarios, the role of (renewable) hydrogen in the Dutch energy system increases significantly (although, once again, the specific size of this share in 2050 varies widely across the scenarios considered);
- In all scenarios, neither coal nor nuclear plays any role in power generation in the Netherlands by 2050, partly because these technologies are not competitive under the (assumed) scenario conditions or because new investments in these technologies are considered (assumed) to be not socio-politically acceptable by 2050;
- Across the energy supply scenario studies reviewed in this chapter, there is a high consensus (‘robustness’) on the (renewable) energy sources of heat supply in 2050. These sources include in particular geothermal energy, residual heat, solar thermal energy, ambient heat and – to address (very) high winter peaks of heat demand or system (heat network) breakdowns – heat boilers running on biomass, hydrogen or green gas. Across these studies, however, there is also a high diversity (‘uncertainty’) regarding the technical potentials or projected volumes of these heat supply sources in 2050 as well as the projected volumes or shares of heat supplied through (district) heat networks in total heat supply;
- In all scenarios, emergent technologies that are still nearly or fully absent – or not included – in the reviewed scenario studies are deep geothermal electricity generation and ocean power (tidal, wave, osmosis), partly because of ignorance or unfamiliarity with these technologies or because they are (assumed or appear to be) less important for the Netherlands up to 2050.

On the other hand, the main differences (‘uncertain elements’) observed across the energy supply sector scenarios reviewed in the current report include:

- In general, as already indicated above, there is a wide variety of scenario outcomes in terms of total energy supply and the mix of (renewable) energy supply technologies by 2050. These differences in outcomes are mainly due to underlying scenario uncertainties and resulting differences in assumptions made regarding the key determining factors of energy supply such as the domestic availability (including imports), the socio-political acceptability and the relative cost developments of compering energy sources and technologies.
- More specifically, observed values for total primary energy use in 2050 range from approximately 1400 PJ to 2200 PJ across the various scenarios reviewed, while energy conversion losses – i.e. when moving from primary to final energy use – vary between 10 and 40%. These differences in energy use are due to differences in (the definition and calculation of) the primary/final energy mix as well as differences in assumptions with regard to future developments in sectoral energy demand (including energy savings).
- Although offshore wind becomes a dominant power generation technology in most of the scenarios reviewed, overall installed capacity figures for offshore wind vary widely between 5 and 105 GWe across all scenarios considered.
- Some scenarios foresee a major role for renewable energy technologies such as solid biomass, deep geothermal heat or solar thermal heat, while in other scenarios these technologies play hardly or no role at all by 2050.
- Although almost all scenarios foresee a growing, significant role of hydrogen by 2050, observed values regarding this role vary widely across the scenarios reviewed. Moreover, while some scenarios foresee a significant role of

hydrogen in a wide variety of end-users' applications (including power generation by utilities and low-temperature heat production in the built environment), other scenarios show that its role focuses only on a limited set of energy functions (notably for providing high-temperature heat and transport services).

More generally, to conclude, the future demand and supply of climate-sustainable technologies in scenario studies – in particular onshore/offshore wind, sun PV, biomass, nuclear, hydrogen, P2X, CCS/CCU, geothermal energy, etc. – depends basically on the assumptions made with regard to (i) the domestic availability – including imports – of these technologies, (ii) their socio-political acceptability, and (iii) the costs of these technologies relative to alternative, competing options.

*Energy infrastructure*
In general, almost all studies reviewed in the current report project that – as part of the energy transition – yearly costs for energy infrastructure (electricity, gas, heat) increase significantly up to 2050 (+50-300%), although most of these studies do not make an adequate distinction between 'conventional' infrastructure investment and operational costs (including conventional replacements and reinforcements) versus 'additional' infrastructure costs (i.e. additional costs due to the energy transition).

In particular, both investment and operational costs of the *electricity* network are projected to increase substantially over the coming decades due to the further electrification of energy system – i.e. the further penetration of emerging P2X technologies across all energy demand sectors – as well as the growing share of variable energy sources (sun/wind) in total power generation, resulting in higher electricity transport flows, higher volatility of these flows and, notably, higher peaks in electricity demand/supply (requiring reinforcement and expansion of power grid capacities).

Estimates of future power grid capacities and associated costs, however, vary widely across the scenarios and studies reviewed depending on a variety of factors, in particular (i) the assumed timing, speed and (ultimate) share of the penetration of P2X technologies, notably of (variable) power demand/supply technologies such as electric vehicles (EVs), heat pumps (HPs), sun PV, electrolysers (P2G), etc., (ii) the realizable potential and associated costs and benefits of (local) flexibility options – such as electricity storage or demand response – in order to reduce power peaks and the resulting electricity grid capacity needs, and (iii), the location of P2G electrolysers, i.e. converting (renewable) electricity to hydrogen at locations close to the power generation facilities or near industrial areas with hydrogen demand, including the total (domestic) demand for green hydrogen and the extent to which it will be produced/consumed at home or imported/exported abroad.

More specifically, scenario studies of regional DSOs in the Netherlands (Alliander, Stedin) on the impact of the energy transition on their regional electricity distribution network show that this impact – notably in terms of the incidence or risk of overloaded (congested) grid assets, the need for additional grid reinforcements, as well as the opportunities, costs and benefits of reducing these reinforcements by deploying (local) flexibility options – varies significantly across the studies and scenarios considered, depending on the current (existing) capacities of their distribution networks and the assumptions made with regard to the first two factors mentioned above.

With regard to the future *gas* infrastructure, the major issues concern the implications of the transition from fossil gas to renewable, climate-sustainable gases – such as green/blue hydrogen, biomethane or other green gases – for the existing gas network, including the extent to which this network can be used for the emerging, climate-sustainable gases, the grid adjustments and capacities needed, the costs involved and the resulting networks tariffs. In general, there is some consensus ('robustness') that – to some extent – the existing gas infrastructure can be used for the transport of climate-sustainable gases, that the existing gas capacities are usually sufficient to do so and, hence, that the additional capacity investment costs are limited (or even zero).

On the other hand, however, there is uncertainty – or even controversy – with regard to the necessary adjustments to the existing gas infrastructure for the transition toward climate-sustainable gases, the available and required gas storage capacities, and the resulting, related costs involved – including the costs of well-integrated electricity and gas networks – depending on assumptions made with regard to (i) the technical characteristics and current conditions of the existing gas infrastructure, (ii) the volume levels and time profiles of future demand and supply – including trade – of the climate-sustainable gases, and – as mentioned before – (iii) the location of P2G electrolysers.

Finally, with regard to the future (district) *heat* networks, (limited) available scenario studies seem to agree that, in principle, there is a substantial potential to increase the role of district heating significantly in the coming decades (up to a factor 7 in 2050, compared to the current situation). The actual future role of (district) heat networks, however, depends in particular on (i) the specific scenario assumed, notably the assumed level of local/regional/national energy self-sufficiency, (ii) the (assumed) future cost developments of these networks relative to the cost developments of alternative, renewable heat options in the built environment, industry and horticulture, as well as (iii) the regulatory framework to provide clarity – including the right incentives – to heat network investors and operators.

## 8.3 Suggestions for further scenario research

This final section includes some suggestions for further scenario research with regard to the energy transition in the Netherlands.

*Integrated energy transition scenario study*
There is a need for a fully, truly and regularly updated integrated energy transition scenario study for the Netherlands, based on a (techno-economic) cost-optimization modelling approach, followed or supplemented by a (socio-economic) policy simulation approach. Preferably, such a study should (at least) include the following elements:

- All major energy demand and supply sectors as well as all major energy technologies, energy carriers and energy sources (including energy sources for industrial feedstocks and international bunker fuels);
- All major GHG emission sources and abatement options;
- All major energy infrastructures (electricity, gas, heat);

- All major flexibility options of the energy system as a whole over different time frames, varying from (less than) one hour to interannual seasons, including different types of flexible, carbon-free energy supply, energy storage, demand response, cross-border energy trade, etc.;

In addition, such an integrated energy transition scenario study could – or, ideally, 'should' – include the following methodological options:
- Sensitivity analyses to show the impact of critical (but usually highly uncertain) scenario assumptions on scenario outcomes such as, for instance, the domestic availability or socio-political acceptability of major GHG abatement options, in particular CCS, biomass, nuclear, geothermal energy, etc.,
- Spatial (local, regional) implications of the energy transition;
- Dynamic outcomes and implications of the energy transition, i.e. in addition to the (static) scenario outcomes and implications for a certain target year (e.g., 2030 or 2050) also the (dynamic) scenario outcomes and implications for certain intermediate years should be determined, resulting in so-called 'energy transition pathways';

As noted above, such an integrated transition scenario study should (preferably) be based on an integrated, cost-optimization modelling approach in order to determine the mix of sustainable energy and GHG mitigation options for achieving a certain abatement target in a certain year at the lowest social costs (within a set of techno-economic constraints and other socio-political objectives). Subsequently, or complementary, a socio-economic or agent-based policy simulation modelling approach could – or should – be applied in order to determine (i) the policy measures and instruments as well as the socio-economic and behavioral changes that are needed to realize this social, cost-optimal mix of sustainable energy and GHG mitigation options, (ii) the socio-economic impacts of these measures, instruments and changes, including the resulting energy transition (e.g., on energy poverty or income distribution), and, if these impacts are considered to be socially undesirable or even acceptable, (iii) additional policy measures to reduce or correct these impacts.

*Sectoral energy transition scenario studies*
In addition to a fully, truly and regularly updated energy transition scenario study for the energy system as a whole, there is also a need for similar scenario studies for specific energy (demand) sectors in the Netherlands, in particular for long-term (2050), deep decarbonization (95%) studies for the transport sector (including all subsectors), agriculture (including all subsectors), industry (including all energy uses and feedstocks of all industrial subsectors) and, to a lesser extent, the built environment (including both households, services and other buildings) as these specific sectoral studies are either lacking or existing, available studies show major shortcomings (as outlined in the sectoral chapters 2 up to 5 of the current report, as well as in Section 8.2 above).

*More attention for developments on the demand side of the energy transition*
As put forward in Section 8.1 above, almost all energy transition scenario studies – even for the above-mentioned, so-called 'energy demand' sectors – focus predominantly on the supply side of the energy transition in these sectors, i.e. how can the (assumed, give) energy demand of these sectors be met in a more climate-sustainable way, while paying far less attention to – or even ignoring or neglecting –

the demand side of the energy transition in these sectors, i.e. in particular the determinants – such as the underlying needs for products and services – and the expected future developments and changes in the level, structure and time profiles of the sectoral energy demand categories (including the options for – and rate – of energy savings of these categories).

This applies in particular for the transport sector (as argued in Section 8.2 above) as well as for the industrial sector (given all the expected changes in industrial demand structures and levels due to pursuing the energy transition, the circular economy, etc.) but also for the built environment and the agricultural sector. Therefore, there is a need for sectoral energy transition scenario studies (as well as integrated scenario studies for the energy system as a whole) that pay more attention to the developments and changes on the demand side of the transition of the energy system, including underlying development and changes in the need for sectoral products and services, and the resulting implications for the level, structure and time profiles of sectoral energy demand as well as the mix of supply options to meet this changing demand in a climate-sustainable way.

*Other suggestions for further scenario research*
In addition, there are several other options for further scenario research on (key elements of) the energy transition in the Netherlands. Just to mention four of them:

- Firstly, further research on the domestic availability – including possible imports – and socio-political acceptability of critical, but still (highly) uncertain GHG abatement options such as CCS/CCU, biomass, nuclear, geothermal energy, etc.;
- Secondly, further research on the implications of the energy transition for the existing energy infrastructure (electricity, gas and heat networks), including the further integration and optimization of these networks, the required infrastructural adjustments and policy measures, the infrastructural investment and operational costs involved, as well as the implications of the infrastructural changes, adjustments and investments for the mix and geographical location of climate-sustainable technologies such as P2G electrolysers or other P2X technologies;
- Thirdly, further research on the (feasible) potentials and impacts of flexibility options – notably of various types of energy storage and demand response – across all energy sectors and all time frames (from hours and days to, in particular, yearly seasons), including the policy measures and implications to unlock and realize these potentials in order to achieve an energy system that is both sustainable, reliable and affordable;
- Last, but not least, further research on the role of human behavior and (socio-economic) policy issues of the energy transition and, in particular, how to better include these factors in future scenario (modelling) studies.

A final suggestion is that energy transition scenario studies should pay more explicit attention to clarifying and explaining the major assumptions and input parameters of the scenarios explored, including sensitivity analyses of the key assumptions and parameters of these scenarios in order to underline the uncertainty (of the scenario outcomes) regarding these variables, to indicate the impact of these variables on the scenario results, and to enhance the understanding and comparability of the scenario outcomes across different studies.

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