MASTER'S THESIS - MASTER ENERGY SCIENCE

Reaching the 1.5 °C target through deep CO_2 emission reduction: the Netherlands as a case study

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ABSTRACT

Carbon dioxide is considered the driving force of enhanced global warming by many scientists. Hence, multiple studies have addressed the role of carbon dioxide emissions and enhanced global warming, but only few include a *carbon budget* in their research. This study thus aims to undertake such an approach, and to explore the possibilities of the Netherlands to keep within a generous nationalised carbon budget based on GDP PPP of 3.17 $GtCO_2$ that limits global average temperature increase to 1.5 °C above pre-industrial levels by 2050. With current emissions amounting to 162.9 $MtCO_2$ per year, this leaves 19.5 years of current emissions until this budget is fully depleted. Most of these CO_2 emissions originate from the use of fossil fuels, primarily gas, coal and oil. This indicates a necessity of a transition towards using less CO_2 emitting resources such as solar energy, wind energy and biomass. An existing bottom-up energy system model is updated and expanded to include heating technologies for the built environment and the industry sector, as well as energy storage throughout various sectors. Technologies such as wind and solar energy, carbon capture and storage, biofuels and heat pumps will be applied in these sectors to remain within the national carbon budget. For example, the electricity generation by 2050 will consist of almost 500 petajoule (~75 %) of wind energy, while the built environment and the industrial sector will generate almost 450 petajoule (~50 %) of heat through heat pumps. Carbon capture and storage technologies will play a minor role in the electricity sector throughout the modelling period and are further scattered within the industry sector in the fuel conversion sector and the production sector. This leads to a CO_2 emission reduction of 58 % by 2030 and 83 % by 2050 when current proposed policy is taken into account. The overall costs of the system up to 2050 will amount to over 733 billion €, which is equal to 1.9 % per year of the GDP PPP of the Netherlands up to 2050. Further pursuing the development of the model is recommended since the carbon budget used in the study is unfairly large for the Netherlands. Added to this, highly unrealistic swift action by 2020 is required to remain within the carbon budget. Research into the implications of restrictions of this swift action is suggested. More research is also advised on the flexibility of the electricity system and on the Netherlands with respect to other countries and their developments towards future pathways.

ABBREVIATION LIST

Below, the abbreviations and their full names used in this paper can be found.

Abbreviation	Full form
AF	Availability factor
BECCS	Bioenergy with carbon capture and storage
CBS	Statistics Netherlands
CCS	Carbon capture and storage
CF	Capacity factor
CHP	Combined heat and power
CO_2	Carbon dioxide
EEU	Extra-European Union
EU	European Union
ECN	Energy Research Centre of the Netherlands
EV	Electric vehicle
FOM	Fixed operation and maintenance
GDP	Gross domestic product
GDP PPP	Gross domestic product based on Purchasing Power Parity
GE	Gas engine
GT	Gas turbine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
INV	Investment costs
IPCC	International Panel on Climate Change
JRC	Joint Research Centre
MARKAL	MARket ALlocation
MCHP	Micro combined heat and power
MVR	Mechanical vapour compression
NGCC	Natural Gas Combined Cycle
NPP	No proposed policy
OECD	Organisation for Economic Co-operation and Development
PBL	Netherlands Environmental Assessment Agency
PC	Pulverised Coal
PV	Photovoltaics
RVO	Netherlands Enterprise Agency
SER	Social and Economic Council of the Netherlands
ST	Steam turbine
TAB	Threshold Avoidance Budget
TEB	Threshold Exceedance Budget
VOM	Variable operational and maintenance
WGIII	Working group III
$\eta_{e,LHV}$	Electrical efficiency on a lower heating value basis
$\eta_{th,LHV}$	Thermal efficiency on a lower heating value basis

UNITS AND CONVERSION

Below, the units and conversion values and their full names used in this paper can be found.

Unit	Full name	Conversion	
J	Joule	1	J
MJ	Megajoule	$1*10^{6}$	J
GJ	Gigajoule	$1*10^{12}$	J
PJ	Petajoule	$1*10^{15}$	J
W	Watt	1	W
kW	Kilowatt	$1*10^{3}$	W
MW	Megawatt	$1*10^{6}$	W
GW	Gigawatt	$1*10^{9}$	W
PJ/a	Petajoule per year	$3.1536*10^{10}$	W
t	Tonne	1	t
Mt	Megatonne	$1*10^{6}$	t
Gt	Gigatonne	$1*10^{9}$	t
€	Euro	1	€
M€	Million euro	$1*10^{6}$	€
billion €	Billion euro	$1*10^{9}$	€

1. INTRODUCTION

The correlation between the increase in global average surface temperature and carbon dioxide (CO_2) emissions has become more and more apparent in recent years. The relationship is reliable, consistent and almost linear, according to the International Panel on Climate Change (IPCC, 2014a), and robust over a range of CO_2 emissions and a vast timescale (Rogelj, Schaeffer, et al., 2016). Policies and agreements that are supposed to inhibit anthropogenic climate change are therefore mainly focused on curbing CO_2 emissions and thereby restraining this global average temperature increase.

One of such agreements is the well-known *Paris Agreement*, signed in 2015 by 194 countries. In this agreement, it was agreed to '[hold] the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change' (United Nations Framework Convention on Climate Change, 2015).

Since the link between CO_2 emissions and temperature increase has been established, any level of global CO_2 emissions will result in a certain global average surface temperature increase. Inversely, any level of increase in the global average surface temperature may be expressed as a finite amount of CO_2 that may be emitted until this level is surpassed. This amount may also be referred to as a *carbon budget* (Van Vuuren, Boot, Ros, Hof, & den Elzen, 2016). The IPCC aggregates studies on carbon budgets in their Synthesis Report (IPCC, 2014a). The carbon budget would usually be presented as a global budget, but it can be argued that this can also be divided amongst nations. However, since there is no consensus internationally on how to share the carbon budget fairly amongst nations (Van Vuuren et al., 2016), countries lack knowledge on how to contribute to reaching the 1.5 °C target. Rogelj, den Elzen, et al. (2016) have also recognised this lack of knowledge and conclude that proposals made by countries in the Paris Agreement are insufficient to reach the 2 °C target, let alone 1.5 °C.

Such is the case in the Netherlands as well. Being a relatively prosperous, industrialised country, the Netherlands ranks high in CO_2 emissions per capita (#25 in 2015 (European Commission, n.d.)) and therefore also in absolute CO_2 emissions (#31 in 2014 (The World Bank, n.d.)). As a relatively small country, the Netherlands would logically not be expected to rank this high. The trend in CO_2 emissions reveals one of the causes: since 1990 the CO_2 emissions have increased slightly from 162.9 $MtCO_2$, fluctuating around the same figure throughout the years (CBS, 2017). Although this trend may not be wholly attributed to an inability to reduce CO_2 emissions, as economic growth also plays a part, it does show the Netherlands has been lagging in reducing their CO_2 emissions drastically. It will most likely continue to do so, as currently proposed policy project a 12 % decrease in CO_2 emissions compared to 1990 by 2030, while 40-50 % reduction compared to 1990 levels is needed (Van Vuuren et al., 2016).

The IPCC identifies a carbon budget of 2250 Gt of CO_2 from 1870, of which 400 Gt CO_2 from 2011 onward to limit global average temperature increase to 1.5 °C, as found by 66 % of model runs. They do, however, note that a limited amount of research has been done on the carbon budget for the 1.5 °C target. Based on the research by the IPCC, analysis by Millar et al. (2017) established a similar carbon budget for 1.5 °C of 375 Gt CO_2 from 2014 onward. This small difference is caused by inconsistencies between present-day emissions and simulations that start in 2010. With current emissions of 35.9 Gt CO_2 per year (2015 levels; Boden, Marland, & Andres, 2015), this gives around 11 years of current emissions before a temperature increase of 1.5 °C is inevitable. This small window indicates the high need of realising deep CO_2 emissions reduction and swift action by all nations.

Some research has been done on how to divide the carbon budget between nations. For example, the study by Raupach et al. (2014) examines how to distribute the carbon budget by different factors such as per capita, Gross Domestic Product (GDP) and shared responsibility. Also, the Climate Fairshares project, undertaken by scientists of the Stockholm Environment Institute and Friends of the Earth, attempts to equitably divide the carbon budgets of the IPCC amongst nations that are wealthier and ones that are not (Climate Fairshares, n.d.). They also factor in the wealth of countries so that they can provide financial support to developing countries. However, a common denominator in these studies is that they do not further examine what actions by the nations are required to stay below their national carbon budget.

Numerous studies focus on national efforts to help limit the global average temperature increase to 1.5 °C. They do so by using the goal of 80 % CO_2 emission reduction compared to 1990 by 2050 as established in the Paris Agreement (such as European Commission, 2012; International Energy Agency (IEA), 2000; Ministerie van Economische Zaken, 2016). These studies focus on the Netherlands, or the EU as a whole, and show the feasibility of 80 % CO_2 emission reduction, but neglect to take national carbon budgets into account. Also, significant variations in the technology mix allowing for these deep CO_2 emission reductions can be found. Technologies that have little to none, or even negative, CO_2 emissions are, for example, solar power, wind power, nuclear power, biomass, carbon capture and storage (CCS) and hydrogen. As many more of these alternative mitigation technologies exist, it is unclear which technologies, or a mix thereof, could realise the 1.5 °C target. For example, the European Commission (2012) suggests using hydrogen amongst other fuels for transportation, while the IEA (2000) and Ministry of Economic Affairs (2016) do not. This illustrates the difficulties for policymakers to focus their policy on stimulating the development and implementation of specific technologies.

According to Statistics Netherlands (CBS, 2017), the most prominent contributors to the total CO_2 emissions are the energy sector, the industry sector, households and commercial (henceforth: built environment), the transport sector and the agricultural sector. These *high-emission sectors* are therefore the primary focus of this study. This study will also limit the timeframe to 2050. As policy makers lack the knowledge on the mix of technologies that lead to profound CO_2 emission reduction, this leads to the following research question:

How can Dutch high-emission sectors develop until 2050 so as not to exceed the national carbon budget and contribute to limiting the global average temperature increase to 1.5 °C above pre-industrial levels?

This research question allows for research that investigates the environment and development of these sectors in the Netherlands. It will yield both investment costs up to 2050 as well as an overview of the composition of these sectors by 2050. This is relevant for policymakers, who can then pinpoint for which technologies research-and-development and investments are needed. It will also give insight into whether or not the 1.5 °C target can be achieved and, if so, how this is possible. This is especially relevant when comparing scenarios on costs or the mix of technologies present. This will have its implication for the society in the Netherlands, but maybe also of other countries as the conclusion of this study and its method may also be applied to other countries.

2. METHOD

To answer the research question, a detailed model of the energy system of the Netherlands has to be made, together with projections on how it will develop in the future. For this, the model generator MARKAL (for MARket ALlocation) was used. MARKAL describes the energy system of one or more regions and can be used for estimating energy dynamics over a horizon of multiple periods (Loulou, Goldstein, & Noble, 2004), using time steps of five years. It aims to find a solution that satisfies energy demand through a technology-oriented and disaggregated approach. The solution provides a set of technologies representing the least cost configuration for an energy system meeting both energy demand as well as other constraints, such as on emissions (Taylor, Upham, McDowall, & Christopherson, 2014). Recent applications include modelling the Bangladesh energy sector until 2035 using constraints on CO_2 emissions and a carbon tax (Mondal, Mathur, & Denich, 2011), an analysis of US renewable fuels policies such as mandates, subsidies and carbon taxes (Sarica & Tyner, 2013) and investigating carbon capture and storage options in the Dutch electricity sector, using the MARKAL-NL-

UU model developed by van den Broek, Faaij, & Turkenburg (2008). The latter provides the MARKAL-NL-UU model that is used in this study. The model uses 'perfect foresight', meaning it foresees the nature and timing of constraints over the whole modelling period and finds the least-cost technology configuration over this period. The MARKAL-NL-UU model that was provided contained the high-emission sectors of the Netherlands, but not all in the level of detail required to sufficiently answer the research question. This means it had to be adapted before it could be applied. The research consisted of six steps, for which the method is explained below.

Step 1: Establish national carbon budget

First, the carbon budget of the Netherlands needed to be established. Since the IPCC only quantifies a global carbon budget, a national carbon budget had to be established. There are multiple ways of doing so reasonably, and numerous studies have been conducted on the matter, all implementing one or multiple basic dimensions (Höhne, den Elzen, & Escalante, 2014):

- *Responsibility*: concerns the historical contribution to global emissions or warming, primarily by developing countries. It is based on Article 3 of the Paris Agreement, which states that 'the developed country Parties should take the lead in combating climate change and the adverse effects thereof' (United Nations Framework Convention on Climate Change, 2015).
- *Capability*: capacity or ability to pay for mitigation. Also based on Article 3 of the Paris Agreement, which ensures that the least capable countries may have a less ambitious reduction effort to secure their basic needs.
- *Equality*: Equal rights per nation - equal emission allowances based on characteristics of countries, such as GDP, population or current emissions.
- *Cost-effectiveness*: allocation based mitigation potential or cost-effectiveness - emissions reduced in each country to the extent that the marginal costs of further reductions are the same everywhere (carbon tax equal everywhere).

It was found that opinions of experts were divided on which of these dimensions to use when dividing the global carbon budget during expert interviews. Including either capability or cost-effectiveness in calculating the national carbon budget requires extensive research and a multinational approach, which goes beyond the scope of this research. Therefore, it is chosen to nationalise the global carbon budget on the basis of *equality*. It was found that an approach using *responsibility* will lead to a negative carbon budget. Therefore, this approach is not taken into account but instead applied in a sensitivity analysis.

The *equality* principle can be implemented in multiple ways. For example, one can take the current emissions of all countries and see what percentage the Netherlands contributes. This same percentage of the global carbon budget by 2050 is then available for the Netherlands. Also, the land area, the population or the GDP on the basis of Power Purchasing Parity (GDP PPP) of a country compared to the world can be used to calculate a percentage for the Netherlands, with which its national budget can be calculated. It is deemed illogical to use current emissions by the Netherlands. As current emissions are already quite high, since the Netherlands is a developed country, this would mean that the Netherlands would also get a substantial national carbon budget. This is deemed unfair compared to an underdeveloped country, which would have a lower amount of emissions compared to the Netherlands and, consequently, a lower national carbon budget. Land area has no relation to CO_2 emissions and is quite an arbitrary figure which would favour scarcely populated countries immensely, which is why this is also not considered. This leaves a division on the basis of population and GDP PPP.

Step 2: Technology inventory

MARKAL-NL-UU has been used in different studies since its development in 2008 (such as in Abdul Manaf, Qadir, & Abbas (2016); van den Broek, Brederode, et al. (2010); van den Broek, Ramírez, et al. (2010); van Meijl et al. (2016); Sun & Chen (2013)) and therefore has been developing and expanding throughout the years. Even so, it is essential to investigate whether all relevant technologies are present in MARKAL-NL-UU that may contribute to deep CO_2 emission reductions. For this, first, an investigation had been made on what technologies may lead to deep CO_2 emissions. All technologies that have been identified can be found in the results section. It is checked whether or not these technologies were already present in MARKAL-NL-UU. These technologies may generally be categorised into three categories:

1) *Technologies that still emit some CO_2, albeit less than their conventional counterparts*

These technologies are replacements or adaptations of conventional technologies. Replacements include technologies that have an overall higher efficiency, therefore needing less input for the same output, leading to lower CO_2 emissions. Adaptations include technologies using carbon capture and storage (CCS), which will lead to quite some reduction of the CO_2 emitted by a conventional process. Since it is generally not possible to capture all CO_2 emitted, this technology will still allow for some CO_2 emissions.

2) *Technologies that emit no CO_2*

These technologies have no input that encompasses CO_2 emissions. This includes all renewable technologies, such as solar and wind energy. It also includes technologies such as heat pumps and fuel cells. These are technologies that allow for a non-CO_2 emitting option of delivering a demand that could previously only be fulfilled in a CO_2 emitting manner by a condensing gas boiler. Heat pumps, and technologies alike, do have an indirect emission of CO_2 since it utilises electricity. However, the technology itself does not directly emit CO_2. Storage technologies, which allow for storing energy that would otherwise be wasted, also belong to this category.

3) *Technologies that have negative CO_2 emissions*

These technologies use more CO_2 in the process than they emit. Although many controversies with bioenergy exists (source), it is widely accepted that if applied correctly, truly sustainable bio-energy with CCS (BECCS) is one such process that has negative CO_2 emissions. The same goes for Carbon Capture and Utilisation (CCU) processes, which use CO_2 in their process for the production of materials.

Step 3: Data inventory

Next, techno-economic data of these technologies was gathered. In this process, data on the residual capacity of technologies currently present in MARKAL-NL-UU was also updated. This led to a model that describes the current situation in more detail. Since the demands, discount rates and energy prices are leading drivers of the model, these were also checked. Constraints were also added in the model, including the established national carbon budget for 2050.

Step 4: Definition of scenarios

In the fourth step, scenarios and its drivers used during the MARKAL-NL-UU runs were defined. The Baseline scenario in this research is a scenario in which the current *transition pathways* for the Netherlands are taken into account. These transition pathways are part of the Netherlands' pledges to the Paris Agreement and describe policies that allow for a gradual transition toward more sustainable sectors (Ministry of Economic Affairs, 2016). These transition pathways also encompass public opinion on specific technologies, making it more relevant to the Dutch situation.

Next to this is the scenario in which all technologies are available and in which the model is free to choose the technology mix of the Netherlands in order to keep within the national carbon budget. This scenario explores whether or not current and proposed policy in the transition pathways are indeed the most cost-effective. This is relevant for policymakers, who may then reflect if those policies are indeed useful.

There are also scenarios that contain the willingness to act. There is quite a difference of opinion with regard to closing down current fossil fuelled generators or retrofitting them, so they emit less CO_2 than previously. This is mainly due to the fact that CCS is not an undisputed technology and many doubts about its safety and impacts on the environment still exist. Therefore, a scenario is run in which no CCS is allowed. Another scenario, however, embraces the use of CCS. This scenario explores the possibility to use BECCS after 2030, instead of closing down the coal-fired power plants.

Step 5: Run MARKAL-NL-UU

In this step, MARKAL-NL-UU was run with the different scenarios and the results were interpreted. During this step, data and the assumptions were reviewed and, if need be, adjusted. This was done with the help of experts, who provided feedback on whether or not the deployment of technologies, and accompanying cost and energy generation, is realistic. This increases the strength of underlying assumptions and the research as a whole.

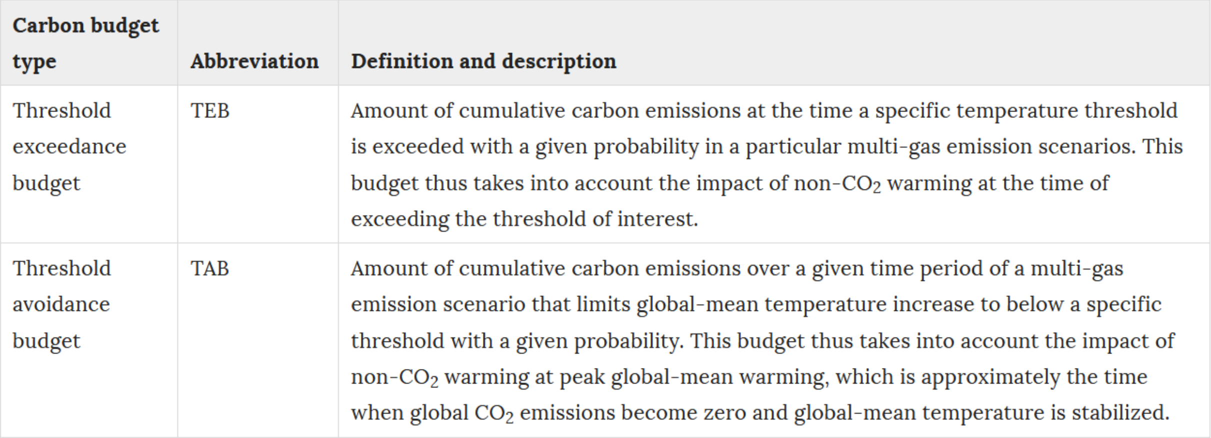
Step 6: Sensitivity analysis

A sensitivity analysis has also been performed. It is an evaluation of the sensitivity of the model outcomes with respect to uncertainty in the used data. This shows what data requires further extensive research so that the outcome of the research becomes more reliable. This is most important for technologies that are dominantly present in the resulting technology mix, to see how little or how much they are affected by changing assumptions. Changing the values of these parameters was done manually, as an automated sensitivity analysis is not feasible due to the complexity of the model. It is a one-at-a-time sensitivity analysis, which means one parameter is varied while keeping the others constant. This type of sensitivity analysis has its strength in revealing the relationship between the varied parameter and the output (ten Broeke, van Voorn, & Ligtenberg, 2016). First, an analysis of the chosen carbon budget is performed. Second, an analysis of the discount rate is done. Last, three alternatives to the Baseline scenario are considered based on the outcomes of the model. When dividing the global carbon budget, no responsibility aspect could be taken into account. This makes that the Netherlands does not take responsibility for historical CO_2 emissions. However, it could be argued that after such an extended period of time, the Netherlands has the possibility of taking responsibility by capturing the CO_2 that has been emitted in previous years using CCS or CCU technologies. Therefore, a model is considered in which the total emissions in 2050 may be a maximum of 0 $MtCO_2$, after which it is possible for the Netherlands to have negative emissions, thereby capturing historical CO_2 emissions. Next to this, the model assumes a substantial amount of biomass that may be used in the Netherlands. Of this amount of biomass, 450 PJ is imported from outside the EU. The CO_2-neutrality of this biomass may be questioned, which is why a model is considered in which this amount of biomass is not available. It is also considered if there are changes to the model outcome when the capture rate of CCS technologies in the electricity sector increase to 100 %, thereby making these technologies more attractive to decrease CO_2 emissions.

3. RESULTS

3.1 National Carbon Budget

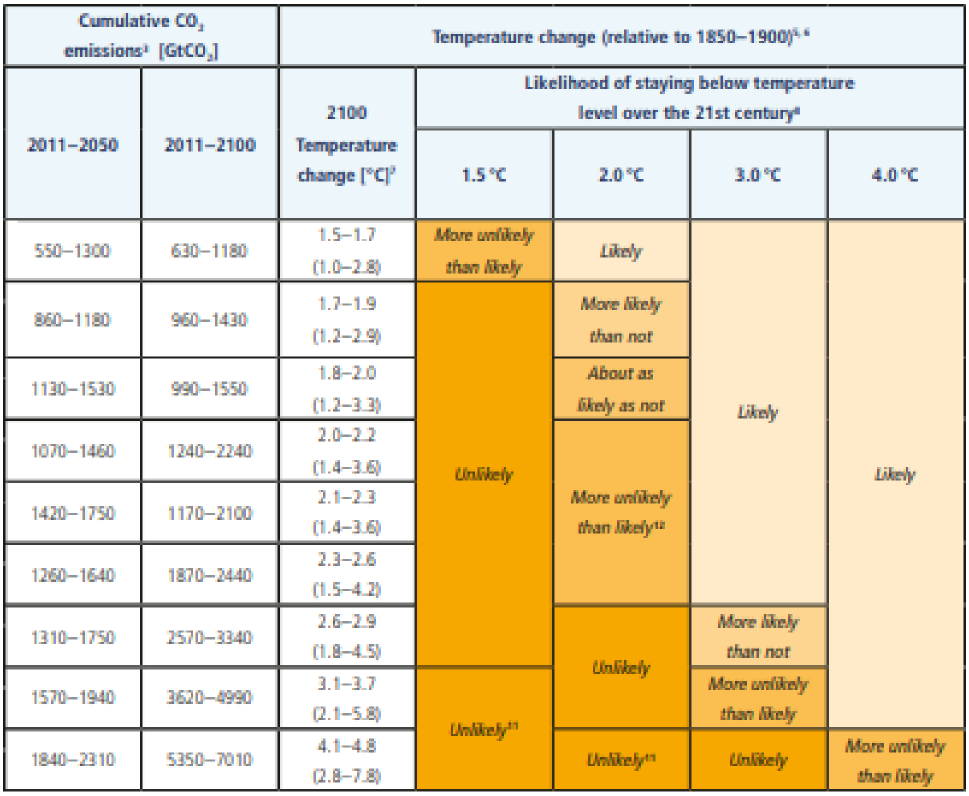
Global carbon budgets are classified by the IPCC in two different categories: those calculated by complex models and simple models, calculated by the IPCC Working Group III (WGIII). The difference in these carbon budgets can be found in the numbers they represent. The complex model carbon budgets are calculated using a Threshold Exceedance Budget (TEB) approach, the simple model carbon budgets using a Threshold Avoidance Budget (TAB) approach. A definition, adapted from table 1 of Rogelj, Schaeffer, et al. (2016), is given below, in Figure 1.



Carbon budget type	Abbreviation	Definition and description
Threshold exceedance budget	TEB	Amount of cumulative carbon emissions at the time a specific temperature threshold is exceeded with a given probability in a particular multi-gas emission scenarios. This budget thus takes into account the impact of non-CO$_2$ warming at the time of exceeding the threshold of interest.
Threshold avoidance budget	TAB	Amount of cumulative carbon emissions over a given time period of a multi-gas emission scenario that limits global-mean temperature increase to below a specific threshold with a given probability. This budget thus takes into account the impact of non-CO$_2$ warming at peak global-mean warming, which is approximately the time when global CO$_2$ emissions become zero and global-mean temperature is stabilized.

Figure 1 - Definitions of threshold exceedance budget and threshold avoidance budget (adapted from Rogelj, Schaeffer et al., 2016)

The TEB approach has the underlying assumption that non-CO$_2$ emissions forcing as a function of cumulative CO$_2$ emissions is similar throughout scenarios. However, Rogelj, Schaeffer, et al. (2016) found that for any given level of cumulative CO$_2$ emissions, the forcing of non-CO$_2$ emissions may differ immensely. Due to the nature of the approach, TEB approaches also assume non-CO$_2$ emissions do not exceed the levels as calculated at the time the TEB was computed. TAB approaches, on the other hand, account for all CO$_2$-equivalent categories when establishing the exceedance probability of the budget. It is therefore chosen to calculate the national carbon budget using the budgets calculated with a TAB approach. TABs for the periods 2011-2050 have been calculated by WGIII and are given below, in Figure 2. It can be seen that a temperature increase of 1.5 °C relative to pre-industrial times is mostly found to be unlikely, the term used by the IPCC for a probability of 0-33 % to stay below the threshold. The cumulative CO$_2$ emissions of 550-1300 GtCO$_2$ are more unlikely than likely (0=<50 %). Since this is the highest probability to stay below a 1.5 °C increase relative to pre-industrial times, this is the budget that will be used in this study.



Cumulative CO$_2$ emissions^{3} [GtCO$_2$]		Temperature change (relative to 1850–1900)^{5,6}				
2011–2050	2011–2100	2100 Temperature change [°C]^{7}	Likelihood of staying below temperature level over the 21st century^{8}			
			1.5 °C	2.0 °C	3.0 °C	4.0 °C
550–1300	630–1180	1.5–1.7 (1.0–2.8)	*More unlikely than likely*	*Likely*	*Likely*	*Likely*
860–1180	960–1430	1.7–1.9 (1.2–2.9)	*Unlikely*	*More likely than not*		
1130–1530	990–1550	1.8–2.0 (1.2–3.3)		*About as likely as not*		
1070–1460	1240–2240	2.0–2.2 (1.4–3.6)		*More unlikely than likely*^{12}		
1420–1750	1170–2100	2.1–2.3 (1.4–3.6)				
1260–1640	1870–2440	2.3–2.6 (1.5–4.2)				
1310–1750	2570–3340	2.6–2.9 (1.8–4.5)		*Unlikely*	*More likely than not*	
1570–1940	3620–4990	3.1–3.7 (2.1–5.8)	*Unlikely*^{11}		*More unlikely than likely*	
1840–2310	5350–7010	4.1–4.8 (2.8–7.8)		*Unlikely*^{11}	*Unlikely*	*More unlikely than likely*

Figure 2 - Cumulative CO$_2$ emissions for the period 2011-2050 and the likelihood of staying below 1.5 °C (IPCC, 2014b)

IPCC (2014a) summarized this output of IPCC (2014b) and further distinguished the probabilities associated with this budget. For a budget of 550-600 $GtCO_2$, there is a 50 % chance of staying below 1.5 °C, for a budget of 600-1300 $GtCO_2$ there is a 33 % probability. This budget can then serve as a basis to calculate the budget for the Netherlands. There are two approaches used: (1) on the basis of current GDP PPP and (2) on the basis of current population. These approaches all use a simple division based on percentages; meaning equal CO_2 emissions per unit. Some demographic data on the Netherlands as well as the world is needed, obtained from the Central Intelligence Agency (CIA). This data can be found in Table 1 below.

Table 1 - Data on the population and GDP PP of the world and the Netherlands

	World	the Netherlands	Source
Population in 2017 (Millions)	7,405.1	17.1	World:(CIA, n.d.-a), the Netherlands: (CIA, n.d.-b)
GDP PPP (billion $\$_{2017}$)	120,200	869.4	World:(CIA, n.d.-a), the Netherlands: (CIA, n.d.-b)
Emissions period 2011 - 2016 ($MtCO_2$)		992.4	(CBS, 2017)

Both approaches yield a national carbon budget from 2010 to 2050, after which Dutch CO_2 emissions in the period 2011-2016 are subtracted (Table 1), yielding a national carbon budget from 2017 to 2050. Results can be found in Table 2 below.

Table 2 - National carbon budgets calculated for the Netherlands

	World ($GtCO_2$)		the Netherlands ($GtCO_2$)		
Population					
	Lower	Upper	Lower	Average	Upper
Budget for 1.5 °C (33-50 %)	550	600	0.28	0.33	0.39
Budget for 1.5 °C (0-33 %)	600	1300	0.39	1.20	2.00
GDP PPP					
	Lower	Upper	Lower	Average	Upper
Budget for 1.5 °C (33-50 %)	550	600	2.99	3.17	3.35
Budget for 1.5 °C (0-33 %)	600	1300	3.35	5.88	8.41

At the moment, the Netherlands emits 167.23 $MtCO_2$/yr (CBS, 2017). The national government targets 0 $MtCO_2$/yr by 2050, meaning a total budget of $167.23 * 32 * 0.5/1000 = 2.68$ $GtCO_2$ when emissions decrease linearly from current levels. Of the two dimensions, the division on the basis of GDP PPP matches this budget the best. Therefore, the average value of the GDP PPP national carbon budget with 33-50 % chance is used as a basis of this study. The other budgets will also be analysed in a sensitivity analysis, results of which can be found in section 3.6.1. National carbon budget

3.2 Technology inventory

The technologies that are available for the Netherlands that could cause deep CO_2 emission reduction are listed in

Appendix I. From this list, a summary of missing technologies categorized per high-emission sector can be made.

3.2.1. The electricity sector

For the electricity sector, most large technologies were already modelled in MARKAL-NL-UU. Table 3 shows the technologies that where not yet modelled. The three technologies that were added to the electricity sector function as electricity storage. When electricity supply is higher than demand due to solar and wind technologies, this electricity may be stored in batteries or in hydrogen. Electricity can then either be supplied by the batteries or supplied by fuel cells, which convert the hydrogen into electricity. Most technologies were found to either have no potential in the Netherlands or to be underdeveloped. The latter case indicates that little to no research had been done on the technology or currently only lab testing or small pilot projects are successful. This signifies high uncertainty on the techno-economic parameters of the technology, meaning these technologies could not be modelled in detail. These technologies may, however, be potentially viable options in the future.

Table 3 - Inventory of technologies in the electricity sector to be added to the MARKAL-NL-UU model

Technology[1]	Added to MARKAL-NL-UU	Reason
Battery electricity storage: power to power	Yes	
Blue energy	No	Underdeveloped
Concentrated photovoltaics (PV)	No	No potential
Concentrated solar power	No	No potential
Fuel cells: hydrogen	Yes	
High head hydropower	No	No potential
Hydrogen electricity storage: power to hydrogen	Yes	
Landfill gas with CCS	No	Underdeveloped
Ocean Thermal Electricity Conversion	No	No potential
Solar water heating	No	No potential
Tidal	No	Underdeveloped
Waste with CCS	No	Underdeveloped
Wave	No	Underdeveloped

[1] References can be found in Appendix I

3.2.2. The industrial sector

The industrial sector can benefit most from technologies that reduce the CO_2 emission for heat used in processes, as is shown in Table 4. Electric boilers, hybrid boilers and electric furnaces may replace conventional gas and coal-fired variants. Heat pumps may be used to upgrade low temperature heat to high temperature heat, thus increasing the energy content. The same process is available for low temperature steam through mechanical vapour recompression (MVR). Currently available chemical conversion processes capturing CO_2, such as manure co-digestion and the production of Urea, were already modelled in MARKAL-NL-UU. Others as proposed by Al-Mamoori et al. (2017) are considered underdeveloped. CCU in the desalination of water is not applicable in the Netherlands, as potable water is not produced by desalination. Mineralization CCU is an underdeveloped technology with many drawbacks, according to Al-Mamoori et al. (2017). Medium temperature heat is implicitly modelled in high-temperature heat, and it is chosen not to model it separately.

Table 4 - Inventory of technologies in the industrial sector to be added to the MARKAL-NL-UU model

Technology[1]	Added to MARKAL-NL-UU	Reason
Chemical conversion CCU	No	Underdeveloped
Desalination CCU	No	No potential
Electric boilers	Yes	
Electric furnace	Yes	
Heat pump	Yes	
Hybrid hydrogen/gas boilers	Yes	
MVR	Yes	
Medium temperature heat	No	Implicitly modelled

Mineralisation CCU	No	Underdeveloped

[1] References can be found in Appendix I

3.2.3. The built environment

For the built environment, the deep CO_2 emission reductions can be found in space heating and hot water use. The technologies are therefore focused on this demand, see Table 5 below. Energy storage may be used to store heat in summer, which may then be used in winter. Electric boilers and small power to heat furnaces may be used to provide heat, replacing conventional boilers. Heat pumps can be applied to pump heat into the house, either from the air or the ground. These heat pumps may use electricity, green gas or both gas and electricity. Geothermal heat, based on a similar principle as ground source heat pumps, may supply heat from deep geothermal layers to a district heating system. Isolation may also be applied, thereby reducing demand for heat and therefore ensuring less heat has to be generated. Three types of insulation are defined; a cheap, moderate and expensive variant. Both electricity and heat can be generated using micro combined heat and power and gas or a small-scale fuel cell and hydrogen. Solar boilers capture the heat from solar irradiation, to supply hot water to a household.

Table 5 - Inventory of technologies in the built environment to be added to the MARKAL-NL-UU model

Technology[1]	**Added to MARKAL-NL-UU**	**Reason**
Aquifer Thermal Energy Storage (ATES)	Yes	
Electric boilers	Yes	
Electric furnace (power to heat)	Yes	
Geothermal	Yes	
Heat pump, air source	Yes	
Heat pump, green gas	Yes	
Heat pump, ground source	Yes	
Heat pump, hybrid	Yes	
Isolation, cheap	Yes	
Isolation, moderate	Yes	
Isolation, expensive	Yes	
Micro combined heat and power (MCHP)	Yes	
Small-scale fuel cell	Yes	
Solar boiler	Yes	

[1] References can be found in Appendix I

3.2.4. The transport sector

The transport sector has already been modelled in MARKAL-NL-UU in great detail, meaning no technology is added in this sector.

3.2.5. The agricultural sector

The CO_2 emissions of the agricultural sector originate mainly due to greenhouses requiring heat, according to the Energy Research Centre of the Netherlands (ECN, 2017). Therefore, deep CO_2 emissions can be obtained by making this heat use renewable, just as in the industry. This is done by storing low-temperature heat from industry in an ATES system or utilizing geothermal heat, as is shown Table 6.

Table 6 - Inventory of technologies in the agricultural sector to be added to the MARKAL-NL-UU model

Technology[1]	**Added to MARKAL-NL-UU**	**Reason**
ATES	Yes	
Geothermal	Yes	

[1] References can be found in Appendix I

3.3. Data inventory

3.3.1. Model drivers in MARKAL-NL-UU

Demands

Demands are driving factors in models such as MARKAL-NL-UU. It is therefore vital that these demands are updated in order to describe the current a realistic development according to the latest insights. Table 7 shows the energy intensive demands that are present in MARKAL-NL-UU. The demands for materials, such as ammonia and cement, were defined by Tsiropoulos (2016). It is assumed that these demands, which were calculated up to 2030, do not further change after 2030. Electricity and heat demands were also modelled by Tsiropoulos (2016) and originate from late 2015 from ECN (2015). These demands incorporate policies established in 2012. District heat demands were determined by Brouwer, van den Broek, Seebregts, & Faaij (2015). The rest heat demands are the heat demands for the sectors as calculated by ECN (2015), after which the district heat demands from Brouwer et al. (2015) were subtracted. For the electricity demand, double counting is avoided for conventional industrial operations that are explicitly modelled by subtracting 10 PJ per year from 2010 onward. For the rest heat demand in industry, 60 PJ is subtracted to avoid double counting. Vehicle kilometres were last updated by van Vliet, van den Broek, Turkenburg, & Faaij (2011), using values from the ‘Welfare and Environment’ study from 2006 (Janssen, Okker, & Schuur, 2006). This study calculates a growth of 15 to 21 % of vehicle kilometres from 2010 to 2040[1]. In a more recent version of the study (Centraal Planbureau & Planbureau voor de Leefomgeving (PBL), 2015) a growth of around 19 % is calculated in the same period[2]. It is therefore deemed unnecessary to update these demands in MARKAL-NL-UU, as a similar growth in 2015 is estimated as was in 2006. Refer to Appendix II for all demands as specified in MARKAL-NL-UU.

Table 7 - Energy intensive demands in MARKAL-NL-UU

Demand	Unit	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	Source
Ammonia	Mt	2.0	2.0	2.0	2.2	2.4	2.7	2.9	2.9	2.9	2.9	2.9	Tsiropoulos (2016)
Cement	Mt	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Tsiropoulos (2016)
Hydrogen	Mt	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Tsiropoulos (2016)
Refinery	Mt	32.9	32.9	32.9	32.7	30.2	29.9	28.9	28.9	28.9	28.9	28.9	Tsiropoulos (2016)
Steel	Mt	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	Tsiropoulos (2016)
Urea	Mt	1.1	1.1	1.1	1.2	1.3	1.4	1.5	1.5	1.5	1.5	1.5	Tsiropoulos (2016)
Electricity	PJ	373.7	403.7	418.5	411.3	420.8	425.8	429.5	441.7	451.5	461.5	471.8	ECN (2015)
Agricultural district heat	PJ	18.7	20.0	61.0	62.0	74.0	79.0	87.0	94.0	103.0	109.0	116.0	Brouwer et al. (2015)
Agricultural rest heat	PJ	120.7	97.8	26.3	29.9	18.9	16.1	10.2	10.2	10.2	10.2	10.2	ECN (2015)
Industrial district heat	PJ	141.0	141.0	141.0	142.0	144.0	144.0	133.0	132.0	132.0	130.0	127.0	Brouwer et al. (2015)

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[1] Depending on the figure for 2010. Data for 2010 has to be read from a graph and is estimated to be between 220 and 230 billion passenger-kilometres.

[2] The growth from 2010 until 2030 is 13 % and from 2010 until 2050 is 25 %. The average is a growth of 19 % from 2010 to 2040, if linear growth is assumed between 2030 and 2050.

Industrial rest heat	PJ	258.0	261.3	209.5	192.5	195.9	208.5	232.1	232.1	232.1	232.1	232.1	ECN (2015)
Built environment district heat	PJ	33.0	33.0	24.0	27.0	26.0	31.0	29.0	29.0	30.0	32.0	33.0	Brouwer et al. (2015)
Built environment rest heat	PJ	407.0	415.2	462.1	421.9	412.9	404.7	403.4	403.4	403.4	403.4	403.4	ECN (2015)
Bus kilometres	Bv-km	0.6	0.6	0.7	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	Janssen, Okker & Schuur (2006)
Personal vehicle kilometres	Bv-km	91.2	96.9	100.9	105.0	109.2	113.7	118.3	123.1	128.1	133.3	138.7	Janssen, Okker & Schuur (2006)
Truck kilometres	Bv-km	6.8	6.8	7.1	7.4	7.7	8.0	8.3	8.6	9.0	9.3	9.7	Janssen, Okker & Schuur (2006)
Van kilometres	Bv-km	15.0	18.2	19.0	19.7	20.5	21.4	22.2	23.1	24.1	25.1	26.1	Janssen, Okker & Schuur (2006)

Economic data

Energy prices also influence the choices of energy technologies and are a driving factor in the model. The prices of the primary energy carriers, except biomass, can be found in Table 8 below. Other prices, such as the prices for different biomass energy carries, can be found in Appendix III. All prices were last updated by Tsiropoulos (2016) for the period 2015-2030. These were then extrapolated to 2050. The discount rate, also an important factor in the model, is assumed to be 7 %.

Table 8 - The prices for primary energy carriers in MARKAL-NL-UU

Technology	Units	2015	2020	2025	2030	2035	2040	2045	2050
Bituminous coal	€$_{2010}$/GJ	2.4	2.8	3.0	3.1	3.4	3.6	3.8	4.1
Crude oil	€$_{2010}$/GJ	11.5	9.5	11.5	13.4	13.4	14.2	14.9	15.7
Geothermal	€$_{2010}$/GJ	0	0	0	0	0	0	0	0
Hydro	€$_{2010}$/GJ	0	0	0	0	0	0	0	0
LPG	€$_{2010}$/GJ	9.4	9.6	10.1	10.6	10.6	10.6	10.8	11.1
Naphtha	€$_{2010}$/GJ	12.7	10.5	12.6	14.8	14.8	15.6	16.4	17.3
Natural gas	€$_{2010}$/GJ	6.0	5.0	6.1	7.2	7.3	7.8	8.3	8.7
Solar	€$_{2010}$/GJ	0	0	0	0	0	0	0	0
Uranium oxide	€$_{2010}$/GJ	2.0	2.2	2.3	2.4	2.6	2.7	2.8	3.0
Waste	€$_{2010}$/GJ	0	0	0	0	0	0	0	0
Wind	€$_{2010}$/GJ	0	0	0	0	0	0	0	0

[1] Prices from 2030 to 2050 are extrapolated from values in MARKAL-NL-UU.

3.3.2. Techno-economic data updated in MARKAL-NL-UU

Updates to techno-economic data are necessary only for technologies that have been modelled in early stages of the model. Due to previous work performed by Tsiropoulos (2016), which had a high focus on the industry and agriculture sector, it assumed that these technologies are not in need of updating. Data on the transport sector was updated latest when it was added to the model by Van Vliet, et al. (2011). However, due to the complexity of this sector, updating data in this sector would require a study in itself, which makes that it is chosen to leave the sector as is. Therefore, only data in the electricity sector is examined. Data from the Joint Research Centre (JRC, 2018) was used in order to check whether it needed updating. Most data that was present in MARKAL-NL-UU matches the data, except for solar PV and wind technologies. This can be explained by the fact that the data in this sector was last updated by Brouwer, van den Broek, Seebregts, & Faaij (2015), while these technologies develop quickly. All other technologies in the electricity sector in MARKAL-NL-UU can be found in Appendix IV. Below, in Table 9, the updated investment cost data are given, as well as fixed operation and maintenance (FOM) percentages. Data from JRC (2018) is given in €$_{2015}$, while MARKAL-NL-UU uses data in 2010 €. Therefore, the data from JRC to €$_{2010}$ by multiplying by 0.93, as is the conversion factor based on the inflation rates published by the Organisation for Economic Co-operation and Development (OECD, 2018b).

Table 9 - Techno-economic data updated in MARKAL-NL-UU

Technology	Unit	2015	2020	2030	2040	FOM (as a percentage of investment costs per year)
Solar PV	€$_{2010}$/kW	1063	672	401	326	2.5 %
Wind offshore	€$_{2010}$/kW	3265	2229	1446	1259	2.0 %
Wind onshore	€$_{2010}$/kW	1017	923	784	718	3.0 %

3.3.3. Techno-economic data added to MARKAL-NL-UU

Below, in Table 10, the techno-economic data that were added to MARKAL-NL-UU are shown. Where possible, values for investment and operation and maintenance costs representative for the Netherlands are used. For example, averages of twelve technologies were used for each variant of heat pumps, of which investment data represents total costs of replacing a conventional boiler with a heat pump for Dutch residences. For insulation, it was found that significant differences exist between residences built before 1992, residences built after 1992 and buildings in the commercial sector. Therefore, separate technologies were constructed for each of these building categories. Further information on insulation can be found in Appendix V. For the industry sector, technologies and corresponding data as suggested by Royal VEMW (2017) for the Netherlands have been used. Otherwise, values are used from similar countries, like Denmark. This is applicable to operation and maintenance costs for heat pumps. General values applicable to the European Union or the world are also used, as was the case with the investment costs of fuel cells and MCHPs. Again, whenever needed, cost values were converted to yield 2010 € values. OECD data on exchange rates (OECD, 2018a) and inflation rates (OECD, 2018b) were used.

Table 10 - Techno-economic data added to MARKAL-NL-UU[a]

Sector	Technology	Input	Output	Capacity unit	AF/CF	$\eta_{e,LHV}$	$\eta_{th,LHV}$	INV	FOM	VOM	Lifetime	Cost change
Electricity	Battery electricity storage	Electricity	Electricity	GW	0.95[1]	80 %[2]	-	488[2]	1.4[3]	0.5[3]	9[2]	-70 %[2]
	Fuel cell	Hydrogen	Electricity, heat	GW	0.96[4]	45 %[5]	30 %[5]	764[6]	22.9[7]	7.6[8]	25[4]	-68 %[5]
	Hydrogen electricity storage	Electricity	Hydrogen	GW	0.96[4]	-	70 %[4]	1607[4]	48.2[7]	16.1[8]	25[4]	-68 %[5]
Industry	Industrial electric boiler	Electricity	Heat	GW	0.95[9]	-	95 %[9]	56[10]	1.0[10]	0.1[10]	30[9]	-15 %[11]
	Industrial hybrid boiler	Hydrogen or gas	Heat	GW	0.95[9]	-	95 %[9]	302[9]	109.0[9]	15.0[9]	30[9]	-15 %[11]
	Industrial electric furnace	Electricity	Heat	GW	0.90[9]	-	90 %[9]	26[9]	115.2[9]	15.9[9]	30[9]	-15 %[11]
	Heat pump	Electricity, heat	Heat	GW	0.95[9]	-	300 %[9]	431[9]	34.6[9]	4.8[9]	10[9]	-35 %[5]
	MVR	Electricity, heat	Heat	GW	0.90[9]	-	300 %[9]	122[9]	34.6[9]	4.8[9]	20[9]	-35 %[5]
Built environment	ATES	Electricity, heat	Heat	GW	0.17[12]	-	130 %[13]	1302[13]	11.7[14]	0.3[14]	15[15]	-75 %[5]
	Electric boiler	Electricity	Heat	PJ$_{/yr}$	1.00[11]	-	100 %[11]	39[13]	0.2[11]	0.0[11]	30[11]	-15 %[11]
	Geothermal	Geothermal heat, Electricity	Electricity	GW	0.40[16]	-	75 %[16]	2883[16]	0.1[16]	0.5[16]	40[17]	-35 %[5]
	Heat pump, air source	Electricity, heat	Heat	PJ$_{/yr}$	0.05[18]	-	345 %[5]	43[13]	0.2[11]	0.1[11]	18[11]	-35 %[5]

	Heat pump, green gas	Green gas, heat	Heat	PJ$_{/yr}$	0.05[18]	-	140 %[5]	11[19]	0.2[11]	0.1[11]	20[11]	-35 %[5]
	Heat pump, ground source	Electricity, heat	Heat	PJ$_{/yr}$	0.05[18]	-	390 %[5]	65[13]	0.2[11]	0.1[11]	20[11]	-35 %[5]
	Heat pump, hybrid	Green gas, electricity, heat	Heat	PJ$_{/yr}$	0.05[18]	-	450 %[5]	44[13]	0.2[11]	0.1[11]	20[11]	-35 %[5]
	Insulation <1992 (cheap)	-	-	PJ$_{/yr}$	-	-	-	126[20]	-	-	-	0 %[21]
	Insulation <1992 (moderate)	-	-	PJ$_{/yr}$	-	-	-	267[20]	-	-	-	0 %[21]
	Insulation <1992 (expensive)	-	-	PJ$_{/yr}$	-	-	-	405[20]	-	-	-	0 %[21]
	Insulation >=1992 (moderate)	-	-	PJ$_{/yr}$	-	-	-	2839[20]	-	-	-	0 %[21]
	Insulation >=1992 (expensive)	-	-	PJ$_{/yr}$	-	-	-	1196[20]	-	-	-	0 %[21]
	Insulation buildings (cheap)	-	-	PJ$_{/yr}$	-	-	-	73[20]	-	-	-	0 %[21]
	Insulation buildings (moderate)	-	-	PJ$_{/yr}$	-	-	-	133[20]	-	-	-	0 %[21]
	Insulation buildings (expensive)	-	-	PJ$_{/yr}$	-	-	-	177[20]	-	-	-	0 %[21]
	MCHP	Gas	Electricity, heat	PJ$_{/yr}$	0.96[11]	27.5 %[5]	40 %[5]	19[5]	0.0[11]	3.6[11]	20[11]	-40 %[5]
	Small scale fuel cell	Hydrogen	Electricity, heat	PJ$_{/yr}$	0.96[11]	33.5 %[5]	39 %[5]	164[5]	0.0[11]	0.3[8]	10[11]	-68 %[5]
	Solar boiler	Solar radiation	Heat	PJ$_{/yr}$	0.08[16]	-	70 %[5]	33[13]	0.5[11]	0[11]	20[11]	-63 %[5]
Agriculture	ATES	Electricity, heat	Heat	GW	0.34[12]	-	130 %[13]	1302[12]	11.7[14]	0.3[14]	15[15]	-75 %[5]
	Geothermal	Geothermal heat, Electricity	Electricity	GW	0.68[16]	-	75 %[16]	1987[16]	0.1[16]	0.5[16]	40[17]	-35 %[5]

[a] Given are the availability factor (AF) or capacity factor (CF), electrical lower heating value based efficiency ($\eta_{e,LHV}$), thermal LHV based efficiency ($\eta_{th,LHV}$), investment costs (INV), fixed operation and maintenance (FOM), variable operation and maintenance (VOM) and change in investment for the technologies (cost change). The capacity unit of the technologies differs due to the nature of the technology. When a technology is modelled such that it may not fulfil a demand directly and it therefore needs to be either distributed or applied in a process to fulfil demand, technologies have a capacity unit in gigawatts (GW). When this is not the case, the technology has a capacity unit in petajoules per year (PJ/yr). This has its effect on the values of the technologies. Technologies that have their capacity modelled in GW have an AF whereas technologies that have their capacity modelled in PJ/yr have a CF. The AF has an influence on the CF, as the AF specifies the maximum availability of capacity of a technology. Technologies with a CF have a fixed amount of capacity that is used. Also, INV and FOM are given in million €$_{2010}$/capacity unit, VOM are given in €$_{2010}$/GJ and lifetime in years. The cost change is the percentage change in investment costs from 2015 to 2050 and is assumed to change linearly.

[1] Assumption.

[2] From International Renewable Energy Agency (2017)

[3] Identical operational and maintenance costs are assumed as other batteries given in Viswanathan, Kinter-Mayer, Balducci, & Jin (2013).

[4] It is assumed that the AF of a fuel cell is equal to that of an electrolysis plant, which is the same system in reverse. An AF of 8400 hours is used. The same assumption holds for lifetime. All values based on a PEM electrolysis plant from Götz et al. (2016). For the investment costs, values of 1000 €/kW input and 1250 €/kW input are given. The average is taken and converted to €/kW output, to assure consistency in the values presented.

[5] Values are averages taken from IEA (2011). Value for decrease in costs of electrolysis is assumed similar to large fuel cells due to similarities in the system.

[6] Averages of investment costs are taken from IEA (2015).

[7] Assumption taken from James & Moton (2014), where 3 % of investment costs is used.

[8] VOM is one-third of FOM, according to Hamdan (2014).

[9] Values taken from Royal VEMW (2017). Electric boiler AF and $\eta_{th,LHV}$ are assumed similar to that of hybrid boiler. OPEX are assumed to be distributed similarly as in [10].

[10] From Hers, Afman, Cherif, & Rooijers (2015).

[11] Danish Energy Agency & Energinet (2018). Values for a decrease in costs for industrial boilers and furnace assumed the same of that of residential boilers.

[12] Value for industry taken from small ATES characteristics, value for agriculture taken from large ATES characteristics from Agentschap NL (2012).

[13] Values for these technologies are averages of values found in Arcadis (2016).

[14] ATES use heat pumps for operation. However, there is also O&M costs for the dwellings. It is therefore assumed that FOM and VOM costs are twice as high for ATES as regular heat pumps.

[15] Values from the Netherlands Enterprise Agency (RVO, 2011).

[16] Values are taken from Lensink & Cleijne (2016), which are values used as a base case for renewable technologies in the Netherlands.

[17] Values are from large GSHPs as described in Chua, Chou, & Yang (2010).

[18] Value of Segers (2015) is for AHP. It is assumed that this is similar for all heat pumps. Value shows the amount of hours that heat pumps are used, therefore reflecting the actual situation.

[19] Value is assumed four times lower than a heat pump on electricity, as values from [11] show. This ratio is assumed the same for Dutch heat pumps.

[20] Values are based on Quintel Intelligence (2018), who used [13] for their calculations. More explanation on insulation can be found in Appendix V.

[21] No evidence of cost reduction by 2050 was found in literature. Therefore, it is assumed that there is no cost reduction in 2050.

3.3.4. Residual capacity

The residual capacity in MW of technologies in the electricity sector and the built environment is given in Table 11 below.

Table 11 - Residual capacity in MW

Sector	Technology	2000	2005	2010	2018	2020	2025	2030	2035	2040	2045	2050
Electricity	CHP	2700	2800	2600	2400	1800	100	0	0	0	0	0
	CHP on biomass	25	25	45	45	45	20	20	20	0	0	0
	Gas Engine (GE)	1690	1846	3594	3272	2653	2230	0	0	0	0	0
	Gas Turbine (GT)	996	1012	1210	839	686	403	228	7	0	0	0
	GT peaking plant	173	279	253	154	154	154	124	0	0	0	0
	Hydro[1]	37	37	37	37	37	37	37	37	37	0	0
	Integrated Gasification Combined Cycle (IGCC)	250	250	250	0	0	0	0	0	0	0	0
	Natural Gas Combined Cycle (NGCC) existing	7478	7045	6405	3338	3338	3338	525	525	525	525	525
	NGCC new (2000)	1600	3100	3400	3300	2800	4100	2100	1300	0	0	0
	NGCC new (2010)	0	0	2170	6790	6790	6790	6790	6790	6790	4620	0
	Nuclear	449	449	484	484	484	484	484	0	0	0	0
	Pulverised Coal (PC)[2]	0	0	0	3430	3430	3430	3430	3430	3430	0	0
	PC subcritical[2]	2693	2693	2693	630	630	630	630	630	0	0	0
	PC supercritical[2]	1230	1230	1230	600	600	600	600	600	0	0	0
	Solar PV[1]	1	5	9	2749	2749	2748	2744	2740	1230	0	0
	Steam Turbine (ST)	313	299	208	208	208	208	129	129	79	46	46
	Waste	394	429	586	649	649	649	649	649	649	649	649
	Wind offshore[1]	0	0	228	957	957	957	957	729	600	0	0
	Wind onshore[1]	447	1224	2009	3244	3244	2797	2020	1235	210	0	0
Built environment	Heat pump, air source[3]	6	22	499	2507	2491	2014	472	472	472	0	0
	Heat pump, ground source[3]	59	233	749	1312	1138	622	74	74	74	0	0
	Solar boiler[4]	193	295	403	457	264	161	53	3	3	0	0

[1] Data were taken from (CBS, 2018a).

[2] The newly built coal-fired power plants, *Engie Centrale Rotterdam*, *MPP3* and *Eemshavencentrale,* have a total nameplate capacity of 3430 MW and have been modelled as PC plants by Tsiropoulos (2016). The *Hemweg-8* power plant is modelled as the only remaining subcritical PC power plant. The *Amer-9* power plant is modelled as the only remaining supercritical power plant. The *Amer-8*, *Gelderland-13* and *Borssele-12* power plants were decommissioned in 2015. In 2016, the *MPP3* power plant became operational and in 2017 the *Maasvlakte 1&2* power plants became non-operational. Due to the time steps of five years in MARKAL-NL-UU, the commissioning and decommissioning of power plants can be precisely modelled on the actual dates. To make sure that this has little effect on the outcome, the *Amer-8*, *Gelderland-13* and *Borssele-12* power plants are modelled non-operational in 2015 and the *MPP3* and *Maasvlakte 1&2* power plants are modelled (still) operational from 2015 onward. The *Maasvlakte 1&2* plants are then non-operational by 2020.

[3] Data from CBS (2018a). This data also entails ATES systems, but no data is available on the ratio. It is therefore assumed to all be conventional heat pumps.

[4] Data from CBS (2018c). For solar boilers, a factor of 0.7 kW/m^2 is used, as in RVO & CBS (2015).

3.4 Scenarios

3.4.1. Baseline scenario

The basis of the research contains a scenario in which the current state of and proposed Dutch policy will be taken into account. For this, mostly the Agreement on Energy for Sustainable Growth, or *Energieakkoord* from the Social and Economic Council of the Netherlands (SER, 2013) and an analysis of the *Regeerakkoord*, the coalition agreement, by PBL and ECN (Koelemeijer et al., 2017) are used. The Agreement on Energy for Sustainable Growth is the start of the sustainable transition in the Netherlands and aims to mark the start towards an entirely climate-neutral energy supply by 2050. However, since the document is from 2013, specific aims and goals have been re-evaluated. This means that in some instances, additional policy needed to be established, which has been done during the forming of the most recent Dutch parliament. This led to the *Regeerakkoord*, after which PBL and ECN analysed the policies and their additional effects. Below, the policies from these documents and how this is modelled in MARKAL-NL-UU have been described for each sector.

General

The Dutch state is obliged to carry out the decreed that has been set by the District Court of The Hague, which states that by 2020 the state has to diminish the national greenhouse gasses by 25 % compared to 1990 levels (Urgenda, 2018). This means a maximum level of 122 $MtCO_2$ in 2020. Added to this, a CO_2 emission price of 43 €/tCO_2 by 2030 will be established, according to the *Regeerakkoord*. In the Baseline scenario, a linear growth from 5 €/tCO_2 today and a steady price after 2030 are assumed. These measures can be found in Table 12.

Table 12 - Measures taken in general in the Baseline scenario

Date	Measure	Source
2020	25 % reduction of CO_2 compared to 1990 levels	Urgenda (2018)
2030	CO_2 emission price of 43 €/tCO_2	Koelemeijer et al. (2017)

Electricity

In the *Energieakkoord*, minimum electrical efficiencies for coal-fired power plants have been set. This led to the closing of three power plants in 2016 and two more in 2017, as explained in section 3.3.4. Residual capacityThe *Regeerakkoord* has set the aim to close down all remaining coal-fired power plants by 2030, meaning the remaining power plants are also modelled as non-operational from 2030 onward.

The focus of the *Energieakkoord* on renewable energy is on wind and biomass. For wind onshore, 6000 MW by 2020 is targeted; at the moment, 6600 MW is being developed. However, analysis has shown that it is going to be difficult to get to 6000 MW by 2020 (RVO, 2017), which is why a limit of 6000 MW by 2020 is modelled. The remaining 600 MW is modelled to be installed after 2020. The path for offshore wind as was set in the *Energieakkoord* has since then been changed (RVO, n.d.). Currently, almost 700 MW per year is being realised: 1480 MW by 2020, 2100 MW by 2023 and 7100 MW from 2024 until 2030. The latter two are modelled by 2025 and from 2025 onward, due to MARKAL-NL-UU's time steps. For biomass, a maximum of 25 PJ per year of co-firing has been set by the *Energieakkoord*. The coalition of the Dutch parliament aims to disallow co-firing entirely after 2024, which is again modelled from 2025 onward. Table 13 summarises these measures.

Table 13 - Measures taken in the electricity sector in the Baseline scenario

Date	Measure	Source
Current	Maximum of 25 PJ of biomass in co-firing	SER (2013)
2020	Coal-fired power plants close down	SER (2013)
2020	A total of 6000 MW of onshore wind is installed	SER (2013)
2020	Additional 1480 MW of offshore wind is installed	RVO (n.d.)
2025	Additional 600 MW of wind onshore is installed	SER (2013)
2025	Additional 2100 MW of offshore wind is installed	RVO (n.d.)
2025 onwards	No co-firing allowed	Koelemeijer et al. (2017)
2030	Remaining coal-fired power plants close down	SER (2013)
2030	Additional 7100 MW of offshore wind is installed	RVO (n.d.)

Built environment

A minimum of 1 million households or small businesses should get a substantial part of their electricity needs fulfilled using decentralised renewable energy conversion. However, since there is no quantification of 'substantial' and the built environment is not modelled using units of buildings in MARKAL-NL-UU, this is not modelled.

Table 14 lists the measures taken in the built environment. According to the *Energieakkoord*, 300,000 buildings each year need to improve at least 2 energy labels, meaning they have to increase their insulation value. The *Energieakkoord* only mentions the residential sector for insulation, so it is assumed that the same figure goes for the services sector, which totals over 1.3 million buildings (CBS, 2018a). It is also assumed that the rate of installation of insulation is not higher than 300,000 buildings per year since this rate is sufficient to insulate the entire built environment by 2030 completely. The *Regeerakkoord* states that until 2030, up to 200,000 houses per year have to be heated by means other than natural gas. This means that at least 200,000 investments have to be made in technologies that do not use natural gas. MARKAL-NL-UU does not encompass building units, meaning the average values for the use of natural gas for buildings were used. Using these values, it was possible to calculate how much PJ of gas had to be saved through insulation and how much PJ of heat had to be generated without natural gas, corresponding to the values of the measures taken in the built environment.

Table 14 - Measures taken in the built environment in the Baseline scenario

Date	Measure	Source
2030	300,000 investments each year made in insulation for houses	SER (2013)
2030	300,000 investments each year made in insulation for buildings	Assumption
2030	A total of 2.4 million houses do not use natural gas	SER (2013)

Industry and agriculture

The industry and agriculture sector already undertake some incentives for energy reduction and the use of biomass, but little policies have been established to further reduce CO_2 emissions in these sectors. Investments in process efficiency is exogenously modelled in MARKAL-NL-UU, which is why no measures will be modelled to implement these investments. For agriculture, the *Regeerakkoord* identifies policies on land use and methane emissions, which are outside the scope of MARKAL-NL-UU.

Transport

Many policy measures for the transport sector are proposed in the *Energieakkoord*. According to the *Energieakkoord*, by 2020 10 % of personal vehicles are required to have a plug and electrical transmission. This means that 10 % of personal vehicles need to be either hybrid or electric vehicles (EVs). By 2025, 15 % of the personal vehicles are wholly electric, and 15 % are either hybrid or electric. Also, bus transport needs to be fuelled by renewable energy entirely. By 2030, the transport sector may only emit a maximum of 25 $MtCO_2$/yr and all new personal vehicles sold should have zero CO_2 emissions. The latter is considered as direct CO_2 emissions, meaning only the use of renewable fuels or electricity is permitted. Lastly, by 2050, the transport sector should reduce their CO_2 emissions by 60 % compared to 1990 levels, amounting to 12 $MtCO_2$/yr. A timeline is given in Table 15 below.

Table 15 - Measures taken in the transport sector in the Baseline scenario

Date	Measure	Source
2020	10 % of personal vehicles are hybrid or electric	SER (2013)
2025	15 % of personal vehicles electric, 15 % hybrid or electric	SER (2013)
2025	100 % renewable energy used for bus transport	SER (2013)
2030	A maximum of 25 $MtCO_2$ emitted by 2030	SER (2013)
2030	All new personal vehicles have zero emissions	Koelemeijer et al. (2017)
2050	60 % CO_2 emission reduction compared to 1990 levels	SER (2013)

3.4.2. Other scenarios

Since the policy measures considered in the Baseline scenario are sometimes only proposed and not yet translated into concrete targets, it is not certain that these will indeed take into effect. It also does not indicate that these policies will indeed lead to the most cost-effective way of realising deep CO_2 emissions. Other scenarios will thus not take into account proposed policies and also assume that policies that have effect after 2020 may be changed in due time. This signifies that all policies described in the Baseline scenario that have effect after 2020 will not be modelled in the other scenarios. This leads to a first alternative scenario, in which 'No Proposed Policy' (NPP) is taken into account. Another scenario will have a large focus on BECCS in order to realise deep CO_2 emissions. Currently, only 30 % of the total fuel input into coal-fired power plants may consist of biomass after 2030. This scenario, therefore, explores the possibility of not closing down the coal-fired power plants by 2030 but instead use them as a CO_2 reduction possibility. The last scenario explores the possibility of excluding CCS technologies ('No CCS') as an option to realise deep CO_2 emissions. Even though it is considered nearly inevitable to use CCS, it is still a debated technology, because it may have adverse side effects according to some organisations (see e.g. The House of Representatives Standing Committee on Science and Innovation, 2007). A summary of the main characteristics of the scenarios can be found in Table 16 below.

Table 16 - Characteristics of the scenarios

	Baseline	NPP	BECCS	No CCS
Proposed policy after 2020	Yes	No	No	No
100 % BECCS	No	No	Yes	No
CCS	Yes	Yes	Yes	No

3.5 Results of MARKAL-NL-UU run

Below, the results of the Baseline scenario are presented, after which the results of the other scenarios are also displayed.

3.5.1. Yearly CO_2 emissions

The yearly CO_2 emissions of the Baseline scenario can be found in

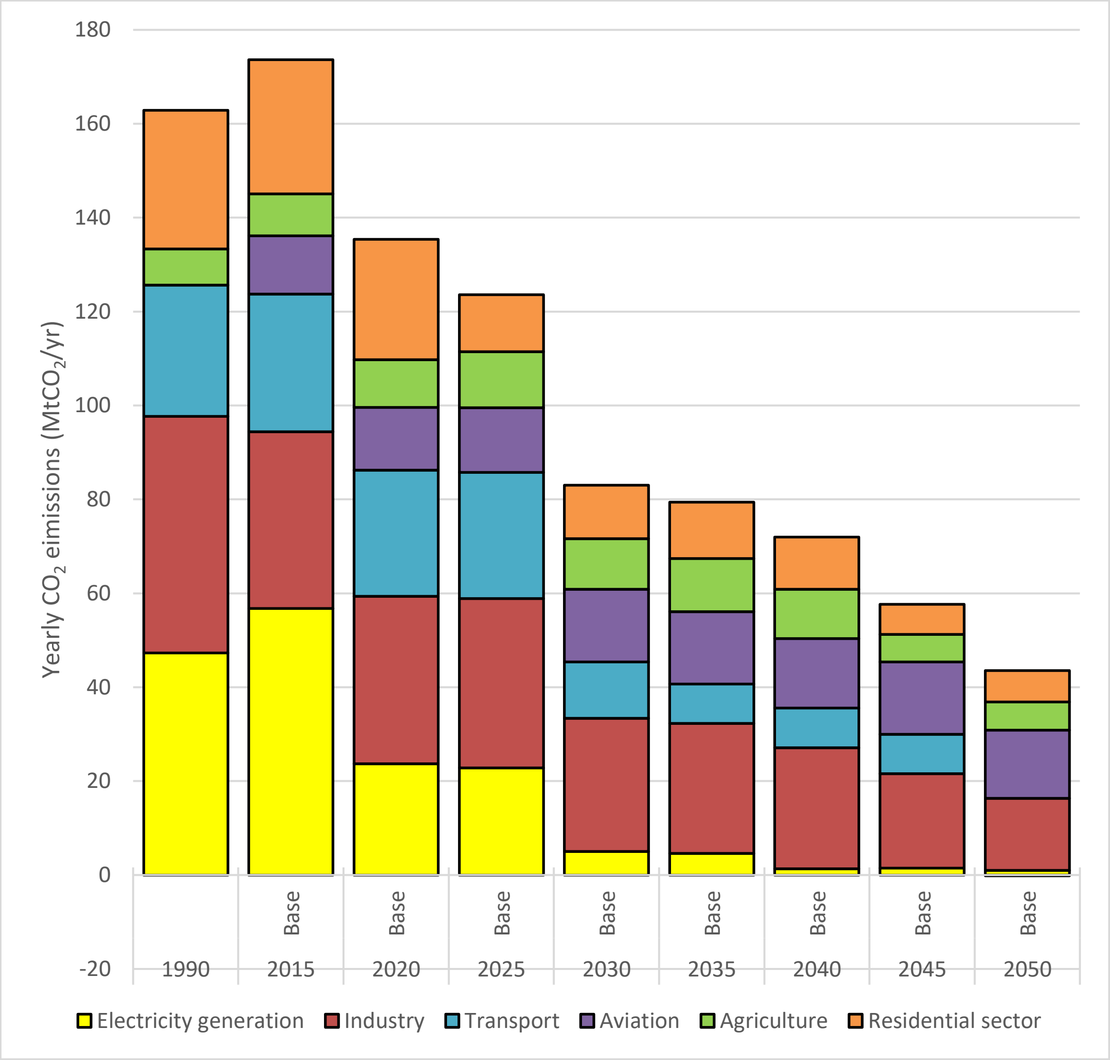


Figure 3 below. The comparison of the number of emissions calculated by the model in 2015 and the emissions calculated by *Emissieregistratie* (RVO, 2018) can be found in Table 17 below. The emissions from aviation are taken from CBS (2018d). There is some discrepancy between the actual values and the calculated values. This can be explained by the fact that the industry, agriculture and household sectors all utilise heat generated as a by-product in the electricity sector. The CO_2 that is emitted during this process is entirely allocated to the electricity sector in MARKAL-NL-UU. On the other hand, CO_2 emitted by small natural gas technologies is wholly allocated to the agricultural sector and the built environment. However, some of this may also be used by the industrial sector.

Table 17 - Comparison of calculated CO_2 emissions in 2015 by MARKAL-NL-UU and actual CO_2 emissions in 2015

Sector	2015 in MARKAL-NL-UU	2015 in the *Emissieregistratie* and CBS (2018d)	Unit
Electricity generation	56.8	53.9	$MtCO_2$
Industry	37.6	45.9	$MtCO_2$
Built environment	28.6	26.0	$MtCO_2$
Transport	29.3	29.0	$MtCO_2$
Agriculture	8.9	8.1	$MtCO_2$
Aviation	12.4	13.2	$MtCO_2$

Total	**173.6**	**176.1**	$MtCO_2$

Figure 3 presents the CO_2 emission development in the baseline scenario. The policies that are modelled have its impact on the emissions. The constraint that was set due to the decreed of Urgenda makes that the Netherlands needs to reduce its CO_2 emissions quite significantly by 2020. The constraint of 122.24 $MtCO_2$ omits aviation since these emissions are not taken into account by Urgenda. The decreed is set on domestic emissions, while aviation emissions are international. Therefore, only the emissions of the electricity, industry, built environment and transport sector amount to 122.24 $MtCO_2$. Also, the substantial increase of wind in the electricity sector makes that this sector diminishes its CO_2 emissions quite drastically by 2020. By 2030, the coal-fired power plants close down, which is why there is a significant drop in the emissions in the electricity sector. These power plants are substituted by the increase of capacity in wind energy. By 2030, the entire built environment has installed a new form of insulation. Up to 2030, this insulation is gradually installed, which is why a gradual decrease of CO_2 emissions in this sector can be seen. From 2030 onward, all new bought personal vehicles may only be zero-emission vehicles resulting in a decrease of 55 % of CO_2 emissions in this sector between 2025 and 2030.

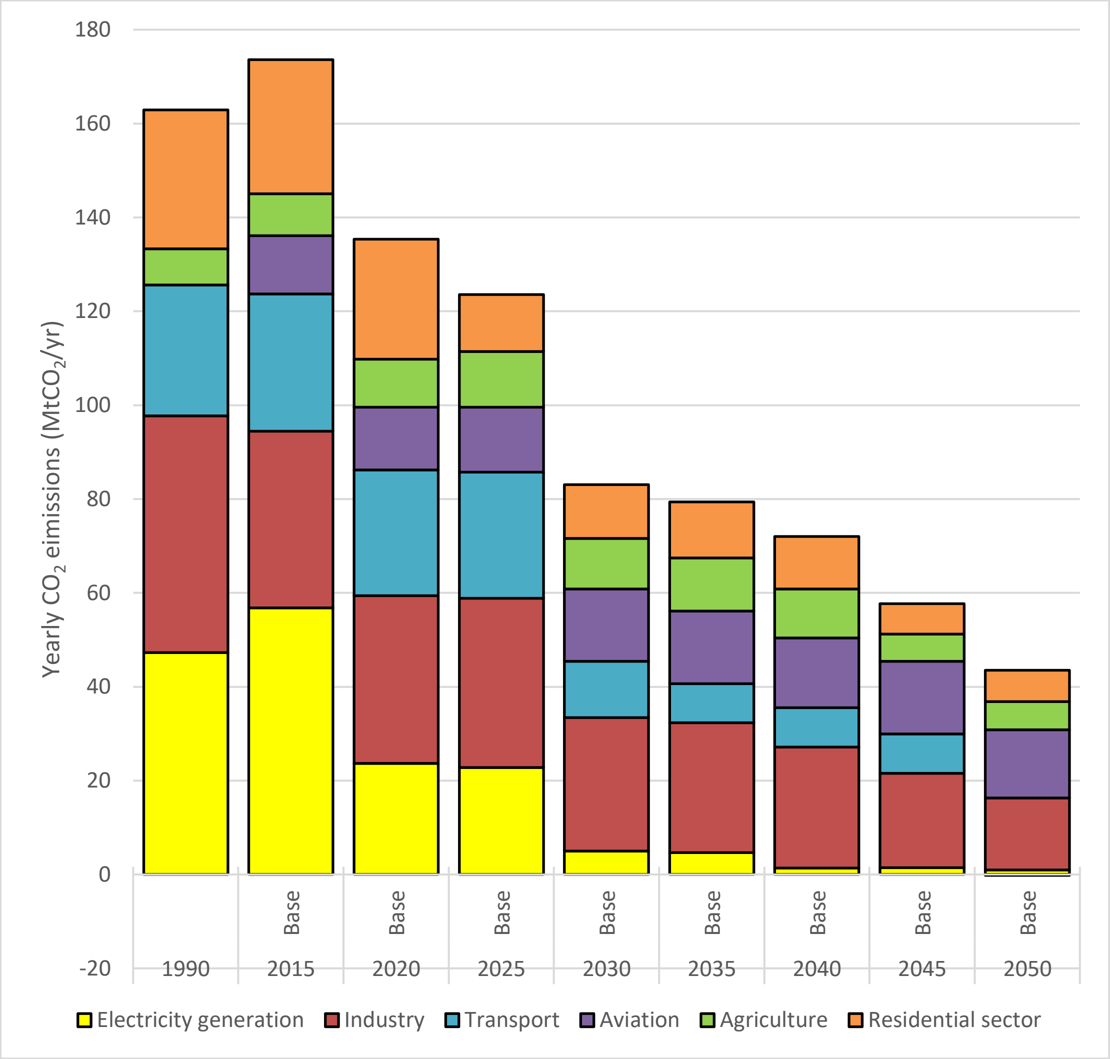


Figure 3 - The development of yearly CO_2 emissions

3.5.2. Technologies installed per sector

The electricity sector

The amount of electricity produced by power plants can be found in Figure 4 below. As time progresses, more and more CO_2 emitting technologies are substituted by CO_2-free technologies. In 2020, some PC power plants are retrofitted with a CCS technology, and some are substituted by NGCC power plants and wind turbines. This explains the substantial decrease in CO_2 emissions in this sector by 2020. By 2030, when all coal-fired power plants close, wind and solar energy dominate the sector. The increase of wind capacity results in a significant drop in CO_2 emissions, while at the same time all coal-fired power plants are prohibited to operate. A few CO_2 emitting power plants remain until 2040 when only NGCC plants are left. Throughout the years, NGCC-CCS plants are a prevalent technology that allow for a low-CO_2 emission sector. As can be seen in Figure 5, there is quite some unused capacity of PC plants in the period after 2030. The capacity of solar rises significantly in 2030, as does the electricity generated by solar energy. By 2050, the ratio of capacity installed for solar and wind energy is 1:1.4, while the electricity output is 1:5. This shows that the potential for solar energy is limited, due to the location of the Netherlands. Back-up capacity for the intermittent energy technologies is installed as batteries, amounting to over 30 GW of back-up.

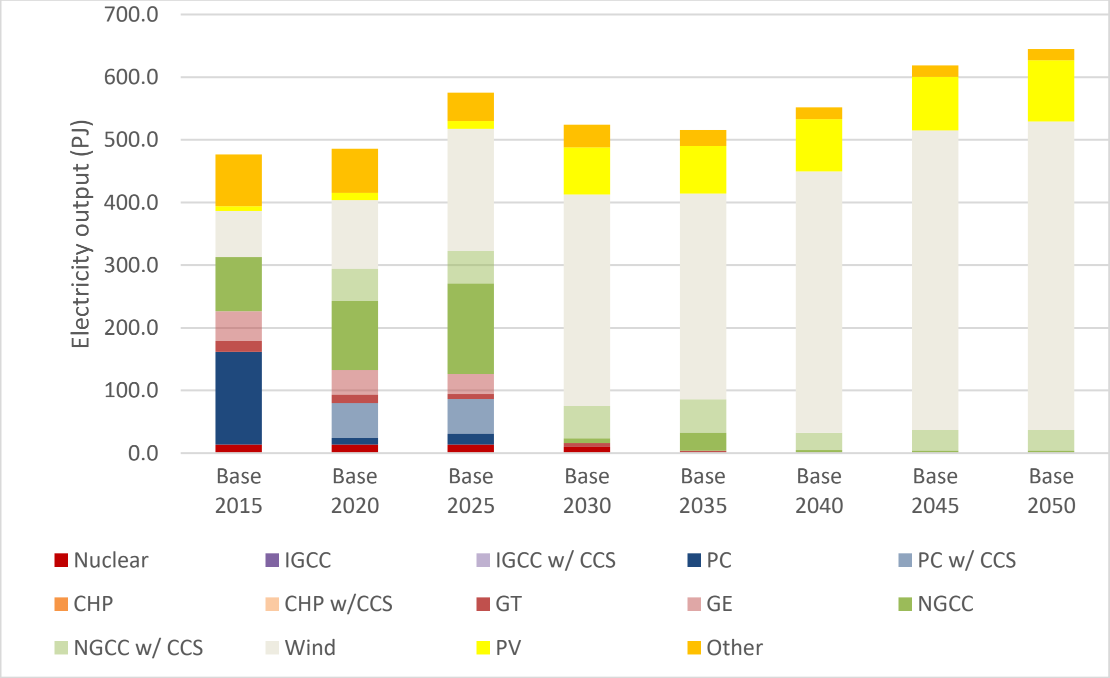


Figure 4 - Power plant electricity output throughout the years

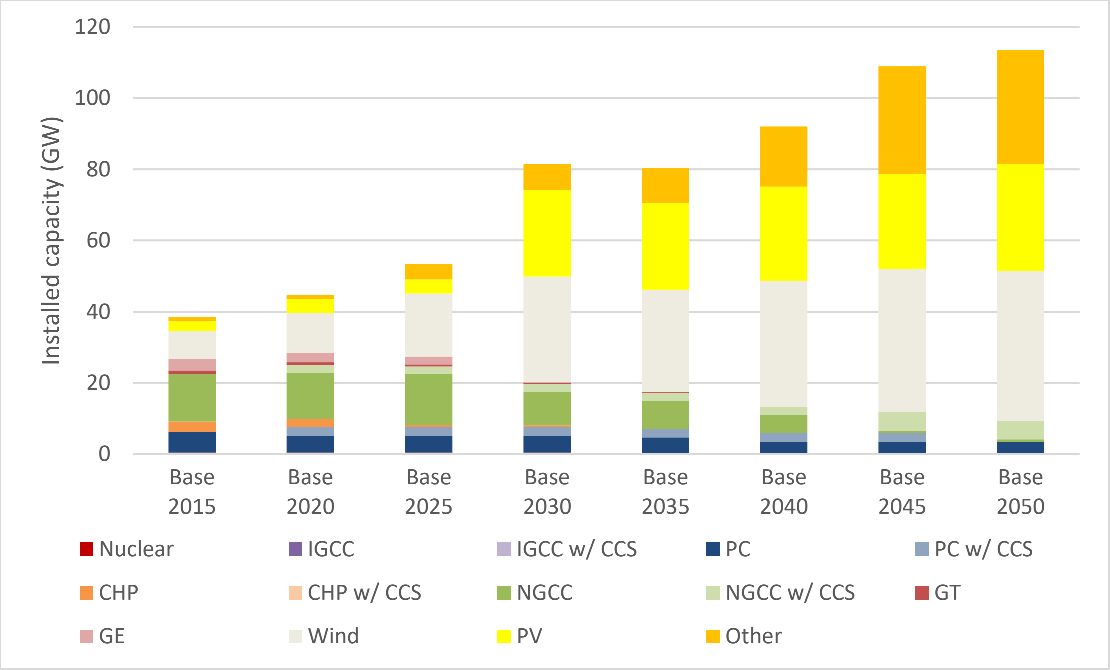
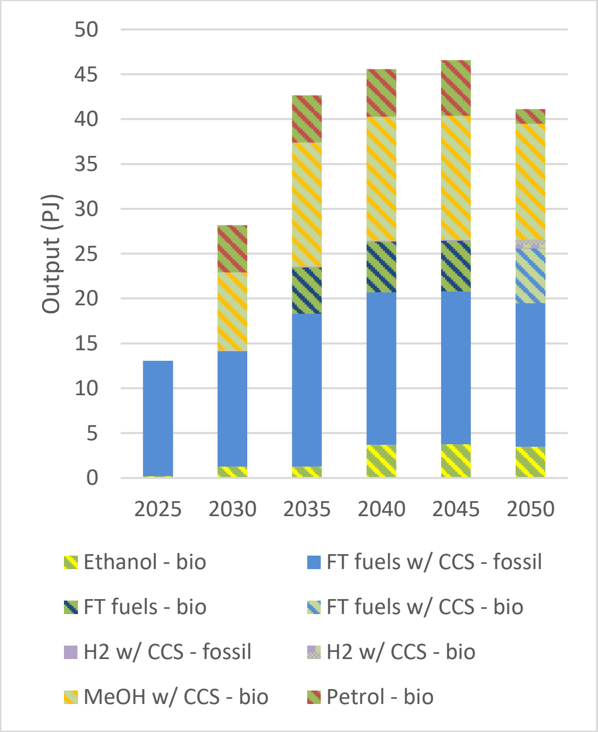


Figure 5 - Power plant capacity throughout the years

Electricity is also always supplied by the industrial sector, where it is a by product of some conversion processes. The capacity and electricity generated by the industrial sector can be found in Figure 6 and Figure 7 below.



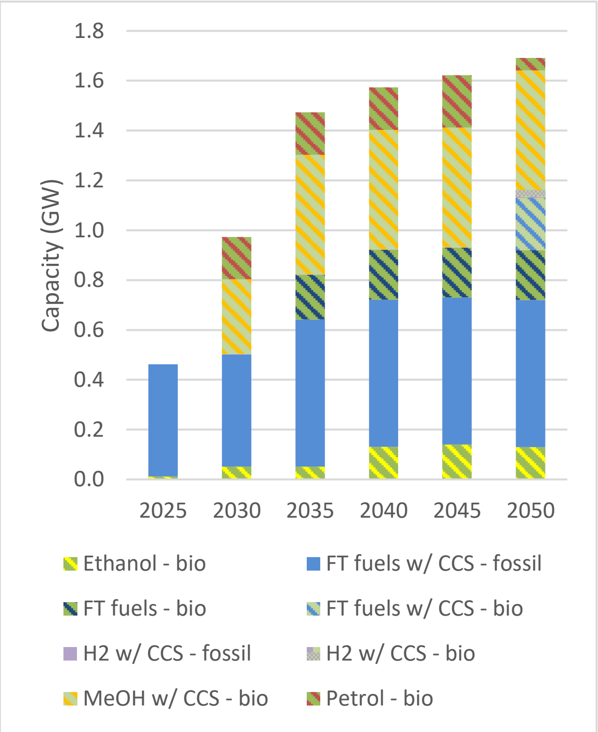


Figure 7 - Electricity output in the industry sector

Figure 6 - Electricity capacity in the industry sector

The industrial sector

The industrial sector is divided into four sub-sectors: the heat sector, the conversion sector, the chemical sector and the refineries and steel sector. The heat sector supplies heat to sectors that are not explicitly modelled in MARKAL-NL-UU, such as the food and beverages sector. The conversion sector converts fossil resources and biomass energy carriers into fuels that are used by the transport sector. The chemical sector provides chemicals either directly to a demand or to be used in other conversion processes in the chemical sector. The refineries and steel sector is the sector in which the most energy-intensive production processes are modelled. These are based on existing production plants in the Netherlands. Activities within the sub-sectors can be seen in Figure 8 through Figure 11.

In the heat sector, gas boilers generating are rapidly phased out between 2020 and 2045. Instead, biomass is used in furnaces, and heat pumps are used to generate high-temperature heat. Electric boilers are installed in the period before 2020 to promptly diminish CO_2 emissions in this sector to fulfil the decreed by Urgenda. After 2020, these are not operational anymore.

In the fuel conversion sector, the production of petrol and diesel is slowly replaced by other fuels that have either CCS installed or utilise biomass resources for conversion. By 2030, almost all fossil fuels are out of the system, except for some fuels used in trucks and remaining vehicles. Jet fuel remains highly dependent on fossil fuels as the aviation sector is bound only by the national carbon budget constraint. As CO_2 reducing technologies are more expensive for the production of jet fuel than CO_2 reducing technologies in other sectors, MARKAL-NL-UU rather opts for CO_2 reduction in other sectors.

The chemical conversion sector is a relatively small sector within the industry sector, which means that little change occurs within the sector. Some fossil fuels are replaced by biomass counterparts, as can be seen in Figure 10.

In the refineries and steel sector, CCS technologies are quickly implemented by 2050. This is done so that the industry sector will decrease its emissions by an additional 6 $MtCO_2$/yr (~29 %) by 2050 to remain within the national carbon budget.

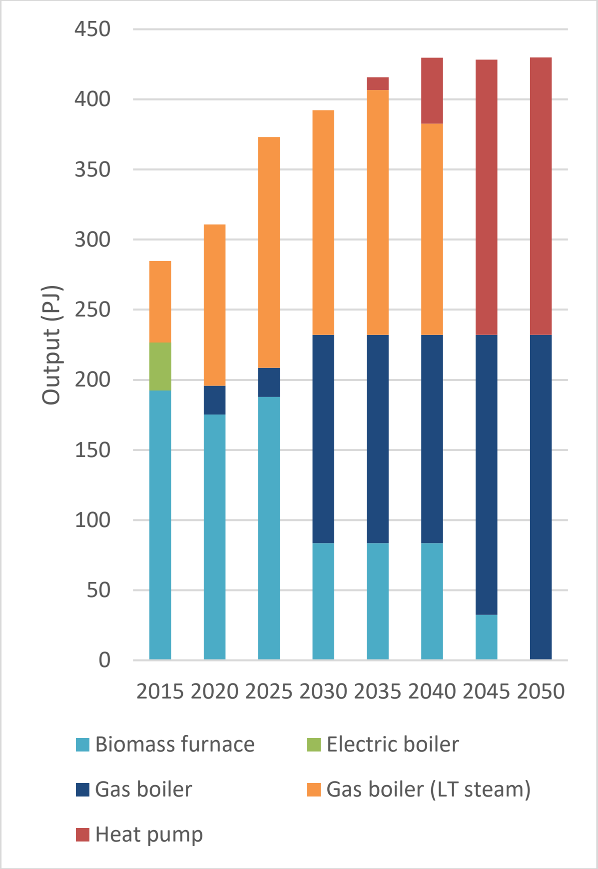


Figure 8 - Activities within the heat sub-sector

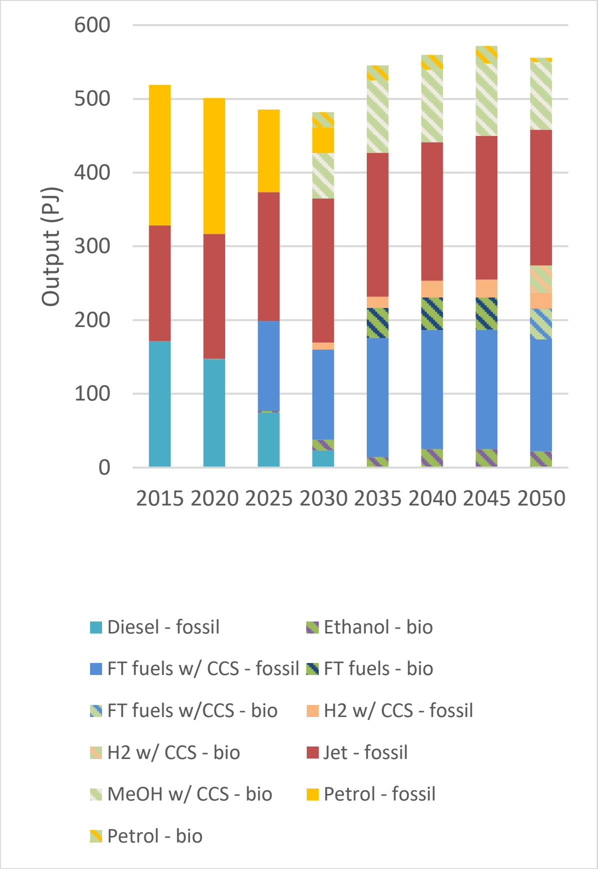


Figure 9 - Activities within the conversion sub-sector

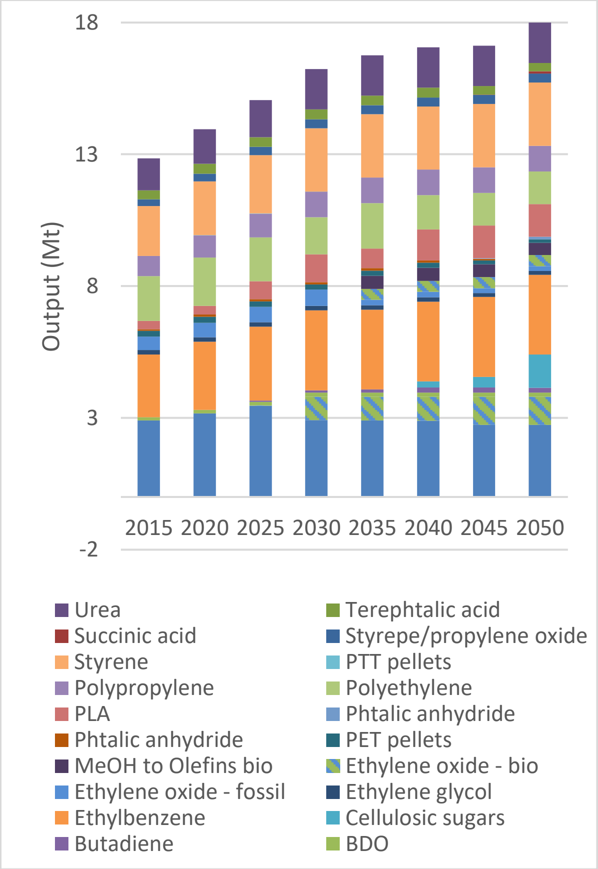


Figure 10 - Activities within the chemicals sub-sector

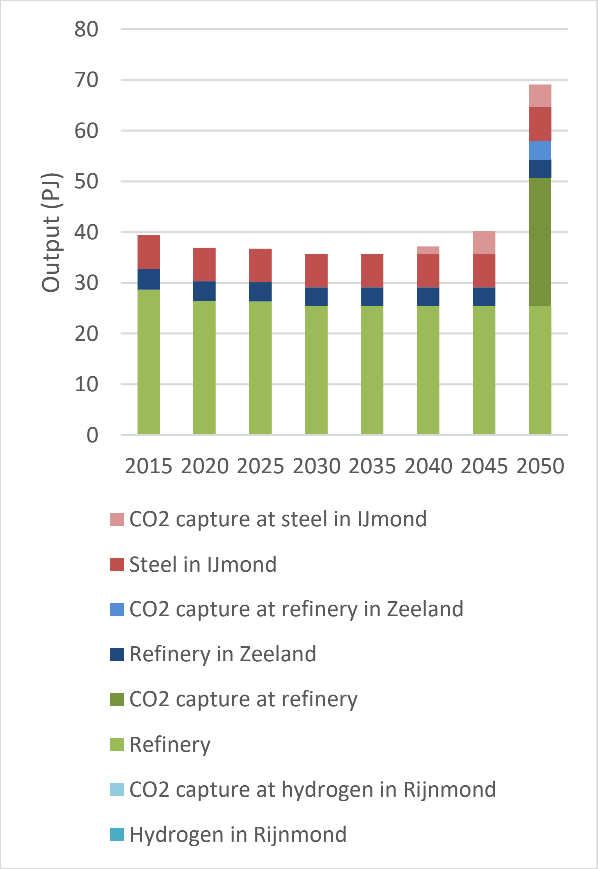


Figure 11 - Activities within the production sub-sector

The built environment

The built environment quite rapidly replaces its gas boilers for less CO_2 emitting technologies. Figure 12 shows the mix of technologies applied in the built environment throughout the years. Hybrid heat pumps, because of their high efficiency, replace the gas boilers by 2025, making that the amount of CO_2 emissions decreases rapidly. Insulation for buildings and for residences built before 1992 slowly make their way into the technology mix as well, together saving 140 PJ/yr of heat demanded from 2030 onward. As time progresses, condensing gas boilers are replaced by district heat exchangers, which utilise the heat from the electricity and industry sector, therefore making this heat CO_2 neutral for the built environment. Wood stoves, although a CO_2 neutral technology, play a minor role in heat generation for the built environment.

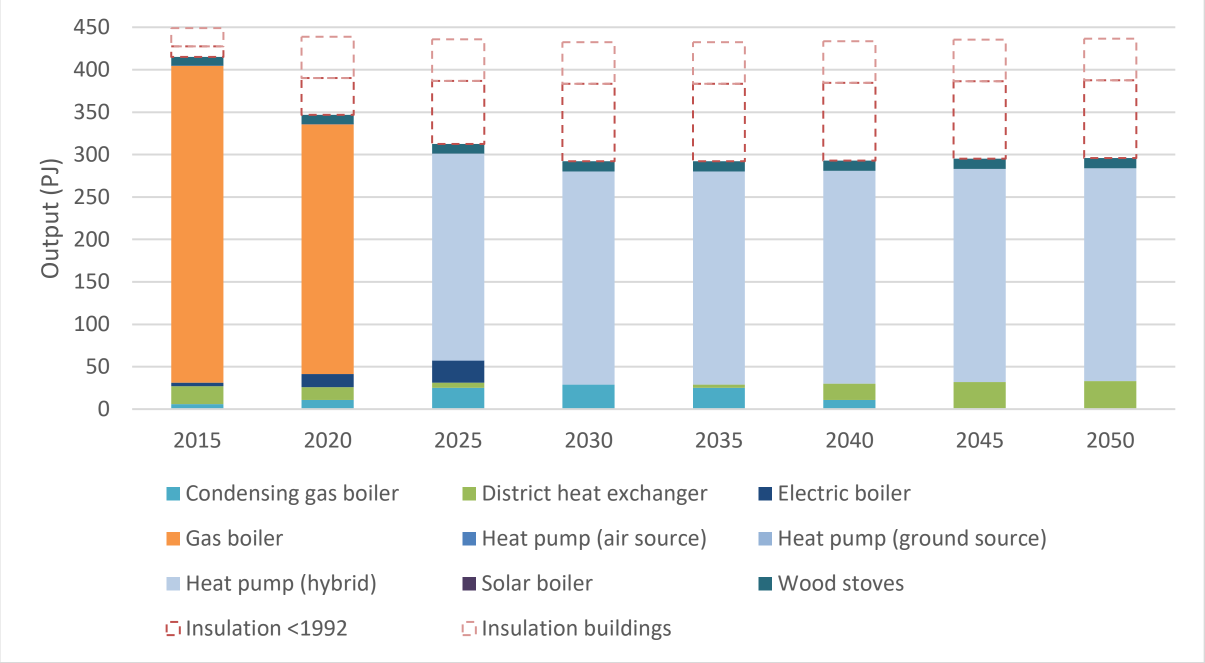


Figure 12 - Activities within the built environment

The transport sector

Figure 13 presents the activities within the transport sector up to 2050.In the transport sector, vehicles on petrol continue to dominate the field. However, the majority of these vehicles run on bio-based petrol from 2030 onwards, fully using bio-based petrol by 2045. This is because newly sold vehicles are prohibited to have direct CO_2 emissions. Hybrid electric and EVs are only forced into the sector due to the constraints set by policy, since these technologies are only used from 2020 until they are decommissioned, 12 years later. Hydrogen, a potentially viable fuel in the transport sector, plays only a minor role, with under 10 % of transport demand fulfilled by these transport technologies.

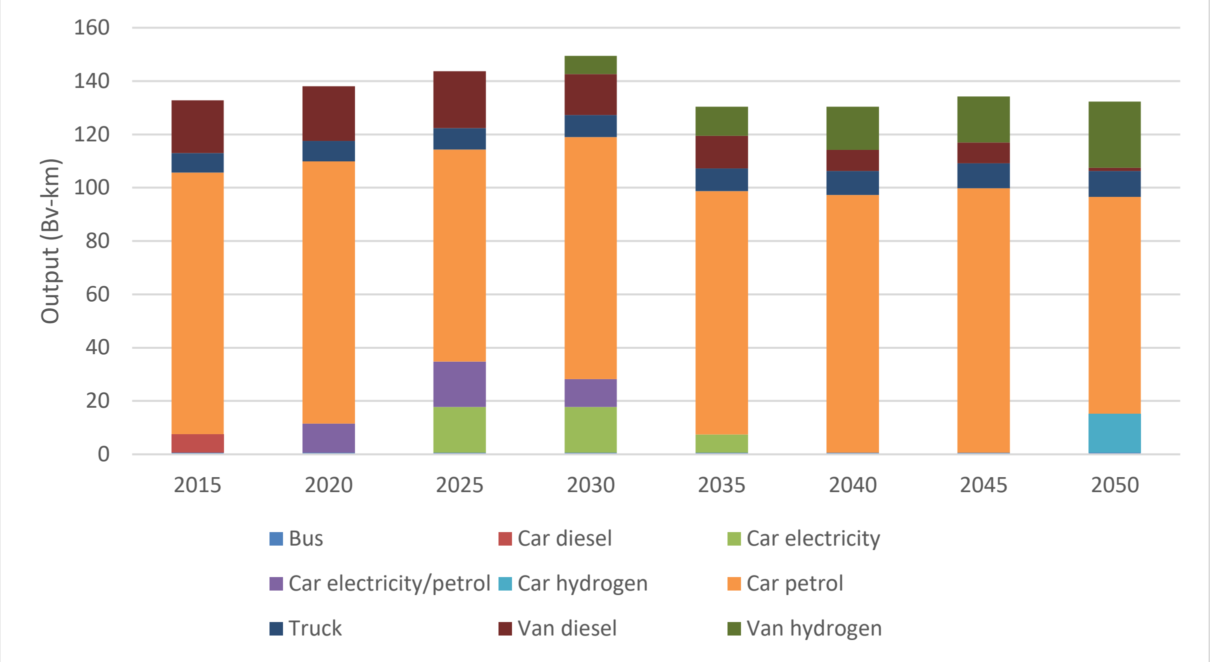


Figure 13 - Activities within the transport sector

The agricultural sector

As shown in Figure 14, the agricultural sector remains dependent on gas boilers, due to the fact that this is the only technology applicable to fulfil rest heat demand. Up to 2025, part of the district heat demand in the agricultural sector is fulfilled using heat formed as a by-product in gas engines. Gas boilers fulfil the rest of the district heat demand. Low-temperature steam, a by-product of the CHP on biogas and biogas production, covers only a small amount of the district heat demand.

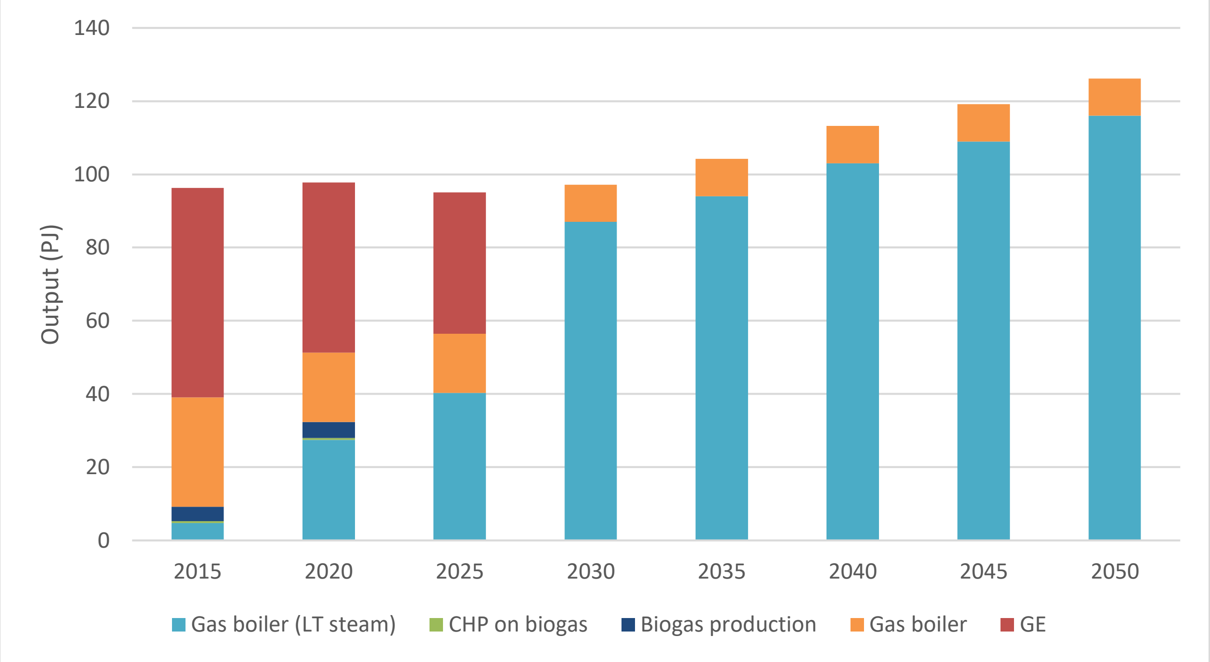


Figure 14 - Activities within the agricultural sector

3.5.3. Yearly costs

The implications for the yearly costs can be found in Figure 15 below. Due to the low lifetime of vehicles, these dominate the investment portfolio. Therefore, the figure is also given without the investments in vehicles in Figure 16 below. The figures represent the total investments in a five year period. In the period 2015-2019, some investments are already made. This has two causes. The first is that investments made in the period 2015-2018 are also accounted for and the second is that the model already factors in investments done before 2020. For example, in the heat sub-sector in the industrial sector, electric boilers are installed and in the built environment, insulation technologies are applied. Up to 2030, a lot of investments are made in the electricity sector for wind technologies. Closing down the pulverized coal power plants has little effect in 2030 since investments made in wind technology up to that year is almost sufficient to satisfy demand. This is complemented by investments made in PV technologies. In 2040, investments are made in more wind technologies. The industrial sector is changing continuously throughout the years. Investments are made in 2025 in CCS technologies for the conversion sector, while in 2030 investments are made in biomass boilers for heat and more CCS in the conversion sector. In 2035, heat pumps are installed, and the conversion sector further gets expanded. By 2050, a lot of investments are made in CCS technologies in the production sector. In the built environment, the investments are first made in the relatively cheap insulation technology for buildings. When this is finished, the insulation for buildings built before 1992 is installed, up to 2030. In 2025, a lot of capacity in hybrid heat pumps is also installed. Due to their lifetime of 20 years, these investments are made once again in 2045.

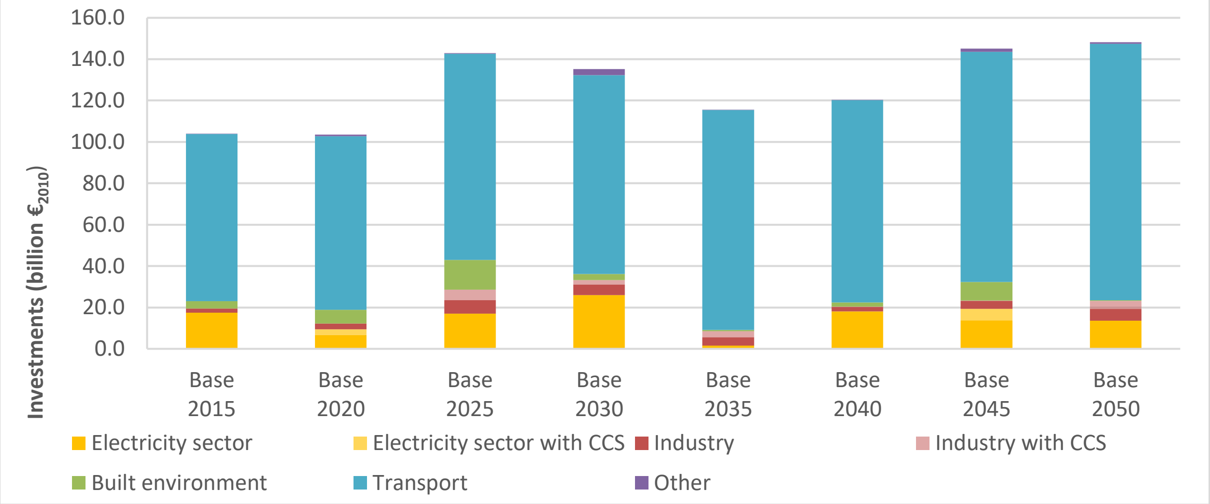


Figure 15 - Investments over time

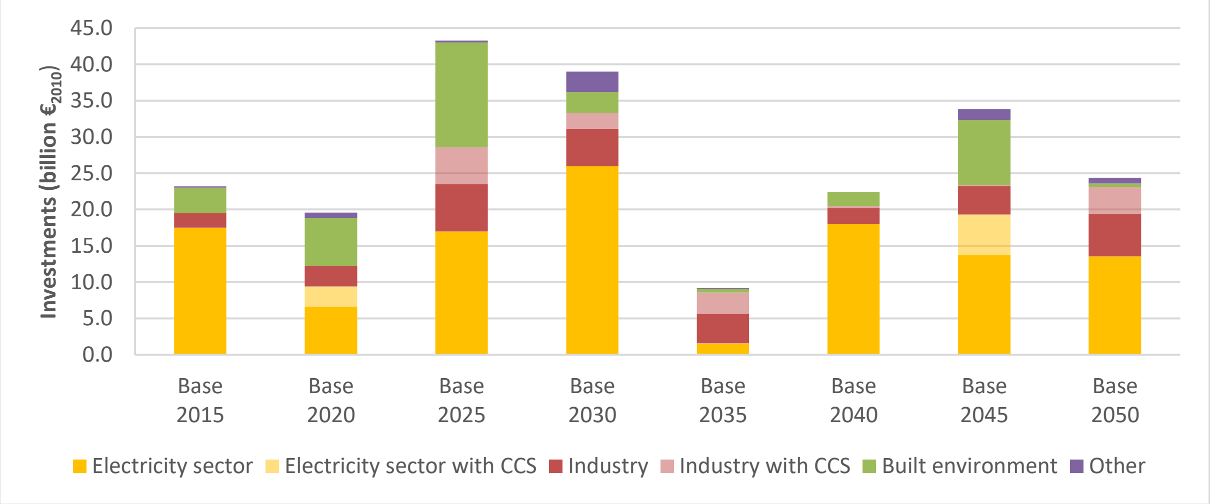


Figure 16 - Investments over time without the transport sector

3.5.4. Primary energy use

The primary energy use in the Netherlands in the period 2015-2050 is given in Figure 17 below. It can be seen that the use of natural gas in decreases significantly throughout the years. The use of coal is almost the same in 2015 as in 2050. For coal, however, the application shifts from being used in electricity generation to being used as a feedstock for fuel conversion. This can be clearly seen in 2020, in which no coal is used for conversion yet, and almost all coal-fired power plants are out of use. Oil, being used in the conversion sector as well, almost completely fades out in the system. Naphtha, being an essential feedstock for jet fuels, remains almost identical through the years. Uranium oxide is only used in nuclear plants, which are not allowed after 2030. Wind energy gets used more as time progresses, while biomass also plays a significant role in primary energy use. Solar energy increases rapidly in 2030 and remains almost constant afterwards. Waste is constant throughout the years.

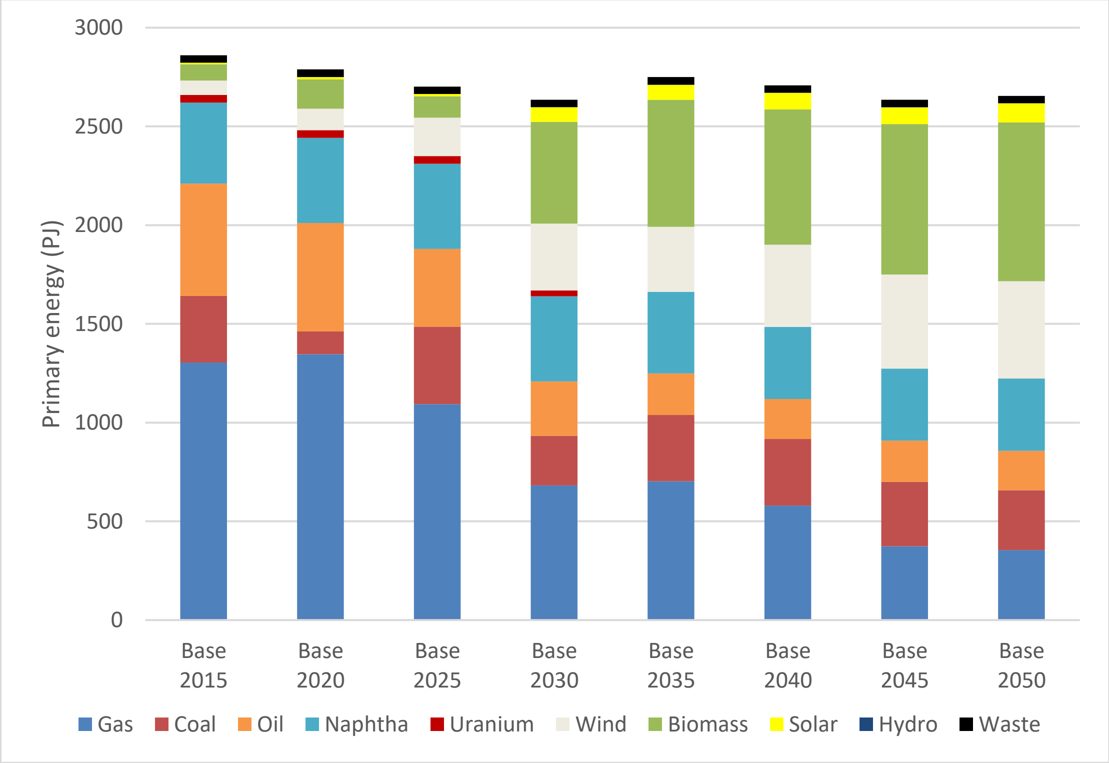


Figure 17 - Primary energy use

As can be seen in Figure 18, renewable energy shares increase over time. In 2050, the share of renewable energy amounts to over 50 %, of which the majority comprises of wind and biomass.

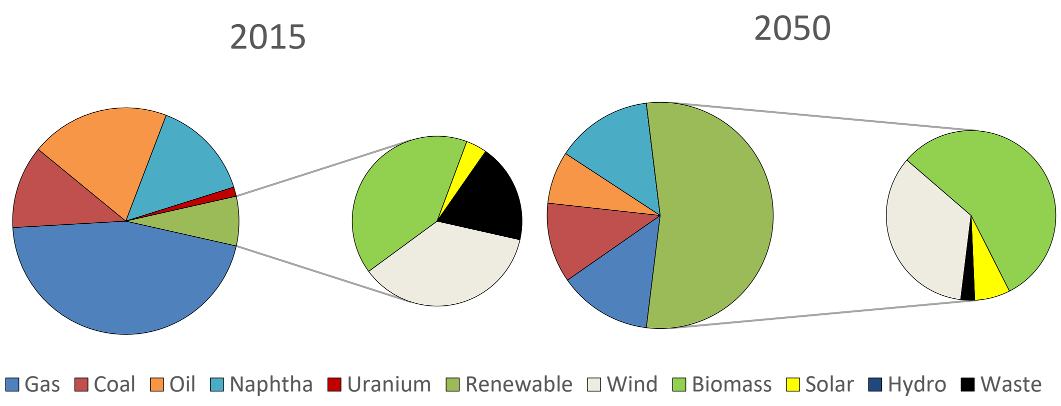


Figure 18 - Primary energy use for 2015, 2030 and 2050

3.5.5. Scenarios

The scenarios as proposed give a slightly different outlook of the route towards getting to the 1.5 °C target. Most prominently different is the amount of CO_2 emissions per year. As can be seen in Figure 19, the scenarios are no longer constrained by the decreed of Urgenda. The Dutch State has gone into appeal in the case of Urgenda, meaning that this target may not become binding. This option is therefore left out in the other scenarios. For the NPP and BECCS scenario, this means that the emissions in 2020 may be higher than that of the Baseline scenario. Instead of decreasing the CO_2 emissions swiftly, this means that it is more cost-effective to do this later on. For the No CCS scenario, it is urgent that CO_2 emissions are diminished quickly, in order for the cumulative CO_2 emissions to remain within the national carbon budget.

There is no difference in the NPP and the BECCS scenario. This means that even though the option of 100 % BECCS is available in the latter scenario, it is not necessary to include this in the technology portfolio in order to stay within the national carbon budget. In these scenarios, the gas boilers are not substituted by hybrid heat pumps until 2030, which explains the difference in this sector in 2025. Due to the fact that there is no need for these scenarios to get a CO_2 neutral transport sector, the emissions of this sector are not reduced significantly in 2030, as opposed to the Baseline scenario. There are no hybrid or EVs used in this scenario, but instead, it is chosen to invest in more diesel vehicles. This diesel is partially produced using the Fischer-Tropsch plants with CCS. This shows that electric and hybrid vehicles are not the most cost-effective technology to reduce CO_2 emissions in the transport sector. Only by 2050, the transport sector changes rapidly, in which even negative emissions due to CCS is available. At that point in time, more diesel vehicles are used which use bio-based Fischer-Tropsch fuels with CCS.

The No CCS scenario does not have the possibility to reduce emissions through CCS, which is why in this scenario the emissions by 2020 need to be reduced more swiftly. This is done so that by 2050, the emissions can be more significant than in the Baseline scenario, in which CCS is applied throughout the sectors. With 2020 being only a short time away, this is considered impossible. In order to reduce its emissions by 2020, this scenario becomes completely coal-free. Instead, this scenario relies heavily on natural gas in the electricity sector and wind energy. This also results in high use of heat pumps in the industrial sector instead of natural gas boilers. Biomass also plays a more significant role in this scenario than in any other. This leads to a significant portion of biogas production in the agricultural sector and the use of hydrogen from biomass sources in transport by 2050.

The total system costs of the scenarios, however, do not differ more than 10 billion $€_{2010}$ as can be seen in Table 18 below. However, the base scenario is indeed more expensive due to existing and proposed policies.

Table 18 - Total system costs for the scenarios

Scenario	**Baseline**	**NPP**	**BECCS**	**No CCS**
Total system costs (billion $€_{2010}$)	733.5	722.6	722.6	735.1

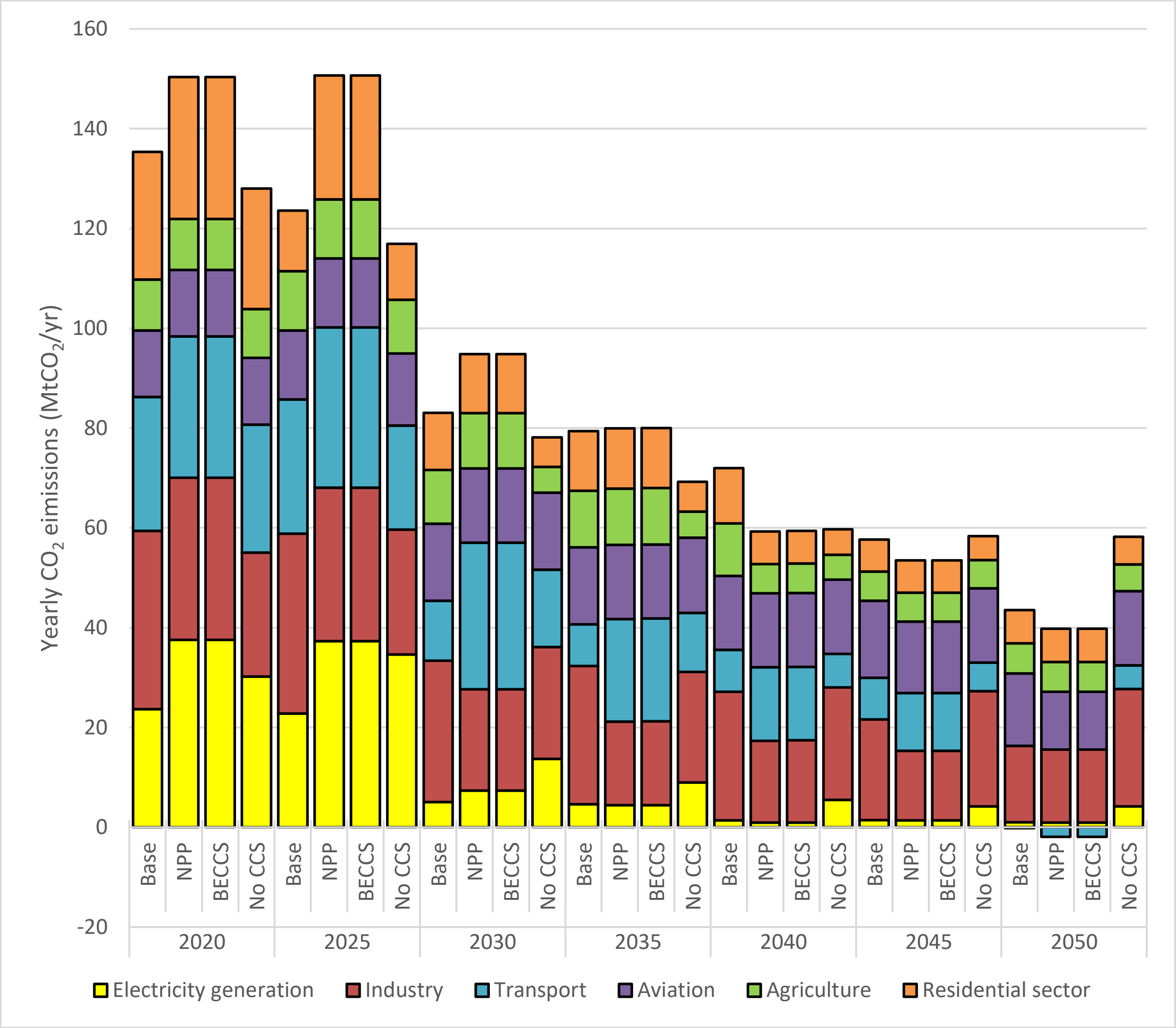


Figure 19 - Yearly emissions of CO2 per year and per scenario

3.6 Sensitivity analyses

Three sensitivity analyses are carried out. First, the carbon budget is examined. As was shown in Table 2, all carbon budgets have a specific range. The average of the carbon budget on the basis of GDP PPP was taken, but the upper and lower values are also considered. The average value for the carbon budget on the basis of population is also considered. The lower and upper value for this budget is not further discussed, as the difference is so minor that this will not yield significantly different results. Second, the value for the discount rate is changed. The higher the discount rate is, the later more expensive technologies will be installed. It is examined what the effect is in the Baseline scenario. Finally, three alternatives to the Baseline scenario are considered based on the outcomes of the model. As described before, these include an analysis where zero CO_2 in 2050 is allowed, one in which no extra-European Union (EEU) biomass is allowed and another of an increase in the capture rate of CCS technologies in the electricity sector to 100 %.

3.6.1. National carbon budget

What can be seen in Figure 20 is that CO_2 emissions develop quite differently between the three variants with the average, lower and upper value of the national carbon budget on the basis of GDP PPP. The further in time, the larger the differences between the amounts of CO_2 emitted each year in these three variants. Due to the discount rate, an expensive technology is considered less expensive when applied at the end of the modelling period. CCS technologies will therefore rather be applied towards 2050 instead of in earlier years. Due to the larger national carbon budget, investments in these technologies are postponed as much as possible. In total, however, the total costs do not differ significantly.

Vast differences can be seen in the division of the carbon budget on the basis of GDP PPP and population. Should the division be made on the basis of population, a very swift change has to take place. Due to 2020 being in just a short time, this scenario is considered infeasible. The carbon budget will also have its influence on the total costs of the system, which is over 45 billion € higher than in the Baseline scenario, see Table 19.

Table 19 - Costs per carbon budget scenario

Scenario	Baseline	Lower, GDP PPP	Upper, GDP PPP	Average, population
Total costs (billion €$_{2010}$)	733.5	734.5	732.5	786.1

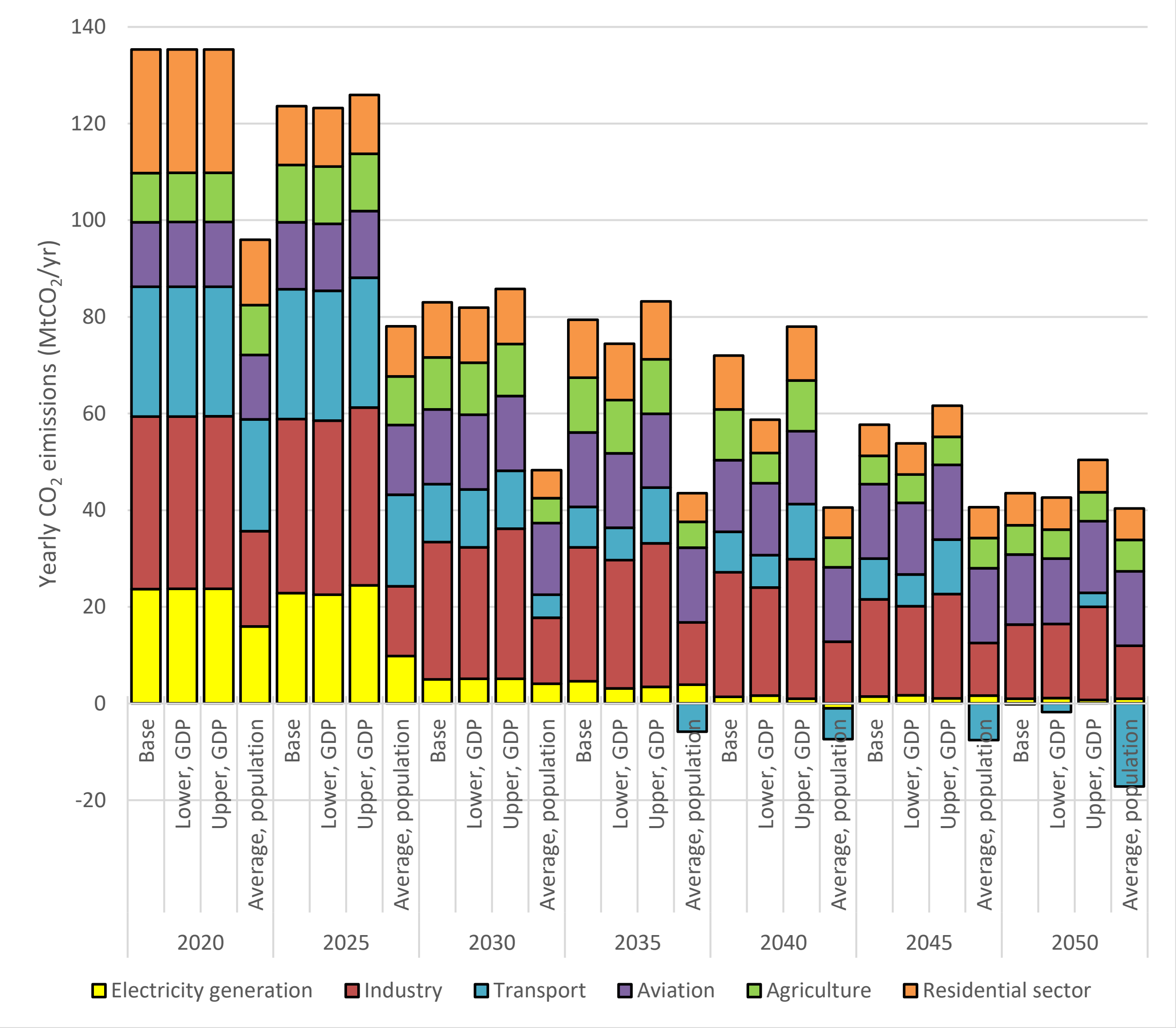


Figure 20 - Yearly emissions of CO2 per year and per different carbon budget scenario

3.6.2. Discount rate

The discount rate is of great influence to the model. The discount rate makes that the model is more likely to invest later in the period of the run, due to its function to minimise costs. The higher the discount rate, the later the model will invest in technologies. As can be seen in Figure 21, this has its influence on the technologies that the model will invest in. CCS technologies, being relatively expensive, become more prominent at the end of the model period due to a higher discount rate. It compensates for the emitted CO_2 in earlier years. This can be best seen in Figure 21, where model runs with a discount rate of 7 % (Baseline), 11 % and 15 % are shown.

The variation in discount rate also shows a variation in total system costs. Although the model invests in more expensive technologies, the higher the discount rate gets, the total system costs are lower than in the Baseline scenario. This is due to the nature of the discount rate. When not discounting the total costs, the costs increase when the discount rate does, as can be seen in Table 20. This shows that more expensive technologies are needed when increasing the discount rate, as is to be expected.

Table 20 - Total costs of the discount rate scenarios

Scenario	Baseline	11 %	15 %
Total costs (billion €$_{2010}$)	733.5	467.2	349.0
Total undiscounted costs (billion €$_{2010}$)	697.1	707.9	733.0

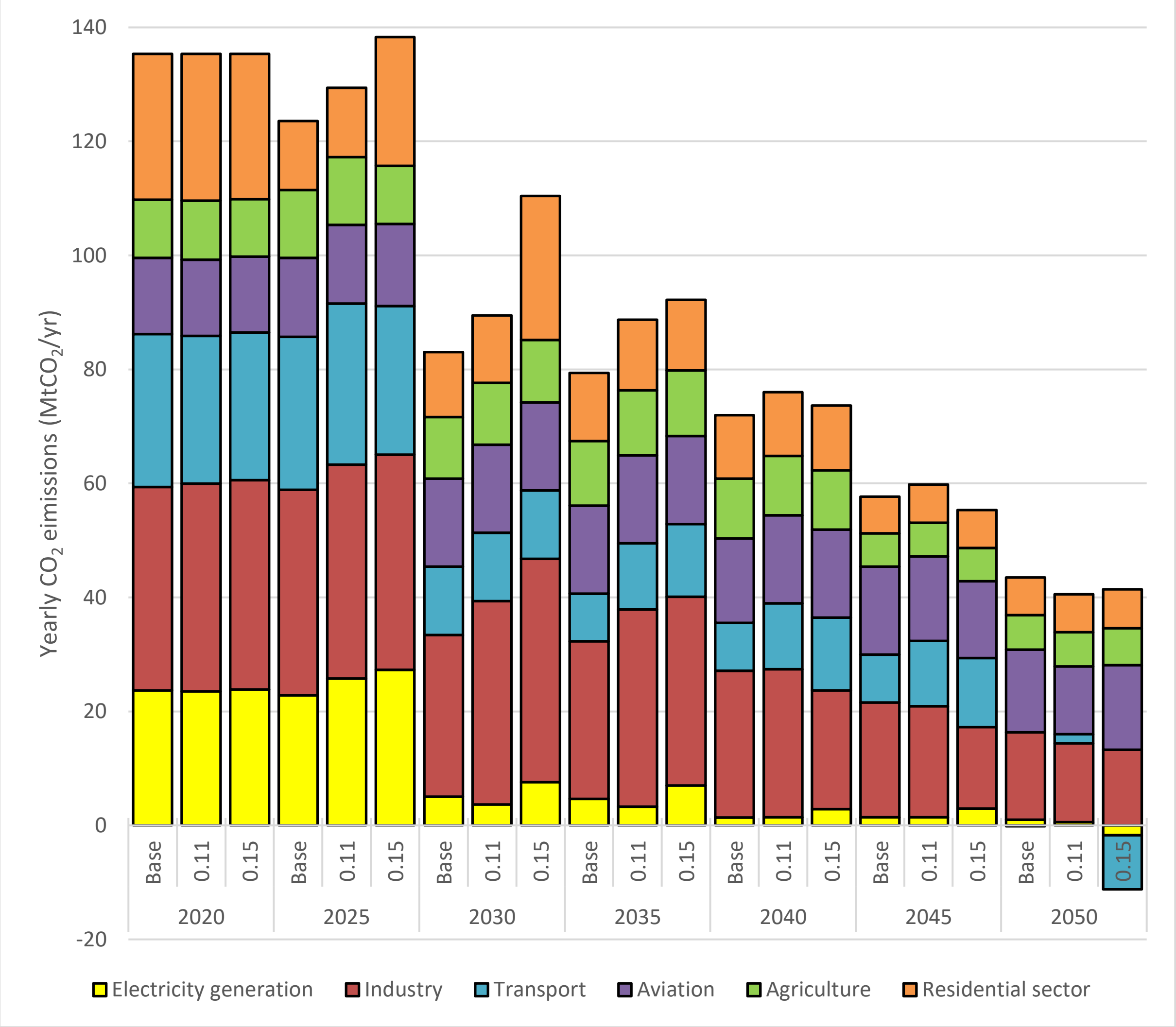


Figure 21 - Yearly emissions of CO2 per year and per different discount rate scenario

3.6.3 Zero $MtCO_2$ in 2050, no extra-EU biomass and 100 % capture rate CCS

In Figure 22, it can be seen that the zero $MtCO_2$ emission by 2050 sensitivity variant lags behind the Baseline scenario up until 2045. Even though this sensitivity variant has to get to 0 CO_2 emissions, it still fulfils the complete carbon budget before reaching this target in 2050. This means that this scenario waits until the last moment to invest in high-cost technologies, like CCS. This can be explained due to the discount rate, as was seen in earlier sensitivities as well. Added to this is the electrification of the sectors and the use of renewables. For example, in the built environment, 250 PJ is generated by solar boilers. In the Baseline scenario, this is done by hybrid heat pumps. These are not deployed in the Zero CO_2 scenario.

For the No EEU biomass scenario, the most significant difference with the other scenarios is the maximum amount of biomass that is used in 2050. The maximum amount of biomass used is 431 PJ in 2050. This has to be compensated by other primary energy sources, like coal and naphtha. This is mostly used in the transport and industry sector, which is coupled with CCS. The remaining biomass that is available in the system is used as energy-efficiently as possible, which is why hydrogen vehicles and vehicles on renewable diesel are quite prevalent in this scenario.

The 100 % capture rate scenario makes that the electricity sector diminishes quite rapidly compared to the Baseline scenario. Due to a higher CR, the electricity sector has a higher remaining capacity of non-CCS electricity plants throughout the years. This also leads to the fact that fewer investments have to be made in other sectors to diminish the CO_2 emissions. In the end, however, this does not lead to significantly other total costs. This is the same in the other scenarios, as can be seen in Table 21.

Table 21 - Total costs per scenario

Scenario	Baseline	Zero CO_2	No EEU biomass	100 % CR
Total costs (billion €$_{2010}$)	733.5	734.0	738.3	733.0

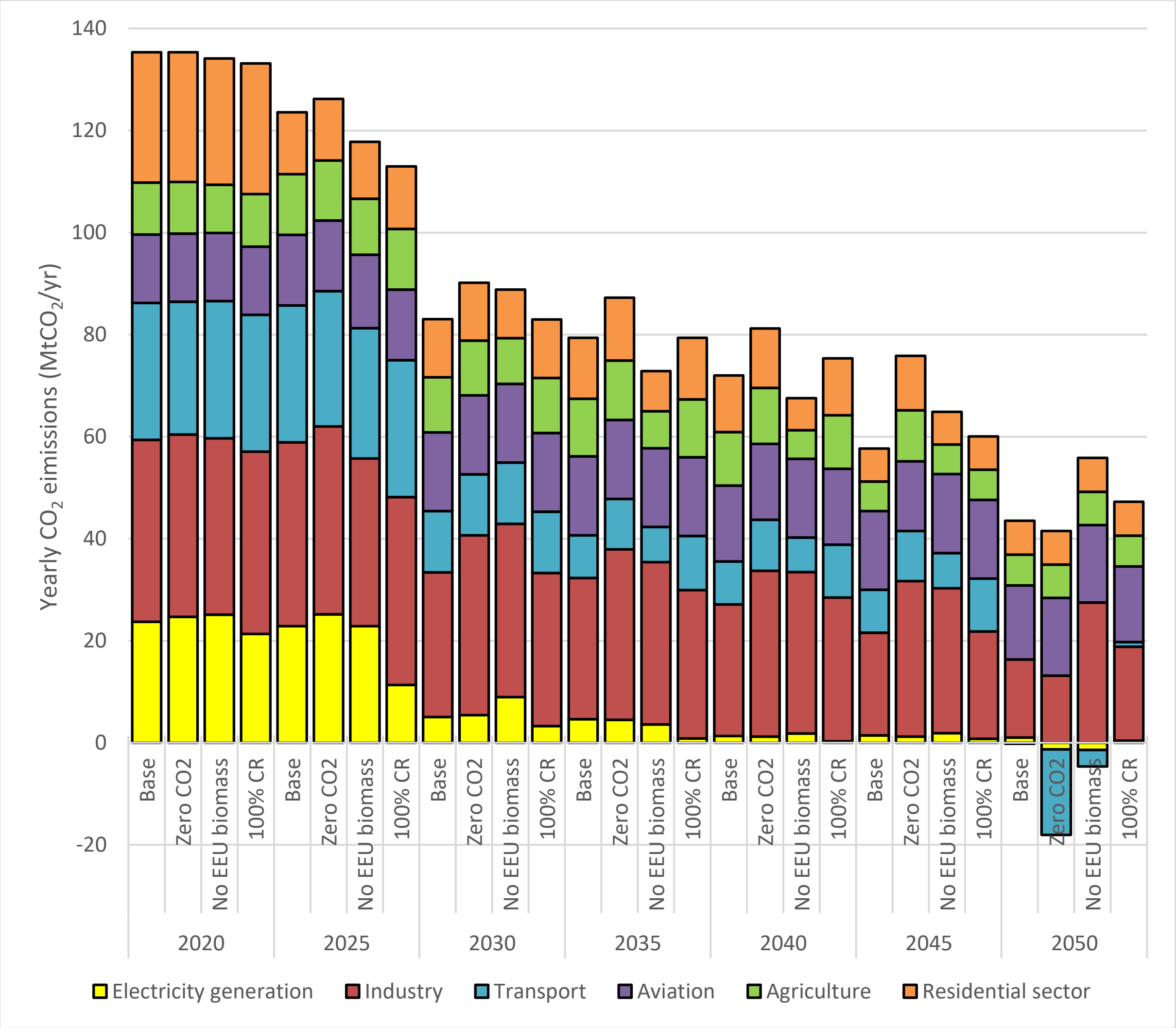


Figure 22 - Yearly emissions of CO2 per year and per different scenario

4. DISCUSSION

The results of this research show that the Dutch high emission sectors have to drastically change in order to stay within the national carbon budget. All sectors evolve from mainly using fossil fuels to using renewable energy, such as wind, low-CO_2 emitting fossil-based technologies, such as hydrogen with CCS, and electric technologies, such as heat pumps. When considering the average national carbon budget on the basis of GDP PPP and with proposed policy taken into account, the most significant change has to be made in the electricity sector by 2020. This is due to the decreed set by the court in the case of Urgenda vs the Dutch State. After this, the transport sector must change drastically due to its ability to switch to alternative fuels in combination with CCS. The built environment will also change significantly, by switching to non-natural gas using technologies. Overall, the results show that it is possible for the Netherlands to keep within this carbon budget. With a discount rate of 7 %, associated costs will amount to over 0.7 trillion € over the period 2018 to 2050. When proposed policy is not taken into account, this could drop with 11 billion €, which is just over 1.5 % of the total costs.

4.1 Data and research approach limitations

This research has four primary drawbacks that might be of influence to the results and therefore its implications on policy. First, as is in the nature of linear programming models, small cost differences may change the portfolio of technologies selected to reduce CO_2 emissions. Sensitivity analyses have been conducted to assure these costs differences are not significant. For example, when assuming the same costs for all personal vehicles in the model, it is found that about 50 % more hydrogen vehicles were installed as opposed to hybrid vehicles. However, the share of hydrogen vehicles was just under 10 % in personal transport demand, causing no difference in overall costs. When assuming that the investment costs for electricity generation was not updated, as was done in section 3.3.2. Techno-economic data updated in MARKAL-NL-UU, investment costs for wind technologies would be ~35 % higher and solar investment costs ~170 % higher. The installed capacity of wind and solar technologies would then be 40 and 6 GW as opposed to 42 and 30 GW by 2050, with overall costs rising by 4 billion € and the electricity sector being more dependent on NGCC-CCS and CHP plants and electricity storage in batteries. Although the investment costs on wind energy do not afflict a large difference, the investment costs for solar PV do. However, the difference in investment costs for solar PV is extravagant and exceptional. Investment costs for other technologies are not expected to change by comparable magnitudes in the foreseeable future.

Second, the model anticipates that swift action has to be taken so that by 2020 the CO_2 emissions may be reduced by 25 % compared to 1990 levels. As the current levels and 1990 levels are comparable, this signifies a 25 % CO_2 emission reduction of current levels within a narrow time frame. Technical or regulatory restrictions that inhibit these rapid changes due to the inability to transform in such a brief period may have been underestimated in this research. For example, the model indicates a need for insulation as well as electric boilers in the industry sector before 2020. Since these technologies require an extensive change in these sectors, the CO_2 emissions reductions by 2020 might have been overestimated, which has an impact on the emissions after 2020 as well. Such rapid changes within the sectors is considered highly unlikely.

Third, there are some peculiarities in the MARKAL-NL-UU model that should be addressed. This considers the built environment and CCS technologies in the industry sector. The rest heat demand for the built environment is not modelled with a load pattern, which means that seasonal differences cannot be taken into account. However, technologies such as heat pumps and electric boilers are rarely used in summer, while being extensively used in winter. Such seasonal differences may be of large importance in the model, as it influences the timing of electricity supply and demand, especially as heat pumps will demand 55 PJ/yr by 2050 in the built environment. The CCS technologies in the industry sector are applied only in 2050, in order to quickly diminish CO_2 emissions in this sector by 6

$MtCO_2$ (~29 %). This is device in the model applied so that swift emission reduction may be achieved, although this would sensibly not occur in reality.

Last, a discount rate of 7 % has been used in the model. As was shown in the sensitivity analysis of the discount rate, this may be of a high influence on the outcomes of the model. The higher the discount rate, the more favoured cheaper technologies are at the beginning of the modelling period. Analysis has shown that on average, a discount rate of 5.7 % is used in EU member states, with the Netherlands usually using a 5-9 % discount rate (Suvorava, Richmond, Patel, Bell, & Mesa, 2016). Using lower discount rates, expensive technologies such as CCS, wind and solar power might be more prevalent in the outcomes. This signifies that the results might not be fully applicable to other nations within the EU, as these countries usually apply different discount rates.

4.2 Contribution to knowledge and policy

With these limitations acknowledged, contributions to knowledge in the field and policy measures can be established. This research is a first time analysis of a non-linear decrease of CO_2 in multiple sectors to remain within a nationalised carbon budget. It has also shown that multiple different pathways may be considered, such as a pathway in which no CCS is taken into account or in which a low biomass potential is considered. This has the following seven implications for policymakers in the Netherlands.

First, it is shown that fast action is required to fulfil the decreed as set by Urgenda for 2020 emissions. In the electricity sector, CCS technologies have to be applied to PC and NGCC plants and in the built environment, insulation will have to be installed. With 2020 fast approaching, this indicates a swift change is necessary within these sectors. Even with currently established policy, it is highly unlikely for these technologies to be applied by 2020. When this decreed is not taken into account, high CO_2 emission reduction will have to occur using CCS technologies or an extensive amount of biomass. Therefore, policy focused on these technologies has to be established that will compensate for not reducing CO_2 emissions by 25 % compared to 1990 levels by 2020.

Second, policy at this moment is focused on electrical personal vehicles, while the NPP scenario has shown that this is not the most cost-effective pathway for reducing CO_2 emissions in the transport sector. This pathway, however, does rely on a large amount of biomass to be imported by the Netherlands. By 2050, almost 820 PJ/yr of biomass needs to be imported, most of which to be used in the transport sector. Therefore, policy needs to be focused on securing a large amount of biomass to be imported into the Netherlands. Even with no EEU biomass available, the Netherlands will still require almost 450 PJ/yr to be imported by 2050. This dependency on biomass imports could be relieved by electrification of the transport sector, which proposed policy suggests is the direction the Netherlands heads towards. This will have its implications on the overall costs, as well as the electricity generated. When analysing the possibility of using only EVs to be sold from 2030 onwards, this will cost an additional 14 billion € (1.9 %) up to 2050 and will require an additional 60 PJ/yr (10 %) of electricity to be generated by 2050 in the Baseline scenario. When policy is directed towards no EEU biomass and efforts to minimise biomass use even further by electrification of the transport sector, this will cost an additional 9 billion € (1.5 %) up to 2050 and an additional 40 PJ/yr (6 %) of electricity demanded by 2050.

Third, policy for CCS has to be established. Although a scenario without CCS is modelled to be feasible, the CO_2 emissions by 2020 will have to be diminished to 128 $MtCO_2$/yr (a 28 % decrease). This is considered to be impossible to achieve in such a short time span. Therefore, to remain within the national carbon budget, CCS technologies are vital throughout the entire period up to 2050. This will ensure that CO_2 emissions will not have to be diminished to 128 $MtCO_2$ by 2020, as CO_2 emissions may be captured in later years. Although the *Regeerakkoord* does mention CCS as technology for the future, actual policy has yet to be established.

Fourth, by 2050 almost 650 PJ/yr of electricity is generated, where 470 PJ/yr is demanded for technologies that are available today. The rest of the electricity is needed due to the use of electricity based technologies within the sectors as opposed to conventional fossil fuel counterparts. Currently around 410 PJ/yr of electricity is demanded, meaning that there is an increase of around 240 PJ/yr (~58 %) by 2050, of which 55 PJ/yr in the built environment. This indicates that a heavy reinforcement of the electricity distribution network is necessary. In the Netherlands, this is the responsibility of the government controlled Transmission System Operators and Distribution System Operators. Befitting policy therefore needs to be established that allows these parties to appropriately reinforce the electricity grid, to prevent instability of the network.

Fifth, the Netherlands, along with other nations, has set targets for emission reduction by 2030 and 2050. By 2030, 55 % of CO_2 emissions have to be reduced compared to 1990 levels (Koelemeijer et al., 2017) in order to limit the global average temperature increase to 1.5 °C. At the moment, the *Regeerakkoord* targets a 49 % decrease of CO_2 emissions, which corresponds to limiting the global average temperature increase to well below 2 °C, according to Koelemeijer et al. (2017). When not taking account emissions by aviation, the Baseline scenario calculates a 58 % decrease of CO_2 emissions by 2030, which indicates that a targeted 49 % emissions reduction would only be sufficient if more CO_2 would be reduced after 2030. A target of 55 % is more in line with the model outcome. When no proposed policy is taken into account, the emission reduction target in 2030 would be 51 %. This reveals that currently proposed policy leads to more CO_2 emissions after 2030 than when no proposed policy is taken into account. Therefore, more CO_2 emissions will already have to be reduced by 2030. This implicates that, if the government retains the target of reducing 49 % reduction by 2030, policy measures have to be established for after 2030 to allow for more CO_2 reduction in the period 2030-2050. Technologies used in the NPP scenario such as PC-CCS and biofuels in transport as opposed to EVs will then require tailored policy measures. Should the government want to retain policies as currently proposed for after 2030, additional policy measures will have to be established to decrease CO_2 emissions by 2030 by at least 55 % and preferably even by 58 %. For 2050, the target set by the Paris Agreement is a reduction of 80-95 % compared to 1990 levels. The Baseline scenario models an 83 % reduction by 2050, the NPP scenario 84 % by 2050. This is both in the range set by the Paris Agreement. However, policy needs to be established to ensure this target to be set. Policy targeting 80 % reduction (35.6 $MtCO_2$/yr by 2050) would be insufficient, while a target of 95 % (8.1 $MtCO_2$/yr by 2050) is over-ambitious when considering a budget divided by GDP PPP up to 2050. However, as the Zero CO_2 sensitivity variant shows, even 100 % reduction of CO_2 emissions compared to 1990 levels is possible. Establishing policy targeting such extreme emission reductions would indicate the Netherlands takes into consideration the *responsibility* dimension, thereby relieving the burden on developing countries that the nationalised carbon budget based on a division of GDP PPP sets.

Sixth, policy is established in which coal-fired power plants are phased out by 2030. This ensures the reduction of emissions in this sector due to the replacement of coal by natural gas and wind and solar energy. However, the model projects a shift of coal used for electricity generation towards coal used in the conversion sector. Due to CCS technologies applied in the conversion sector, emissions from coal are captured, leading to profound CO_2 emission reduction. This seems contradictory to what the policy is established for, as coal is still used in the system. Also, it seems remarkable that policy is established that will have to lead to large investments within the electricity sector, only for the use of primary energy to shift to another sector. Therefore, if current policy is designed in order for coal to be abolished as a primary energy source, additional policy for the conversion sector should also be established.

Last, it was shown that not all established and proposed policy is either insufficient or redundant. In the NPP scenario, the capacity of offshore wind will need to increase by 19 GW after 2030. In the Baseline scenario, due to proposed wind policy, this capacity will already increase by 9 GW in the period 2020-2030, after which 10 GW will be installed after 2030. This indicates a more gradual increase in offshore wind capacity, which is deemed more viable. Policy focussing on insulation is also found to be sufficient to completely reinsulate the built environment by 2030. This insulation ensures a lower energy demand for heat by the environment, which consequently makes CO_2 reductions less challenging. Current and proposed policy in these sectors is therefore believed to be adequate.

4.3 Further research

The data and research limitations and policy implications signify the necessity for four further research areas on this topic. First, suggested is to further analyse a national carbon budget for the Netherlands in which other dimensions, particularly that of *responsibility*, are taken into account. Using these carbon budgets for the Netherlands could have a significant influence on the outcome, as was demonstrated in the sensitivity analysis of the national carbon budget. However, this also directly indicates the need for research on technical and regulatory restrictions. A stringent national carbon budget, as with a carbon budget division based on population, will indicate a CO_2 emission reduction of 41 % by 2020 if limitations are not taken into account. Technical and regulatory restrictions will most likely not allow for such a significant emission reduction, which means that also research will need to be done to investigate the impact of these restrictions on the transition pathway.

Second, further sensitivity analyses concerning investment costs data are also recommended, as small differences in costs may lead to large differences in outcome. Sensitivity analyses on cost data will allow for policymakers to identify technologies that occur in practically all solutions. Policy measures on these technologies may then be established, as these technologies are then considered absolutely necessary to remain within the national carbon budget.

Third, the model is also heavily reliant on biomass, both from outside as well as within the EU, and coal. Biomass renewability is a contested topic (see e.g. Sachs, 2007), which is why further studies are suggested into the actual renewable biomass potential within the Netherlands up to 2050. Coal is considered to have many environmental and public health risks (see e.g. Union of Concerned Scientists, 2017). Parties concerned with climate change will therefore most likely remonstrate with the shift of coal from the electricity to the conversion sector. Further research in a system less reliant on coal as a primary energy resource is therefore advised.

Supplementary research is also urged into the back-up capacity in the electricity sector for the Netherlands and its impact on the development of the other sectors. This also includes flexibility within the electricity system using demand side management, smart grids and the potential of electricity storage. Although a first attempt of including electricity storage is undertaken, more variants of hydrogen storage and battery storage exist, as well as the potential of EVs to act as a battery.

Finally, additional research is recommended for the Netherlands in relation to other countries. In MARKAL-NL-UU, the Netherlands is treated as an isolated country. Although resources are imported into the country, these are not influenced by developments in other countries. For example, the biomass availability as well as the price may be influenced by a large use of biomass by the country from which it is imported. This may lead to an increase in the attractiveness of an alternative resource. Also, an unavailability of coal-fired power plants may not directly result in an increase of renewable electricity but instead an increase of electricity imported from another country which generates this electricity using fossil fuels. This spill-over effect may result in a shift of CO_2 emissions rather than a reduction. These effects may be evaluated in an analysis in which other countries are also examined.

4.4 Evaluation of results

To evaluate the results, earlier research conducted was compared to the results of this study in three manners. First, dominant technologies were compared on their potential in the Netherlands. In the electricity sector, the CO_2 emissions are reliant on a capacity increase of offshore wind and solar PV to 34 and 30 GW respectively. According to Kroon (2017), TenneT anticipates the capacity of offshore wind to increase to 33 GW by 2050 in the Dutch part of the North Sea only. This therefore matches with the installed capacity as determined by MARKAL-NL-UU. Analysis by Folkerts, van Sark, Keizer, van Hooff, & van den Donker (2017) has shown the potential installed capacity of solar PV in the Netherlands to be over 100 GW, indicating that the installed capacity as calculated by MARKAL-NL-UU is achievable. However, a far larger capacity is anticipated by the solar electricity sector. For other sectors, specific values could not be found. However, it has been shown that hybrid heat pumps have a large potential for heating in existing buildings (ECN, 2009), CCS technologies are a robust option in 2050 scenarios (PBL, 2017) and that biofuels will become increasingly important for the Netherlands (SER, 2014).

Second, comparing the results to other researches that investigate the emission reduction pathways to 2050, the importance of dominant technologies may be further investigated. Two studies on the Netherlands by 2050 by PBL (Ros et al., 2011) and Gasunie (2018) were compared to the Baseline and NPP scenario. A basic structure which ranks technologies on their importance is used, in which the influence on the results is evaluated. This importance is ranked *very large* if large capacities are installed or their use is inevitable. The importance is ranked *large* if technologies are dominant in the technology mix in its sector and *limited* if the technology is used, albeit scarcely. An overview of technologies and their importance can be found in Table 22 below.

For the Baseline and NPP scenario, offshore wind and CCS are inevitable and therefore considered of very large importance. The influence of solar PV is large and nuclear energy is phased out by 2035 and therefore considered limited. Geothermal energy is not used throughout the scenarios, while the use of solar heat is limited to currently installed capacity. Heat pumps, however, are used predominantly in both the built environment as well as the industry. The transport sector is primarily fuelled by biofuels, while EVs are only present in the Baseline scenario due to current proposed policy. Hydrogen is used in transport in both scenarios, but its influence is limited.

Ros et al., ranked these technologies using the same terminology. The largest differences can be found in the importance of nuclear energy as opposed to power plants with CCS. In all scenarios in this research, however, nuclear energy is forced to phase out by 2035. Also, Ros et al. (2011) considers electricity and hydrogen in transport as largely important by 2050, while its influence is found to be limited in the scenarios in this research. However, EVs may be used for flexibility in the electricity grid and hydrogen in transport for long distances such as road haulage, according to Ros et al. (2011). In MARKAL-NL-UU, EVs cannot function as electricity storage and hydrogen trucks are not available, which explains the difference in the conclusions of Ros et al. (2011) and the scenarios.

In the analysis of Gasunie (2018), 66 GW of solar PV and 55 GW of offshore wind will be installed. CCS technologies are considered inevitable, especially in the industry sector. In the built environment, geothermal energy and heat pumps dominate the sector. The use of hydrogen in transport is strengthened by offshore wind-parks dedicated to generating hydrogen. A similar option is not present in MARKAL-NL-UU, which might explain the difference in prevalence in the technology mix. Biofuels use is considered limited to be used in heavy transport.

The same approach is used when comparing the Greenpeace Energy [R]evolution (ER) scenario for the Netherlands (Teske, Onufrio, Gianni, Rainer, & Rahlwes, 2013) with the No CCS scenario. As the ER scenario is one of the few scenarios in which CCS technologies are not included, this is the only scenario used in the comparison. In the ER scenario, wind and PV capacity increase to 27 and 37 GW respectively. Geothermal applications, heat pumps and solar thermal technologies will have a large impact in the heat supply of both the industrial and agriculture sector and the built environment. Due to the assumption that no 1st generation biomass is available, its potential remains limited in the ER scenario in the transport sector. Instead, EVs are considered almost equally important, while hydrogen is scarcely used in transport.

Overall, similar technologies are considered dominant throughout the researches. Assumptions on the availability may affect the importance of the technologies, as can be seen in the case of nuclear in electricity generation or hydrogen for transport. Ultimately, the importance of offshore wind, solar PV, CCS, heat pumps and biofuels for transport is generally considered high in the researches.

Table 22 - Rank of importance of dominant technologies in the scenarios of this research and in different studies

Technology	Baseline	NPP	Ros et al. (2011)	Gasunie (2018)	No CCS	Teske et al. (2013)
Offshore wind	Very large	Very large	Large	Very large	Very large	Large
Solar PV	Large	Large	Limited	Very large	Large	Very large
Nuclear	Limited	Limited	Large	Limited	Limited	Limited
CCS	Very large	Very large	Electricity: limited Industry: very large	Very large	Not used	Not used
Geothermal	Not used	Not used	Limited	Large	Not used	Large
Solar heating	Limited	Limited	Limited	Limited	Limited	Large
Heat pumps	Very large	Very large	Very large	Very large	Very large	Large
Electric vehicles	Limited	Not used	Large	Very large	Not used	Large
Hydrogen vehicles	Limited	Limited	Large	Very large	Limited	Limited
Biofuels	Very large	Very large	Very large	Limited	Very large	Large

Third, an analysis of the Paris Agreement goals and implications on Dutch policy (Sterl, Höhne, & Kuramochi, 2017) was also compared to the Baseline and NPP scenario, as well as the No CCS scenario. Sterl et al. (2017) translated Paris Agreement goals into timing for policy measurements in their analysis, both for an option with and without CCS. The comparison can be found in Table 23 below.

Sterl et al. (2017) suggest numerous policy measures that are not necessary according to the results in this research. For example, emissions from the electricity sector have to be diminished to 0 $MtCO_2$/yr according to Sterl et al. (2017). The Baseline and the NPP scenario reduce emissions to 1 $MtCO_2$/yr by 2050, while the No CCS scenario does not get to 0 $MtCO_2$/yr at all. Fossil fuels will always remain in the electricity sector, so without CCS this sector will never reduce its emissions by 100 %. Such deep emissions reductions would only be possible with a 100 % capture rate of CCS technologies or a completely renewable electricity sector. The latter is an option that Sterl et al. (2017) also proposes, while the three scenarios in this research do not. In the built environment, residential buildings have to become gas free according to Sterl et al. (2017). Due to the application of hybrid heat pumps, neither scenario will reach this target. In the transport sector, EVs will have to make up a 100 % share at one point in time (Sterl et al., 2017). A comparison of the Baseline and NPP scenario has shown that no EVs are deployed if these are not forced by policy. In the agricultural sector, emissions will also have to become 0 $MtCO_2$/yr, but neither scenario in this research reaches such profound emission reductions.

Two findings by Sterl et al. (2017) are comparable. Coal in electricity generation has to be phased out quite swiftly, according to the Paris Agreement. The Baseline scenario illustrates a phase-out of coal-fired power plants by 2030 already, while the No CCS scenario requires no coal for electricity by 2020. For the industry sector, Sterl et al. (2017) state that it would be necessary to reduce emissions to 0 $MtCO_2$/yr as well, although they recognise this would be challenging. This is a similar finding as in the scenarios in this research, as the industry is the highest emitting sector by 2050, with an emission reduction of ~60 % in the Baseline and NPP scenario and ~35 % reduction in the No CCS scenario.

Overall, the translation of the Paris Agreement into policy goals by Sterl et al. (2017) seems to calculate that overall emissions have to decrease to 0 $MtCO_2$/yr by 2050 when CCS technologies are applied and by 2035 when no CCS is applied. The scenarios in this research give a completely different outlook. Even when 0 $MtCO_2$/yr is targeted by 2050, this does not entail all sectors to be completely CO_2 free by 2050 but instead some CO_2 emissions from one sector are offset by another sector. This crucial difference is not taken into account by Sterl et al. (2017), thereby presenting a contrasting outcome.

Table 23 - Timing of policy measures as proposed by Sterl et al. (2017) and in the scenarios in this research

	Baseline	NPP	No CCS	Sterl et al. (2017)	Sterl et al. (2017) - no CCS
100% renewables in electricity	Never	Never	Never	2035-2040	2015-2025
No coal in electricity	2030	2030	2020	2030-2035	2010-2020
No emissions in electricity	Never	Never	Never	2045-2050	2025-2035
No emissions in industry	Never	Never	Never	-	-
No gas in built environment	Never	Never	Never	2045-2050	2025-2035
100% EVs in transport	Never	Never	Never	2045-2050	2025-2035
No emissions in agriculture	Never	Never	Never	2045-2050	2025-2035

5. CONCLUSION

In this research, a national carbon budget was established for the Netherlands. This carbon budget corresponds to a 33 to 50 % probability to limit average global surface temperature increase to 1.5 °C compared to pre-industrial levels. It was applied to a linear programming model that describes the electricity, industrial, built environment, transport and agricultural sector and its corresponding CO_2 emissions in detail. Technologies that were not yet present in the model were added, most of which may be applied in the built environment. Technologies for renewable heat generation in the industrial and agricultural sector were also added, as well as options for energy storage throughout the sectors. Using the national carbon budget for the Netherlands, multiple analyses were carried out on the basis of cost-minimisation. The Baseline scenario incorporates current technology pathways of the Netherlands, including proposed policy by the Dutch government, is taken into account. Alternatives to this scenario are also analysed, leading to scenario where no proposed policy is taken into account, where 100 % BECCS is allowed and where no CCS is allowed.

From this analysis, it can be learned that the Netherlands is able to remain within a national carbon budget which allocates a global carbon budget on the basis of GDP PPP until 2050. Through the use of wind and solar energy, CCS technologies in the electricity sector and the industrial sector and heat pumps in the built environment, this may be achieved. An overall cost of 0.7 trillion € is associated with the system, with the overall CO_2 emissions reducing by 51-58 % by 2030 and 83-84 % by 2050. The least reduction of CO_2 emissions are achieved in the industrial sector (~60 %), while the highest CO_2 emissions reduction is achieved in the transport sector (100 - 107 %). Should the Netherlands target no use of CCS technologies, this may also be achieved. However, this is only feasible with a very fast and swift action before 2020, which is highly unlikely in current political and regulatory environment. CO_2 emissions would also already have to be reduced 2020 by 29 %, which is considered highly improbable. Several sensitivity analyses have shed a light on alternatives to the Baseline scenario. the Netherlands may also target emissions of 0 $MtCO_2$/yr by 2050, thereby taking responsibility for historical emissions, no extra EU biomass may be necessary to remain within the national carbon budget, at the expense of an additional 5 billion €, and a 100 % capture rate of CCS technologies in the electricity sector ensures a less strenuous emission reduction, by that ensuring 0 $MtCO_2$/yr by the electricity sector by 2040.

Through these results, several implications on Dutch policy can be deduced. Fast action is required to reduce emissions by 25 % by 2020. Also, additional policy needs to be established to ensure the deployment of CCS technologies. Biomass, a resource which is heavily import dependent, will need to be secured at a level of 450 PJ/yr by 2050. Electrification of personal vehicles in the transport sector is not the most cost-effective pathway, which will lead to an increase of 14 billion € (1.9 %) in costs and an additional 60 PJ/yr (10 %) to be generated by 2050. Even when no EVs are forced into the transport sector, electricity demand will increase by 58 %, in large part due to the electrification of heat demand. This indicates a need to establish policy that allows for a reinforcement of the electricity distribution network.

Further research is necessary to establish a national carbon budget in which the Netherlands takes responsibility for historical emissions. Such a national carbon budget could be considered fairer for developing nations, which would then have the ability to secure basic needs before being troubled with climate policy. Also, technical and regulatory restrictions that will not allow for any significant emission reduction by 2020 will have to be evaluated in further analysis. In this research, it is considered that it is possible to reduce emissions by 25 % by 2020, although this challenge might be not realistic. A more in-depth analysis of the electricity sector and corresponding electricity storage as well as electricity balancing may also give more insight into potentials for these technologies.

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APPENDIX I

Below, per sector, the technologies that were considered can be found. These technologies can all be found summarized in Table 24. The technologies that have been added may be found in section 3.2 Technology inventory

I.1 The electricity sector

1) Technologies that still emit some CO_2

Any existing non-renewable energy technology that still emits CO_2 may be retrofitted with a CCS technology. These technologies were already modelled in MARKAL-NL-UU.

2) Technologies that emit no CO_2

Large-scale renewable technologies are categorized in (1) solar energy, (2) bioenergy, (3) ocean energy, (4) hydropower, (5) wind energy, (6) geothermal energy and (7) nuclear energy.

(1) Solar energy for energy generation can be further distinguished in concentrated solar power (CSP), concentrated photovoltaics (CPV), solar water heating (SWH) and solar photovoltaic (PV) systems. For CSP, CPV and SWH there is no potential in the Netherlands for large-scale electricity generation (refer to figure 2 of Köberle, Gernaat & van Vuuren (2015)). Solar PV was already present in MARKAL-NL-UU.

(2) Bioenergy for electricity generation, known as thermochemical heat (i.e. direct combustion and pyrolysis) was previously determined in and modelled by Tsiropoulos (2016) and are therefore not further discussed in this paper.

(3) Ocean energy consists of ocean thermal energy conversion (OTEC), tidal energy, wave energy and blue energy. OTEC cannot be applied in the Netherlands, due to the lack of large temperature gradients in the ocean along the coast of the Netherlands (figure six of International Renewable Energy Agency (2014)). Wave and tidal energy have been said for long periods of time to have an enormous potential (i.e. by Pelc & Fujita (2002) and more recently by Melikoglu (2018)), but have so far remained underdeveloped. Global capacity of these types of ocean energy is estimated to be merely 500 to 2750 MW (Melikoglu, 2018). It is therefore assumed that these technologies will not be developed for large electricity generation. This same assumption goes for blue energy, which generates electricity using salt gradients. Blue energy is a technology that has yet to prove to be successful on a large scale, with research still being done on the basic principles and still found in research to be a technology with a significant potential (Simoncelli et al., 2018); which indicates the underdevelopment of the technology.

(4) Hydropower can be low head hydropower or high head hydropower. Low head hydropower, in which the water drops less than 20 meters, was already modelled in MARKAL-NL-UU. The geography of the Netherlands does not allow for high head hydropower, meaning it is not added.

(5) Wind energy, both onshore and offshore wind energy, was already present in MARKAL-NL-UU.

(6) Geothermal energy was already present in MARKAL-NL-UU.

(7) Nuclear energy was already present in MARKAL-NL-UU.

Added to this are the technologies that are used for energy storage and fuel cells. Technologies used for energy storage can be further distinguished in electrical storage devices (i.e. capacitors and batteries), energy storage for grid electricity (i.e. pumped hydro and flywheels) and chemical storage (i.e. hydrogen and ammonia). Electrical storage will be modelled in the form of batteries since their potential is the highest (Twidell & Weir, 2015). Energy storage for grid electricity has no potential in the Netherlands since flywheels are considered underdeveloped (Twidell & Weir, 2015) and pumped hydro is not applicable. Chemical storage in the form of hydrogen is also modelled.

3) Technologies that have negative CO_2 emissions

Technologies that have negative CO_2 emissions for electricity generation are already present in MARKAL-NL-UU. It involves technologies that use biological sources that take up CO_2 during their lifetime, after which CCS is applied.

I.2. The industrial sector

The direct emissions of the industrial sector originate from the generation of heat, on-site transportation and electricity generation and process emissions. In total, 80.4 % (41/51 $MtCO_2$) of emissions are related to the generation of low, medium and high-temperature heat (LTH, MTH, HTH) to be used in production. Of the remaining 10 $MtCO_2$, 7 $MtCO_2$ can be attributed to a (chemical) process. These are emissions from ammonia, hydrogen and cement production (Royal VEMW, 2017). Technologies that cause deep CO_2 emission reduction are therefore focussed on these emissions.

1) Technologies that still emit some CO_2

CCS technologies for the industry have already been modelled in MARKAL-NL-UU. This leaves dual hydrogen/gas boilers. These are boilers that use both hydrogen as well as natural gas and replace conventional natural gas boilers. They use electricity when there is a surplus thereof, thereby diminishing the CO_2 emissions as compared to conventional boilers.

2) Technologies that emit no CO_2

There are plenty technologies within the industry that emit no CO_2, which not all will be listed. Technologies that emit no CO_2 which have been added as proposed by Royal VEMW (2017):

1) Heat pumps
2) Mechanical vapour recompression
3) Large-scale electrolysis
4) High-temperature electric furnaces
5) Electric boilers

Large-scale electrolysis is modelled as hydrogen storage in the electricity sector. Also proposed were heat networks and bio-to-chemicals. Heat networks have already been modelled in MARKAL-NL-UU. Biomass for the industry can be dissected into biochemical energy (i.e. (an)aerobic digestion and alcoholic fermentation) and agrochemical energy (i.e. fuel extraction and biodiesel). Biomass can also be used in boilers to produce heat. Technologies using biomass in the industry were previously determined in and modelled by Tsiropoulos (2016) and therefore not further discussed in this paper.

3) Technologies that have negative CO_2 emissions

In MARKAL-NL-UU, medium-temperature heat was not yet explicitly modelled but is implicitly modelled within high-temperature heat. It is chosen not to model medium-temperature heat separately. Within the industry, it is possible to use CCS with biomass as well as using CCU for negative CO_2 emissions. Using CCS in combination with biomass has been modelled in MARKAL-NL-UU. CCU technologies are relatively new, and large barriers still exist. However, there are a few technologies which are found to have potential, as listed in table 2 by Al-Mamoori, Krishnamurthy, Rownaghi, & Rezaei (2017), see Figure 23.

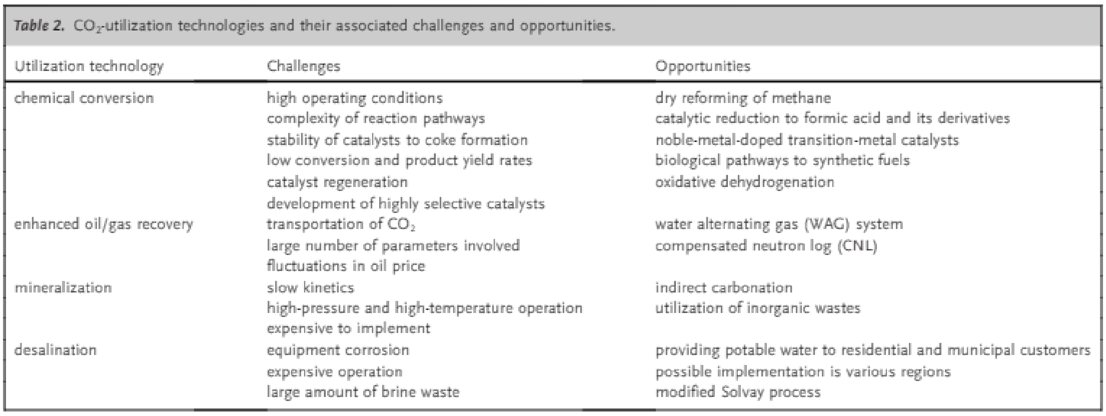
Table 2. CO_2-utilization technologies and their associated challenges and opportunities.

Utilization technology	Challenges	Opportunities
chemical conversion	high operating conditions complexity of reaction pathways stability of catalysts to coke formation low conversion and product yield rates catalyst regeneration development of highly selective catalysts	dry reforming of methane catalytic reduction to formic acid and its derivatives noble-metal-doped transition-metal catalysts biological pathways to synthetic fuels oxidative dehydrogenation
enhanced oil/gas recovery	transportation of CO_2 large number of parameters involved fluctuations in oil price	water alternating gas (WAG) system compensated neutron log (CNL)
mineralization	slow kinetics high-pressure and high-temperature operation expensive to implement	indirect carbonation utilization of inorganic wastes
desalination	equipment corrosion expensive operation large amount of brine waste	providing potable water to residential and municipal customers possible implementation is various regions modified Solvay process

Figure 23 - Table 2 from Al-Mamoori et al. (2017)

The chemical conversion utilisation pathway has been modelled in MARKAL-NL-UU in the production of urea using CO_2. Other CO_2 utilisation pathways as suggested in Al-Mamoori et al. (2017), such as the dry reforming of methane and the production of formic acid and DME are technologies that are still under development. As stated in their research, the primary barrier to implementation of these technologies lies in the development of new catalysts. Until then, these technologies are considered underdeveloped. Enhanced oil/gas recovery is currently modelled in MARKAL-NL-UU, while mineralization is an underdeveloped technology, with many drawbacks. However, a few pilot plants exist, making this a potentially viable technology for the future. Desalination has no potential in the Netherlands since potable water in the Netherlands is not produced by desalination.

I.3. The built environment

For the built environment, the deep CO_2 emission reductions are found in the reduction of energy use and making energy supply renewable. For inspiration, technologies are used that were identified in (RVO, 2015), which are technologies for near-energy neutral buildings. A small-scale fuel cell is not considered by RVO (2015) but added anyway so that hydrogen may also be used in this sector.

1) *Technologies that still emit some CO_2*

Micro CHPs (MCHPs) are household-sized CHP plants that use natural gas to produce both electricity and heat. These technologies may offer an alternative to conventional gas boilers. On a larger scale, a district CHP plant can provide both electricity and gas to large users or a district of houses. Hybrid heat pumps, using both natural gas and electricity, also belong to this category.

2) *Technologies that emit no CO_2*

Technologies that emit no CO_2 are the technologies that use renewable energy for electricity or heat generation or the technologies that have no direct CO_2 emissions. For the built environment, the former entails district CHP that use biogas or wood pellets, heat pumps on green gas, small-scale fuel cells and solar boilers and solar PV. The latter entails district heating, electric boilers, electric furnaces (or power to heat boilers), heat pumps on electricity, both air and ground source and geothermal heat. An option for energy storage, ATES, is also added to this sector. For the reduction of energy use, insulation for both households and buildings is considered (refer to Appendix V).

3) *Technologies that have negative CO_2 emissions*

There are no technologies for the built environment that have negative CO_2 emissions.

I.4. The transport sector

The transport sector has already been explicitly modelled in MARKAL-NL-UU in great detail, meaning no technology is added in this sector. Transport technologies may use diesel and petrol, generated using fossil resources or biofuels, dimethyl ether, electricity, hydrogen and methanol, or a mix thereof, to fulfil transport demand.

I.5. The agricultural sector

The agricultural sector consist mainly of heat for greenhouses (ECN, 2017). Therefore, deep CO_2 emissions can be obtained by making this heat use renewable. For this, CHP plants on biogas can be used, which are already modelled in MARKAL-NL-UU. Also, storing LTH from industry and using it in ATES systems is a possibility for the agricultural sector, as well as deep geothermal heat pumps.

Table 24 - All technologies considered per sector

Sector	Technology	Present?	Is added?
Electricity	Battery electricity storage	No	Yes
	Bioenergy	Yes	-
	Bioenergy with CCS	Yes	-
	Coal with CCS	Yes	-
	CPV	No	No
	CSP	No	No
	Fuel cells (hydrogen)	No	Yes
	Geothermal	Yes	-
	Hydrogen electricity storage	No	Yes
	Hydropower	Yes	-
	Natural gas with CCS	Yes	-
	Nuclear	Yes	-
	OTEC	No	No
	Solar PV	Yes	-
	Solar water heating	No	No
	Tidal	No	No
	Waste/LFG with CCS	No	No
	Wave	No	No
	Wind	Yes	-
Industry	Biomass boiler	Yes	-
	Chemical conversion CCU	Yes	-
	Desalination CCU	No	No
	Electric boilers	No	Yes
	Electric furnace	No	Yes
	Electrolysis	No	No
	Enhanced oil/gas recovery CCU	Yes	-
	Heat pump	No	Yes
	Hydrogen/gas boilers	No	Yes
	Mechanical vapour recompression	No	Yes
	Medium-temperature heat	No	No
	Mineralisation CCU	No	No
Built environment	ATES	No	Yes
	District CHP, biogas	Yes	-
	District CHP, gas	Yes	-
	District CHP, wood pellets	Yes	-
	District heating	Yes	-
	Electric boilers	No	Yes
	Electric furnace (power to heat)	No	Yes
	Geothermal	No	Yes
	Heat pump (air source)	No	Yes
	Heat pump (green gas)	No	Yes
	Heat pump (ground source)	No	Yes
	Heat pump (hybrid)	No	Yes
	Isolation (cheap)	No	Yes
	Isolation (moderate)	No	Yes
	Isolation (expensive)	No	Yes
	Micro CHP	No	Yes
	Small-scale fuel cell	No	Yes

	Solar boiler	No	Yes
	Solar PV	Yes	-
Transport	Petrol vehicles	Yes	-
	Petrol series hybrid vehicles	Yes	-
	Petrol parallel hybrid vehicles	Yes	-
	Diesel vehicles	Yes	-
	Diesel series hybrid vehicles	Yes	-
	Diesel parallel hybrid vehicles	Yes	-
	Diesel/petrol fuel cell vehicles	Yes	-
	Diesel bus	Yes	-
	Diesel series hybrid bus	Yes	-
	Diesel truck	Yes	-
	Diesel parallel hybrid van	Yes	-
	Diesel series hybrid van	Yes	-
	Diesel van	Yes	-
	Hydrogen van	Yes	-
	Hydrogen fuel cell vehicles	Yes	-
	Hydrogen hybrid vehicles	Yes	-
	Electric vehicles	Yes	-
	Electric plug-in hybrid vehicles	Yes	-
	Methanol vehicles	Yes	-
Agriculture	ATES	No	-
	CHP on biomass	Yes	-
	Geothermal	No	Yes

APPENDIX II

Below, in Table 25, all demands as are present in MARKAL-NL-UU can be found.

Table 25 - All demands in MARKAL-NL-UU

Demand	Units	2015	2020	2025	2030	2035	2040	2045	2050
Ammonia	Mt	2.0	2.0	2.0	2.2	2.4	2.7	2.9	2.9
BDO	Mt	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Butadien	Mt	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7
Cement	Mt	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0
Ethylene	Mt	1.0	1.0	1.0	1.1	1.1	1.2	1.4	1.4
Ethylene oxide	Mt	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Glycerin	Mt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen	Mt	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Manure	Mt	19.2	19.2	19.2	19.0	18.7	18.6	18.5	18.5
Phtalic anhydride	Mt	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Polyethylene	Mt	1.7	1.7	1.7	1.8	1.9	2.1	2.2	2.2
PET	Mt	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Polypropylene	Mt	0.7	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Refinery	Mt	32.9	32.9	32.9	32.7	30.2	29.9	28.9	28.9
Rest ethylene glycol	Mt	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7
Rest propylene	Mt	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Rest PTA	Mt	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Steel	Mt	2.0	2.0	2.0	2.2	2.3	2.5	2.7	2.7
Styrene	Mt	373.7	403.7	418.5	411.3	420.8	425.8	429.5	441.7
Urea	Mt	120.7	97.8	26.3	29.9	18.9	16.1	10.2	10.2
Electricity	PJ	141.0	141.0	141.0	142.0	144.0	144.0	133.0	132.0
Agricultural district heat	PJ	258.0	261.3	209.5	192.5	195.9	208.5	232.1	232.1
Agricultural rest heat	PJ	141.8	155.5	145.0	157.0	168.9	182.1	195.2	195.2
Industrial district heat	PJ	33.0	33.0	24.0	27.0	26.0	31.0	29.0	29.0
Industrial rest heat	PJ	407.0	415.2	462.1	421.9	412.9	404.7	403.4	403.4
Jet fuel	PJ	0.6	0.6	0.7	0.7	0.6	0.7	0.7	0.7
Built environment district heat	PJ	91.2	96.9	100.9	105.0	109.2	113.7	118.3	123.1
Built environment rest heat	PJ	15.0	18.2	19.0	19.7	20.5	21.4	22.2	23.1
Bus kilometres	Bv-km	2.0	2.0	2.0	2.2	2.4	2.7	2.9	2.9
Personal vehicle kilometres	Bv-km	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Truck kilometres	Bv-km	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7
Van kilometres	Bv-km	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0

APPENDIX III

Below, in Table 26, all prices as are present in MARKAL-NL-UU can be found.

Table 26 - All prices in MARKAL-NL-UU

Technology	Units	2015	2020	2025	2030	2035	2040	2045	2050
Additional co-digestate NL	€$_{2010}$/t	38.9	38.7	39.3	40.8	41.0	41.6	42.3	42.9
Aromatics	€$_{2010}$/t	684.7	564.7	681.1	797.6	795.8	841.3	886.8	932.3
Beet tops and leaves NL	€$_{2010}$/GJ	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Biodiesel	€$_{2010}$/GJ	16.7	25.7	32.2	32.2	40.0	45.3	50.6	55.9
Blast furnace gas	€$_{2010}$/GJ	0	0	0	0	0	0	0	0
Cattle and pig manure liquid for co-digestate NL	€$_{2010}$/t	1.4	1.4	1.5	1.6	1.6	1.6	1.7	1.7
Common sludges for digestion NL	€$_{2010}$/t	14.3	14.2	14.9	15.6	15.9	16.3	16.8	17.2
Electricity export	€$_{2010}$/GJ	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Electricity import	€$_{2010}$/GJ	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Energy maize for co-digestate NL	€$_{2010}$/t	38.9	38.7	39.3	40.8	41.0	41.6	42.3	42.9
Energy maize for co-digestate EEU	€$_{2010}$/t	81.5	85.8	88.3	92.1	95.5	99.0	102.4	105.8
Energy maize for co-digestate NEU	€$_{2010}$/t	90.3	83.2	84.3	85.8	82.8	81.5	80.3	79.0
Energy maize for co-digestate SEU	€$_{2010}$/t	118.8	120.1	123.3	125.7	127.9	130.3	132.7	135.0
Energy maize for co-digestate WEU	€$_{2010}$/t	73.6	75.8	77.9	80.0	82.1	84.2	86.3	88.4
Ethanol 1st generation	€$_{2010}$/GJ	27.3	25.4	24.3	23.6	18.7	18.7	18.7	18.7
Ethanol 2nd generation	€$_{2010}$/GJ	34.1	32.4	31.0	30.1	28.6	27.3	26.0	24.6
Ethylbenzene	€$_{2010}$/t	1144.0	1144.0	1144.0	1144.0	1144.0	1144.0	1144.0	1144.0
Fuelwood for woodstoves and boilers	€$_{2010}$/GJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Grain maize and cereal crops NL	€$_{2010}$/GJ	6.5	6.3	6.0	5.8	5.6	5.4	5.2	4.9
Grain maize and cereal crops EEU	€$_{2010}$/GJ	8.3	8.1	8.3	8.5	8.5	8.6	8.6	8.7
Grain maize and cereal crops NEU	€$_{2010}$/GJ	8.4	8.2	8.2	8.2	8.0	8.0	7.9	7.8
Grain maize and cereal crops SEU	€$_{2010}$/GJ	9.0	8.9	9.0	9.2	9.2	9.3	9.3	9.4
Grain maize and cereal crops WEU	€$_{2010}$/GJ	7.0	6.8	6.9	7.1	7.0	7.1	7.1	7.2
Hardwood poplar and willow NL	€$_{2010}$/GJ	9.8	9.8	9.6	9.5	9.4	9.3	9.2	9.1
Hardwood poplar and willow EEU	€$_{2010}$/GJ	8.5	8.5	8.8	9.0	9.1	9.2	9.4	9.5
Hardwood poplar and willow NEU	€$_{2010}$/GJ	8.8	8.8	8.9	9.0	9.1	9.1	9.2	9.3
Hardwood poplar and willow SEU	€$_{2010}$/GJ	17.4	17.4	17.4	17.3	17.3	17.3	17.3	17.2
Hardwood poplar and willow WEU	€$_{2010}$/GJ	8.5	8.5	8.7	8.8	8.9	9.0	9.1	9.2
Landscape waste wood NL	€$_{2010}$/GJ	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5
Landscape waste wood EEU	€$_{2010}$/GJ	7.7	7.7	8.0	8.2	8.4	8.6	8.7	8.9
Landscape waste wood NEU	€$_{2010}$/GJ	8.3	8.3	8.4	8.6	8.7	8.8	8.9	9.0
Landscape waste wood SEU	€$_{2010}$/GJ	8.9	8.9	9.2	9.3	9.5	9.6	9.8	9.9

Landscape waste wood WEU	€$_{2010}$/GJ	6.6	6.5	6.7	6.9	6.9	7.0	7.1	7.3
Organic MSW households and other NL	€$_{2010}$/GJ	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Other digestible waste NL	€$_{2010}$/t	33.3	33.6	34.1	34.5	34.9	35.3	35.7	36.1
Other grasses (roadside, forage cuttings) NL	€$_{2010}$/GJ	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3
Other grasses (roadside, forage cuttings) EEU	€$_{2010}$/GJ	5.8	5.8	6.0	6.3	6.4	6.5	6.7	6.8
Other grasses (roadside, forage cuttings) NEU	€$_{2010}$/GJ	5.7	5.6	5.7	5.8	5.9	6.0	6.0	6.1
Other grasses (roadside, forage cuttings) SEU	€$_{2010}$/GJ	7.1	7.1	7.3	7.5	7.6	7.7	7.8	7.9
Other grasses (roadside, forage cuttings) WEU	€$_{2010}$/GJ	4.0	4.0	4.1	4.3	4.3	4.4	4.5	4.6
Perennial grasses: miscanthus and switchgrass NL	€$_{2010}$/GJ	6.9	6.9	6.8	6.8	6.7	6.6	6.6	6.5
Perennial grasses: miscanthus and switchgrass EEU	€$_{2010}$/GJ	8.4	8.4	8.7	9.0	9.2	9.4	9.6	9.8
Perennial grasses: miscanthus and switchgrass NEU	€$_{2010}$/GJ	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3
Perennial grasses: miscanthus and switchgrass SEU	€$_{2010}$/GJ	11.8	11.8	11.9	12.0	12.1	12.2	12.2	12.3
Perennial grasses: miscanthus and switchgrass WEU	€$_{2010}$/GJ	7.3	7.3	7.5	7.6	7.7	7.8	7.9	8.0
Primary forestry residues (chips, fuel) NL	€$_{2010}$/GJ	4.0	4.0	4.1	4.1	4.1	4.2	4.2	4.2
Primary forestry residues (chips, fuel) EEU	€$_{2010}$/GJ	8.7	8.8	9.0	9.2	9.4	9.6	9.8	10.0
Primary forestry residues (chips, fuel) NEU	€$_{2010}$/GJ	10.6	10.5	10.6	10.8	10.8	10.8	10.9	11.0
Primary forestry residues (chips, fuel) SEU	€$_{2010}$/GJ	10.4	10.3	10.5	10.7	10.7	10.8	10.9	11.0
Primary forestry residues (chips, fuel) WEU	€$_{2010}$/GJ	7.7	7.6	7.8	7.9	8.0	8.0	8.1	8.2
Propylene	€$_{2010}$/t	684.7	564.7	681.1	797.6	795.8	841.4	886.9	932.4
Secondary forestry residues NL	€$_{2010}$/GJ	3.3	3.3	3.3	3.3	3.3	3.3	3.4	3.4
Secondary forestry residues EEU	€$_{2010}$/GJ	8.4	8.4	8.7	8.9	9.1	9.3	9.5	9.7
Secondary forestry residues NEU	€$_{2010}$/GJ	9.3	9.3	9.5	9.6	9.7	9.8	9.9	10.0
Secondary forestry residues SEU	€$_{2010}$/GJ	9.9	9.8	10.0	10.2	10.2	10.4	10.5	10.6
Secondary forestry residues WEU	€$_{2010}$/GJ	7.2	7.2	7.3	7.5	7.5	7.6	7.7	7.8
Solid manure for waste incinerator NL	€$_{2010}$/GJ	3.8	3.8	3.8	3.8	3.9	3.9	3.9	3.9
Starch crops NL	€$_{2010}$/t	164.0	173.2	213.0	247.6	272.1	301.1	330.2	359.2
Starch crops EEU	€$_{2010}$/t	346.3	321.1	349.2	356.7	358.1	364.0	369.9	375.8
Starch crops NEU	€$_{2010}$/t	322.7	291.5	319.8	326.3	324.9	328.8	332.7	336.6
Starch crops SEU	€$_{2010}$/t	348.6	320.3	346.8	353.5	352.6	356.7	360.9	365.0
Starch crops WEU	€$_{2010}$/t	319.1	290.9	317.0	323.9	322.8	326.8	330.8	334.9
Sugar imports GL	€$_{2010}$/t	273.1	243.8	269.0	275.4	273.3	276.6	279.8	283.0
Sugar from sugar beets NL	€$_{2010}$/t	277.8	278.1	291.5	300.6	307.4	315.6	323.8	332.0
Sugar from sugar beets EEU	€$_{2010}$/t	324.1	297.0	315.3	315.9	311.5	310.8	310.2	309.5
Sugar from sugar beets NEU	€$_{2010}$/t	317.7	290.8	310.0	313.3	309.5	310.1	310.7	311.3
Sugar from sugar beets SEU	€$_{2010}$/t	346.1	315.7	344.3	351.6	350.7	355.2	359.7	364.2
Sugar from sugar beets WEU	€$_{2010}$/t	291.7	260.8	286.0	292.0	289.2	291.8	294.5	297.1
Used cooking oil NL	€$_{2010}$/GJ	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
Used cooking oil EEU	€$_{2010}$/GJ	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Used cooking oil NEU	€$_{2010}$/GJ	8.4	8.4	8.4	8.4	8.4	8.3	8.3	8.3

Used cooking oil SEU	€$_{2010}$/GJ	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Used cooking oil WEU	€$_{2010}$/GJ	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Vegetable oil global	€$_{2010}$/GJ	16.1	16.5	16.3	16.6	16.7	16.8	16.9	17.1
Vegetable oil from oil crops NL	€$_{2010}$/GJ	17.1	18.2	25.3	27.0	31.1	34.8	38.5	42.1
Vegetable oil from oil crops EEU	€$_{2010}$/GJ	15.9	16.7	21.2	24.8	27.5	30.6	33.7	36.8
Vegetable oil from oil crops NEU	€$_{2010}$/GJ	16.7	17.1	22.3	26.0	28.8	32.1	35.5	38.8
Vegetable oil from oil crops SEU	€$_{2010}$/GJ	14.4	14.7	18.3	21.1	23.1	25.5	27.8	30.2
Vegetable oil from oil crops WEU	€$_{2010}$/GJ	17.2	18.1	18.1	18.1	18.6	18.9	19.2	19.5
Wood and paper waste for incineration NL	€$_{2010}$/GJ	4.3	4.3	4.4	4.4	4.4	4.5	4.5	4.6
Wood and paper waste for incineration EEU	€$_{2010}$/GJ	8.9	8.8	9.1	9.4	9.5	9.7	9.9	10.1
Wood and paper waste for incineration NEU	€$_{2010}$/GJ	2.8	2.9	2.9	3.0	3.0	3.1	3.2	3.2
Wood and paper waste for incineration SEU	€$_{2010}$/GJ	8.1	8.1	8.3	8.5	8.5	8.7	8.8	8.9
Wood and paper waste for incineration WEU	€$_{2010}$/GJ	5.4	5.3	5.4	5.5	5.6	5.7	5.7	5.8
Wood pellets	€$_{2010}$/GJ	7.4	7.4	7.5	7.6	7.7	7.8	7.9	8.0

APPENDIX IV

Below, in Table 27, all technologies in the electricity sector as were previously present in MARKAL-NL-UU can be found.

Table 27 - All technologies in the electricity sector MARKAL-NL-UU

Technology	Available from	Input	Output	Capacity unit	AF/CF	INV	FOM	VOM	Lifetime
CHP	2010	Biogas	Electricity	GW	1	3108	252.0	0	12
CHP	1990	Natural gas	Electricity, steam	GW	-	935	45.9	0	30
CHP	2005	Natural gas	Electricity, steam	GW	-	880	45.0	0	30
CHP	2020	Natural gas	Electricity, steam	GW	-	854	44.6	0	30
CHP	2030	Natural gas	Electricity, steam	GW	-	828	44.1	0	30
CHP	2040	Natural gas	Electricity, steam	GW	-	803	43.7	0	30
CHP (small)	2010	Biogas	Electricity, steam	GW	-	4560	315.0	0	30
CHP w/ CCS	2020	Natural gas	Electricity, steam	GW	-	1413	60.0	0	30
GE	1990	Natural gas	Electricity, heat	GW	-	633	32.4	0.3	15
GE	2000	Land fill gas	Electricity, heat	GW	1	1507	36.3	0.3	15
GE	2000	Natural gas	Electricity, heat	GW	-	589	28.0	0.1	15
Geothermal	1990	Geothermal heat	Electricity	GW	1	1540	32.1	0	30
GT	1990	Natural gas	Electricity, steam	GW	-	958	13.9	1.1	30
GT	1990	Land fill gas	Electricity, steam	GW	1	1953	16.6	0.8	30
GT	1990	Natural gas	Electricity, heat	GW	1	744	11.0	0.5	30
GT	2005	Natural gas	Electricity, steam	GW	-	1439	13.9	2.4	30
GT	2005	Natural gas	Electricity, steam	GW	-	961	37.5	0	30
GT	2020	Natural gas	Electricity, steam	GW	-	903	37.1	0	30
GT	2030	Natural gas	Electricity, steam	GW	-	849	36.8	0	30
GT	2040	Natural gas	Electricity, steam	GW	-	781	36.4	0	30
GT peaking plant	1990	Natural gas	Electricity	GW	0	372	9.1	0.2	30
Hydro	1990	Water	Electricity	GW	-	3588	46.9	0	50
IGCC	2000	Coal	Electricity, heat	GW	1	2009	51.0	0.8	40
IGCC	2010	Coal	Electricity, heat	GW	1	2034	40.0	0.8	40
IGCC	2020	Coal	Electricity, heat	GW	1	1962	38.9	0.8	40
IGCC	2030	Coal	Electricity, heat	GW	1	1892	37.8	0.8	40
IGCC	2040	Coal	Electricity, heat	GW	1	1824	36.7	0.8	40
IGCC capture read retrofit	2010	Coal	Electricity	GW	1	676	33.5	0.2	30
IGCC capture read retrofit	2020	Coal	Electricity	GW	1	676	15.4	0.1	30
IGCC w/ CCS	2010	Coal	Electricity, heat	GW	1	2938	57.0	1.3	40
IGCC w/ CCS	2020	Coal	Electricity, heat	GW	1	2723	53.8	1.2	40

IGCC w/ CCS	2030	Coal	Electricity, heat	GW	1	2524	50.8	1.1	40
IGCC w/ CCS	2040	Coal	Electricity, heat	GW	1	2339	47.9	1.1	40
Manure co-digestion to biogas	2010	Energy maize, manure	Electricity, heat, biogas	PJ/yr	1	18	1.4	0	12
Manure co-digestion to green gas	2015	Biogas	Electricity, green gas	PJ/yr	1	17	1.8	0	12
NGCC	1990	Natural gas	Electricity, heat	GW	1	728	22.2	0.3	30
NGCC	2000	Natural gas	Electricity, heat	GW	1	728	22.2	0.3	30
NGCC	2010	Natural gas	Electricity, heat	GW	1	728	14.6	0.3	30
NGCC	2020	Natural gas	Electricity, heat	GW	1	716	14.6	0.3	30
NGCC	2030	Natural gas	Electricity, heat	GW	1	704	14.6	0.3	30
NGCC	2040	Natural gas	Electricity, heat	GW	1	691	14.6	0.3	30
NGCC capture read retrofit	2020	Natural gas	Electricity	GW	1	545	3.0	0.1	25
NGCC w/ CCS	2010	Natural gas	Electricity, heat	GW	1	1352	21.6	0.6	30
NGCC w/ CCS	2020	Natural gas	Electricity, heat	GW	1	1253	20.3	0.5	30
NGCC w/ CCS	2030	Natural gas	Electricity, heat	GW	1	1161	19.1	0.5	30
NGCC w/ CCS	2040	Natural gas	Electricity, heat	GW	1	1076	18.0	0.5	30
Nuclear	1990	Uranium oxide	Electricity	GW	1	3660	72.8	0	50
PC	2010	Coal	Electricity, heat	GW	1	1695	24.6	0.8	40
PC	2020	Coal	Electricity, heat	GW	1	1608	24.6	0.8	40
PC	2030	Coal	Electricity, heat	GW	1	1526	24.6	0.8	40
PC	2040	Coal	Electricity, heat	GW	1	1468	24.6	0.8	40
PC capture read retrofit	2010	Coal	Electricity	GW	1	813	2.3	0.3	30
PC capture read retrofit	2020	Coal	Electricity	GW	1	678	1.0	0.3	30
PC capture read retrofit	2010	Coal	Electricity	GW	1	788	2.1	0.3	30
PC capture read retrofit	2020	Coal	Electricity	GW	1	648	2.9	0.4	30
PC subcritical	1990	Coal	Electricity, heat	GW	1	1695	46.6	0.3	40
PC supercritical	1990	Coal	Electricity, heat	GW	1	1695	46.6	0.3	40
PC w/ CCS	2010	Coal	Electricity	GW	1	2825	35.9	1.6	40
PC w/ CCS	2020	Coal	Electricity	GW	1	2560	33.2	1.4	40
PC w/ CCS	2030	Coal	Electricity	GW	1	2320	30.7	1.3	40
PC w/ CCS	2040	Coal	Electricity	GW	1	2102	28.5	1.2	40
Sewage water treatment to biogas	2010	Common sludges	Electricity, biogas	PJ/yr	1	3	0.3	0	12
Solar PV	2000	Solar irradiation	Electricity	GW	-	1063	26.6	0	25
Solar PV	2020	Solar irradiation	Electricity	GW	-	672	16.8	0	25
Solar PV	2030	Solar irradiation	Electricity	GW	-	401	10.0	0	25
Solar PV	2040	Solar irradiation	Electricity	GW	-	326	8.2	0	25
ST	1990	Natural gas	Electricity, steam	GW	-	461	18.8	0	30
ST (industry)	1990	Steam	Electricity	GW	1	1983	92.5	0	40

Waste	1990	Waste	Electricity, steam	GW	-	6443	82.7	0	30
Wet organic waste to biogas	2010	Wet organic waste	Electricity, biogas	PJ/yr	1	15	1.1	0	12
Wet organic waste to green gas	2015	Biogas	Electricity, green gas	PJ/yr	1	13	1.5	0	12
Wind offshore	2010	Wind	Electricity	GW	-	3265	65.3	0	25
Wind offshore	2020	Wind	Electricity	GW	-	2229	44.6	0	25
Wind offshore	2030	Wind	Electricity	GW	-	1446	28.9	0	25
Wind offshore	2040	Wind	Electricity	GW	-	1259	25.2	0	25
Wind onshore	1990	Wind	Electricity	GW	-	1017	30.5	0	25

APPENDIX V

For the insulation technologies, the same method is applied as used by Quintel Intelligence (2018). For this, a division has to be made for houses that were built before 1992, houses that were built in 1992 or later and buildings in the services sector. Using this method will require using averages on natural gas use in these types of buildings. From OTB Delft (2013), the values found in the first row of Table 28 for natural gas use per energy label can be extracted. Using the fact that 80 % of natural gas use in a household is used for room heating ECN, Energie-Nederland, & Netbeheer Nederland (2016), this yields the values in the second row of Table 28.

Table 28 - Natural gas use per label

	A - A++	*B*	*C*	*D*	*E*	*F*	*G*
Natural gas (m^3)	1100	1150	1300	1500	1650	1750	1950
Natural gas for room heating (m^3)	880	920	1040	1200	1320	1400	1560

From Agentschap NL (2011) a general trend within houses can be obtained. Regardless of the type of house, houses built before 1992 generally have an energy label that ranges between G and C. Houses built in and after 1992 generally have label B. Therefore, it is assumed that houses built before 1992 have an average natural gas use for room heating of 1304 m^3. Houses built in and after 1992 have an average natural gas use of 920 m^3.

For buildings, this value is more difficult to determine. For this, the value of the amount of natural gas use from the NEV 2017 is used, which is 126.5 PJ (ECN, 2017). Using data from CBS, it is found that there are 1,369,765 buildings in the services sector (CBS, 2018e). On average, 96 % of the natural gas use of buildings is used for room heating, and the lower heating value of natural gas is 31.65 MJ/m^3. This leads to:

$$\left(\frac{126.5 * 10^9 MJ}{1{,}369{,}765\ buildings}\right)/31.65\ m^3\ * 0.96 = 2801\ m^3/building$$

Research from Quintel Intelligence (2018) suggests average R_c values for residences built before 1992, in and after 1992 and buildings of 0.5, 1.8 and 0.6 m^2K/W respectively. Three modes of insulation with ranging R_c values are considered, ranging from cheap to expensive insulation. The upper values that are used are the same as used by Quintel Intelligence (2018). Using their formula for costs[i] of insulation that has been constructed using Arcadis (2016), the cost data for these insulation modes are calculated, as can be seen in Table 29.

Table 29 – R_c values considered and associated costs

	R_c (m^2K/W)			**Costs (€)**		
	Cheap	*Moderate*	*Expensive*	*Cheap*	*Moderate*	*Expensive*
Residences <1992	1	2	3	€ 2,742.83	€ 8,705.52	€ 14,668.20
Residences >=1992	-	2	3	-	€ 8,705.52	€ 14,668.20
Buildings	1	2	2.7	€ 2,742.83	€ 8,705.52	€ 12,879.40

R_c values and energy use are inversely proportional. This means that a doubling in R_c leads, theoretically, to a halving in energy use. Using this information, the amount of natural gas used after insulation can be calculated. From this, the amount of natural gas saved can be calculated, and therefore investment costs for insulation can be deduced, as can be seen in Table 30 below.

Table 30 - Amount of natural gas saved and investment costs for insulation

		Residences <1992	**Residences >=1992**	**Buildings**
Average use (m^3)		1304	920	2801
New use (m^3/a)	Cheap	652	-	1681
	Moderate	326	828	840
	Expensive	217	552	623

Saved (m^3/a)	Cheap	652	-	1121
	Moderate	978	92	1961
	Expensive	1087	368	2179
INV (€/MJ/a)	Cheap	133	-	77
	Moderate	281	2990	140
	Expensive	426	1259	187

Since insulation is only applicable to the amount of natural gas used for room heating, the maximum amount of natural gas saved due to installing this technology has to be calculated as well. For this, the data on the demand for built environment rest heat as given in Table 7 is used. This is a value that is defined for all buildings alike, which is why a division has to be constructed. In the NEV 2017, an average of 69.3 % of energy demanded for heat is for residences, the remaining 30.7 % for buildings. This means that on average, 30.7 % or 122.25 PJ of the heat demand defined in MARKAL-NL-UU is used for buildings.

For residences, the remaining 69.3 % has to be divided amongst the older and newer residences. This can be done using data from CBS on the number of residences in the Netherlands (CBS, 2018f). This data aggregates residences built in periods of 10 years, so assuming linear growth of the number of houses in the period 1985 to 1995, the number of houses built before 1992 is 5,668,967, and the amount of houses built in and after 1992 equals 2,071,755. These residences use $5{,}668{,}967 * 1304m^3 = 7392\ Mm^3$ and $2{,}071{,}755 * 920\mathrm{m}^3 = 1906\ Mm^3$. This means that on average, residences that are built before 1992 use $\frac{7392}{7392+1906} = 0.795$ or 79.5 % of the total amount of natural gas used for heat. The remaining 69.3 % of natural gas used in MARKAL-NL-UU is therefore used for 79.5 % or 182.98 PJ by residences built before 1992 and 20.5 % or 47.18 PJ by residences built in and after 1992.

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[i] This formula is $Costs\ (\text{€}) = 5962.68336734 * (R_c - 0.54)$