PBL Netherlands Environmental Assessment Agency

EXPLORATION OF PATHWAYS TOWARDS CLIMATE NEUTRALITY 2050

Pathways towards a climate-neutral society for the Netherlands in 2050

Summary and Findings
July 2024

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Colophon

Exploration of pathways towards climate neutrality 2050. Pathways towards a climate-neutral society for the Netherlands in 2050.

English translation of the Summary and Findings of the full Dutch report (*Trajectverkenning Klimaatneutraal 2050. Trajecten naar een klimaatneutrale samenleving voor Nederland in 2050*)

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PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all of our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

Contents

Foreword

Our climate is changing rapidly and drastically due to greenhouse gas emissions. This is becoming increasingly visible and tangible in the Netherlands and elsewhere. Climate change has far-reaching consequences for humanity and nature. It is therefore of great importance to limit it as much as possible, and reducing greenhouse gas emissions to zero as soon as possible is a global task.

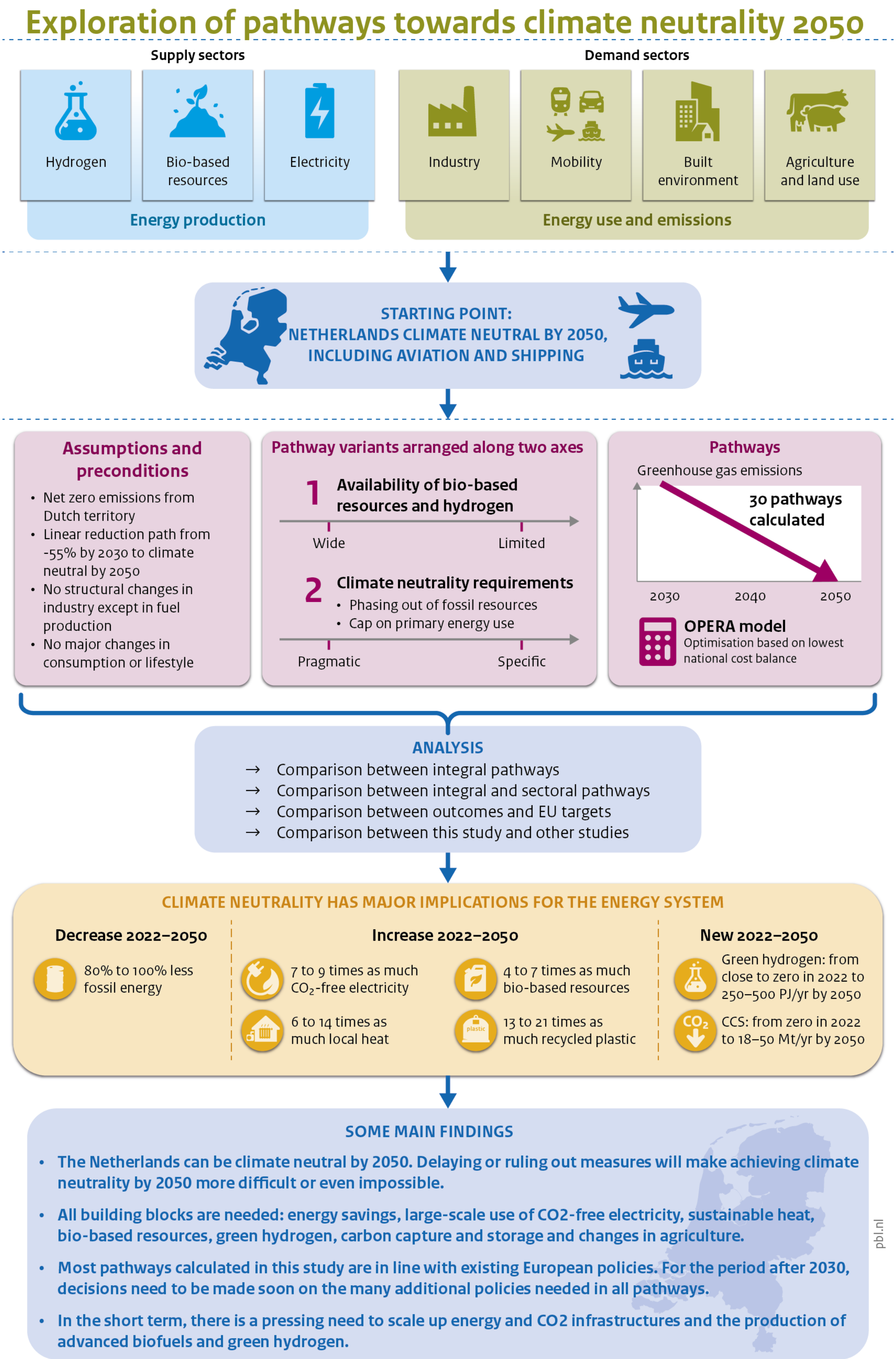
In the European Union and the Netherlands, this task has been translated into the legally defined goal of achieving climate neutrality by 2050. This is not a finishing point, but it is a clear target. In concrete terms, it means that we only have 26 years to fundamentally transform our energy and resource system. This goal represents a societal transformation of unprecedented magnitude, as is also shown in this study, in which we explore potential technical pathways towards climate neutrality.

Effective policy development calls for a clear picture of the technical possibilities and limitations of the specific situation of the Netherlands. That is the purpose of this study, for which we mapped bottlenecks and the pathways towards achieving this goal. This report takes an overall look at all sectors of the Dutch economy, including aviation and shipping, considering both energy and natural resources and also taking the international context and European policies into account.

Achieving a societal transformation, such as the process towards climate neutrality, requires vision and perseverance as well as long-term, consistent and well thought-through policies. It is the role of government not only to set the direction, but also to trust businesses and citizens and provide them with enough space to change and innovate.

Based on this exploration of pathways and other inputs, in the coming years, we will continue to do research to contribute to the knowledge needed for effective policies to realise the transformation towards climate neutrality. Our research will not only focus on the technical and economic aspects of the transformation, as in this study, but will also highlight its institutional and social aspects.

Marko Hekkert
Director-General


Exploration of pathways towards climate neutrality 2050
Supply sectors
Hydrogen
Bio-based resources
Electricity
Energy production
Demand sectors
Industry
Mobility
Built environment
Agriculture and land use
Energy use and emissions
STARTING POINT:
NETHERLANDS CLIMATE NEUTRAL BY 2050,
INCLUDING AVIATION AND SHIPPING
Assumptions and preconditions
• Net zero emissions from Dutch territory
• Linear reduction path from -55% by 2030 to climate neutral by 2050
• No structural changes in industry except in fuel production
• No major changes in consumption or lifestyle
Pathway variants arranged along two axes
1 Availability of bio-based resources and hydrogen
Wide
Limited
2 Climate neutrality requirements
• Phasing out of fossil resources
• Cap on primary energy use
Pragmatic
Specific
Pathways
Greenhouse gas emissions
30 pathways calculated
2030
2040
2050
OPERA model
Optimisation based on lowest national cost balance
ANALYSIS
→ Comparison between integral pathways
→ Comparison between integral and sectoral pathways
→ Comparison between outcomes and EU targets
→ Comparison between this study and other studies
CLIMATE NEUTRALITY HAS MAJOR IMPLICATIONS FOR THE ENERGY SYSTEM
Decrease 2022–2050
80% to 100% less fossil energy
Increase 2022–2050
7 to 9 times as much CO2-free electricity
4 to 7 times as much bio-based resources
6 to 14 times as much local heat
13 to 21 times as much recycled plastic
New 2022–2050
Green hydrogen: from close to zero in 2022 to 250–500 PJ/yr by 2050
CCS: from zero in 2022 to 18–50 Mt/yr by 2050
SOME MAIN FINDINGS
• The Netherlands can be climate neutral by 2050. Delaying or ruling out measures will make achieving climate neutrality by 2050 more difficult or even impossible.
• All building blocks are needed: energy savings, large-scale use of CO2-free electricity, sustainable heat, bio-based resources, green hydrogen, carbon capture and storage and changes in agriculture.
• Most pathways calculated in this study are in line with existing European policies. For the period after 2030, decisions need to be made soon on the many additional policies needed in all pathways.
• In the short term, there is a pressing need to scale up energy and CO2 infrastructures and the production of advanced biofuels and green hydrogen.
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Source: PBL

Summary

It is technically feasible: The Netherlands climate neutral by 2050. But this requires giving it our all

To be climate neutral by 2050, substantial changes are needed in the supply of electricity and heat as well as in the production and use of fuels and natural resources (see Figure S.1). In specific terms, this means saving more energy and producing more electricity from CO_2-free sources such as solar, wind and nuclear power. This electricity must be used instead of fossil fuels. Local heat sources should also be drawn on more often. Another requirement is efficient and large-scale use of sustainable bio-based resources and green hydrogen. The capacity of CO_2 capture and storage (CCS) facilities needs to be increased and put to use, and in addition, agriculture and rural areas have to implement changes. These are not questions of either/or, but of both/and. Ruling out or drastically limiting any of these emission reduction options beforehand makes achieving climate neutrality by 2050 more expensive or even impossible.

This is shown in the present PBL analysis into the various pathways that lead to a climate-neutral Netherlands in 2050. We dedicate particular attention to the period after 2030. We take *climate neutrality* to mean net zero greenhouse gas emissions from Dutch territory. In the calculations we also include the bunker fuels supplied in the Netherlands to international aviation and shipping. Residual greenhouse gas emissions in 2050 will be offset by negative emissions within our borders.

The starting point of this analysis was to design pathways towards climate neutrality for the 2030–2050 period at the lowest national cost — the balance of direct financial costs and benefits from a national perspective. For the purposes of this study, we factor in moderate economic growth and assume the economic structure will not change substantially over time. We do, however, include changes that result directly from a transition to a climate-neutral society, such as developments in fuel production.

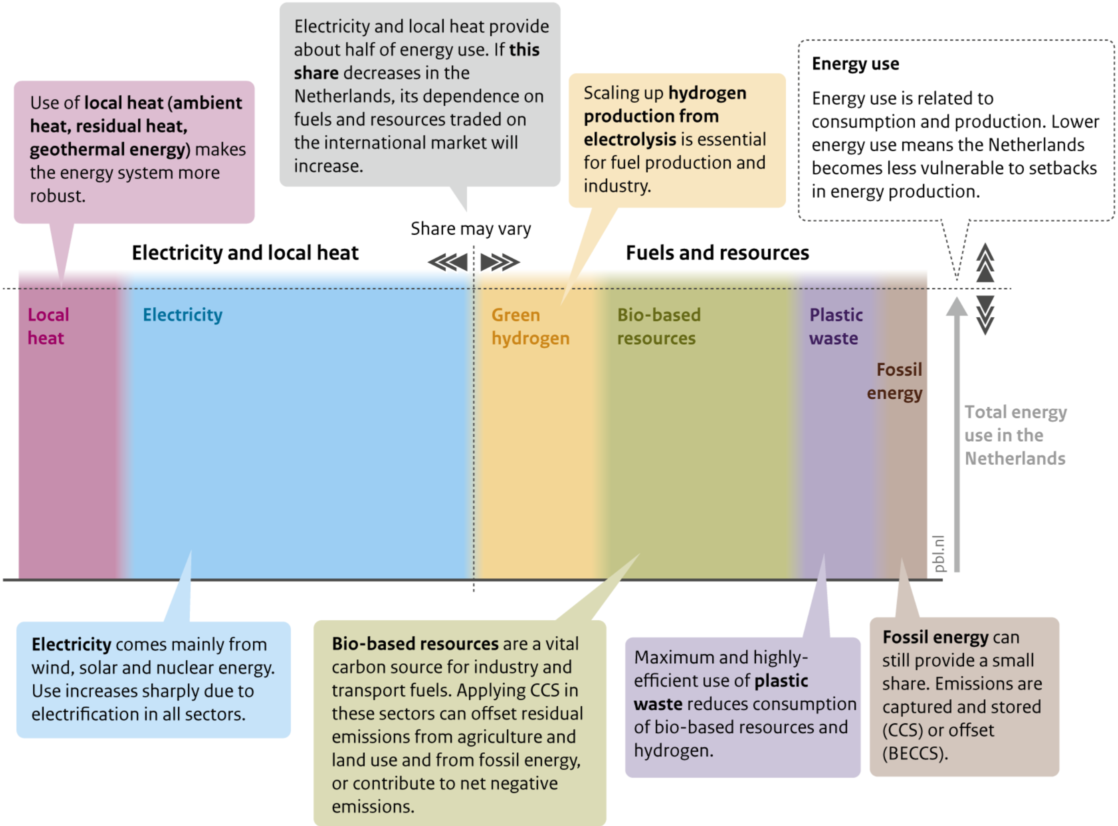
Besides reductions in greenhouse gases, there are other aspects that also play an important role in a transition to climate neutrality. These include the use of scarce space, the availability and use of critical resources, the availability of labour, the distribution of benefits and burdens and the behaviour of consumers, businesses and government authorities. This study does not cover these aspects in detail, but it can provide a starting point for follow-up studies addressing them.

Replacing fossil energy requires an expansion of the production of CO_2-free electricity, CO_2-free heat, bio-based resources and green hydrogen. Their production and use accelerate after 2030

In 2050, electricity production will be around three to five times that of 2022. The production of CO_2-free electricity will increase by a factor of seven to nine (see Figure S.2). In 2022, around 7% of the energy used came directly or indirectly from electricity from wind, solar and nuclear power. Our analysis shows that this is expected to be around 14% in 2030 and between 50% and 60% by 2050.

Figure S.1

Indicative composition of energy use in a climate-neutral energy system

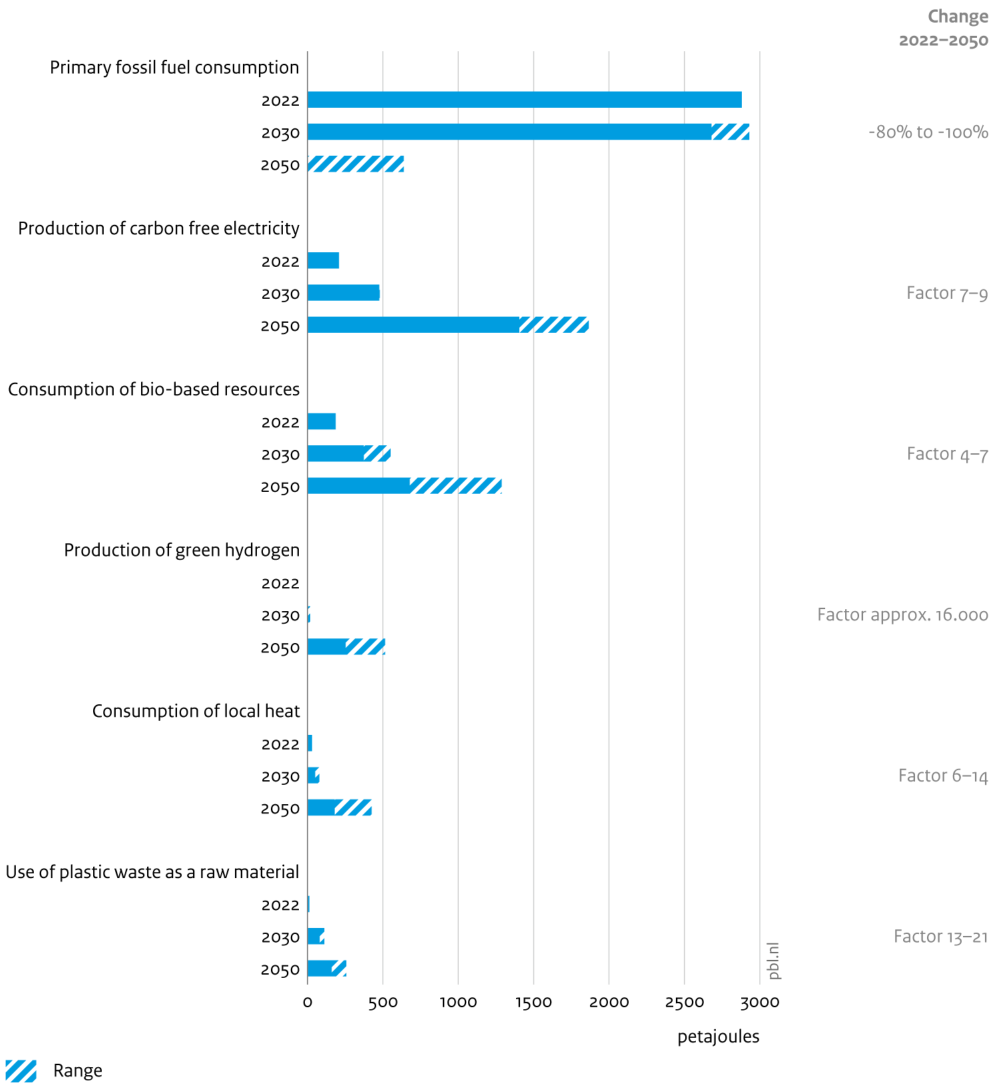


Source: PBL

By electrifying more, we make the Dutch energy system less dependent on international energy markets and fossil energy, but it does raise considerable challenges: both the production of renewable electricity and the capacity of electricity grids need to be developed further.

Other solutions are needed for the share of energy use that is not replaced by electricity. This concerns the transport fuels that remain in use after electrification, particularly those for shipping and aviation, and the raw materials for chemicals and plastics (feedstocks). For these uses, fossil resources can be replaced by bio-based resources, waste and hydrogen from electrolysis (green hydrogen). The remaining CO_2 emissions from fossil energy are captured and stored or offset through negative emissions.
This requires a substantial increase, on an international scale, in both the supply of bio-based resources and green hydrogen, and the capacity of CO_2 storage. At the same time, it is already clear that their availability will be limited. More efficient energy use restricts the need to turn to CCS and energy carriers that are in short supply, and is therefore also of great importance. If the supply of bio-based resources, green hydrogen and CO_2 storage capacity is not expanded in time, achieving climate neutrality will become substantially more costly because of the scarcity that will occur. It may even become impossible under the assumed economic growth and economic structure. In that case, achieving climate neutrality may mean that it will be necessary to adjust levels of consumption, for example by adopting a different lifestyle that uses substantially less energy and resources and releases fewer emissions.

Figure S.2
Outcomes of pathways towards climate neutrality



Source: PBL

Until 2030, the phasing out of fossil energy is still limited. For 2030, we assume achievement of the national target of a 55% reduction in greenhouse gas emissions, compared to 1990 levels. This means that a radical change will need to take place in the limited period of 20 years after 2030 (see also Figure S.2).

Impact of insufficient availability and high cost of bio-based resources and green hydrogen can be softened by reducing demand for fuel and increasing CO_2 storage capacity

In the pathways calculated by PBL, in 2050 the need for bio-based resources will be four to seven times greater than in 2022. As for green hydrogen, the calculations point to a production capacity by 2050 of 250 to 500 petajoules, as compared to today's close-to-zero capacity. The required amount of hydrogen is as large as what can be produced by *all* the green hydrogen projects scheduled up to 2040 in the Netherlands. The vast majority of these is still in the concept or feasibility phase and therefore uncertain.

With limited hydrogen production in the Netherlands, imports will also play a role. In all pathways, substantial imports of bio-based resources are necessary, particularly for advanced biofuel production. High priority needs to be given to scaling up, in the short term and to European levels at least, the production and logistics of green hydrogen and bio-based resources from waste streams, agriculture and forestry. The same applies to maximum and high-quality reuse of plastic waste to produce new plastic.

It is therefore doubtful whether sufficient bio-based resources and green hydrogen will be available in time. Given that these energy carriers are traded on European and global markets, the Netherlands has only limited influence on increasing the availability of bio-based resources and hydrogen production and import. This means a coordinated EU policy is required.

The limited and insecure availability poses a risk for the feasibility of climate neutrality by 2050. The Netherlands can lessen this risk by reducing national demand for fuel and increasing its CO_2 storage. A reduction in demand for fuel may come about through electrification, energy saving and use of local heat sources, such as geothermal, residual and environmental heat. This is relevant for a sector such as the built environment, where at first glance the large-scale use of sustainable gases such as green gas and hydrogen seems to be the easiest option because it requires minimal modifications compared to today's use of natural gas. However, given that the integral pathways foresee issues of scarcity and high costs around these sustainable gases, alternatives such as electrification and district heating still prove to be more attractive.

The Netherlands may be climate neutral by 2050, but that does not necessarily mean it will also be fossil-free

In most of the calculated pathways in this study, the Netherlands will still be using a small amount of fossil energy in 2050. Completely phasing out fossil energy is only possible if more bio-based resources and hydrogen are available in time. If phasing out is socially desirable, it will require specific policies. The CO_2 emissions which in 2050 are still linked to the use of fossil energy must then be captured and stored — under the seabed, for instance. Or we need to compensate for these emissions by capturing and storing biogenic CO_2 rather than the fossil emissions. In this study biogenic CO_2 is mainly released during biofuel production. In this process, CO_2 extracted from the air by plants or trees is permanently stored (negative emissions).

Among the various pathways we explore in this study, the capacity for CO_2 storage in 2050 varies between 20 and 50 million tonnes per year, with most of the stored CO_2 coming from biogenic sources. These negative emissions are also needed to offset any remaining emissions not stemming from energy use. The pathways put these residual emissions in 2050 at between 12 and 17 megatonnes of CO_2 equivalents. Comprising mainly methane and nitrous oxide, the vast majority of residual emissions comes from the agriculture and land use sector — the only sector where it is technically almost impossible to reduce greenhouse gas emissions to net zero (unless the livestock population were to decrease to less than a quarter of its current size in combination with large-scale afforestation). The CO_2 storage capacity is finite and net negative emissions will also be required after 2050. This means that there will still be a need to further reduce non-energy related emissions and phase out the remaining use of fossil energy at that point.

To achieve negative emissions, CO_2 capture and storage during the production of advanced biofuels may gain importance

Advanced biofuels can replace fossil fuels in aviation and shipping. Production of these biofuels needs to get underway before 2030, also with the aim of achieving climate neutrality by 2050.

Biofuel production plants release relatively pure biogenic CO_2. As these plants operate non-stop, CO_2 capture is expected to be cheaper there than at some other emission sources, such as electricity production. Especially after 2040, in electricity production the use of fuels such as natural gas and biofuel is limited to peak-load plants which operate few hours at full load. Due to the relatively low concentration of CO_2 in the combustion gases and the low number of full-load hours, CO_2 capture is much more expensive there. This is why the pathways towards climate neutrality in 2050 do not consider CO_2 capture in electricity production. And in any event, the volume of captured CO_2 would be relatively low because the limited amounts of fuel used in power plants are becoming smaller and smaller due to the growth of wind and solar power in particular.

Even in the case of advanced biofuel production lagging behind, CO_2 capture and storage is more attractive in industry than in power generation, in terms of cost and long-term perspective.

The pathways in this study are based on overarching greenhouse gas emission targets rather than existing policies. Still, most pathways are in line with EU policies

With regard to the main issues, there do not appear to be any major contradictions between the outcomes of this study and the paths towards solutions that EU policy is taking for the period up to 2030 or 2035. This applies especially to pathways with lower CO_2 storage caps, which rely less heavily on negative emissions to offset residual emissions. This is in line with many EU policies that aim to reduce emissions as much as possible within the individual sectors. In addition, many pathways calculated in this study aim for use of relatively expensive technologies (green hydrogen, synthetic fuels) in the early stages, which is also in line with EU scale-up policies that focus heavily on this approach. The calculations also conform to the EU ETS1 Emissions Trading System, provided that it is possible to offset residual emissions against negative emissions within the system.

This study does not explicitly examine the degree to which current policies and other measures still under development contribute to achieving the goals, but it is clear that additional policies are needed in the short term to get on track and maintain a steady course towards climate neutrality in 2050. This study takes a first important step to further analyse this situation and give shape to these policies.

Findings

F.1 Introduction

Towards a climate-neutral Netherlands; that is: net zero greenhouse gas emissions by 2050

In this study — Exploration of Pathways towards Climate Neutrality 2050 — we examine which paths the Netherlands might take to become climate neutral by 2050. By *climate neutral* we mean: the situation where the various economic sectors in the Netherlands emit net zero greenhouse gases, including emissions from fuels for international aviation and shipping that are produced and delivered in the Netherlands.

Bringing greenhouse gas emissions down to zero is a huge task. The Netherlands has set itself an intermediate target for 2030 of a 55% emission reduction compared to 1990 levels. The starting point for this study is a linear reduction path from that 55% in 2030 to climate neutrality by 2050. This is in line with the targets set in the Dutch Climate Act and the policies adopted by the Rutte IV government. This reduction path implies that the emission reduction by 2040 should be around 80%, but definitive targets for 2040 have not been set yet. Recently, the European Commission presented a proposal for an EU emission reduction target of 90% by 2040 (EC, 2024b, 2024a). This could also be a fair and achievable target for the Netherlands (PBL, 2024f). An intermediate target for 2040, which might be more stringent, is still to be decided on in the European Union and the Netherlands in the coming years and, therefore, has not been taken into account in this study.

Climate neutrality cannot be achieved with greenhouse gas reductions alone. For some sectors, agriculture and land use in particular, it is not possible to produce no emissions at all by 2050. This means that these inevitable remaining emissions in 2050 in the Netherlands need to be compensated with the arrangement known as *negative emissions*. This is also in line with the Dutch Climate Act, which stipulates that the Netherlands shall 'reduce net greenhouse gas emissions to zero by 2050 and aim for negative greenhouse gas emissions after 2050' (Staatsblad, 2023).

Emissions from international aviation and shipping are currently not covered by the 2030 and 2050 targets of the Dutch Climate Act. In this study, we choose to explicitly include these sectors as they are also required to become climate neutral under the Paris Agreement. To do this, we adhere to the global targets of the International Civil Aviation Organisation (ICAO) and the International Maritime Organisation (IMO), which both aim for zero emissions around 2050 (ICAO, 2022; IMO, 2023).

Working under moderate economic and demographic assumptions, more than 30 integral pathways are calculated and compared with each other

In this study, we explore more than 30 pathways leading to a climate-neutral Netherlands in 2050. The exercise involves a detailed examination of three economic sectors on the supply side — hydrogen, bio-based resources, and electricity — and four on the demand side — industry, mobility, the built environment, and agriculture and land use.

We base our work on the relatively moderate demographic and economic assumptions that were made in the Climate and Energy Outlook 2022 (KEV 2022) and extrapolated to 2050. The economic structure does not change substantially, except for changes resulting directly from the transition to climate neutrality, such as decreases in refining and in overseas fossil fuel transport. The study shows whether and how the Netherlands can become climate neutral with a more or less unchanged economic structure and moderate economic growth. The study also shows where the greatest technical challenges lie.

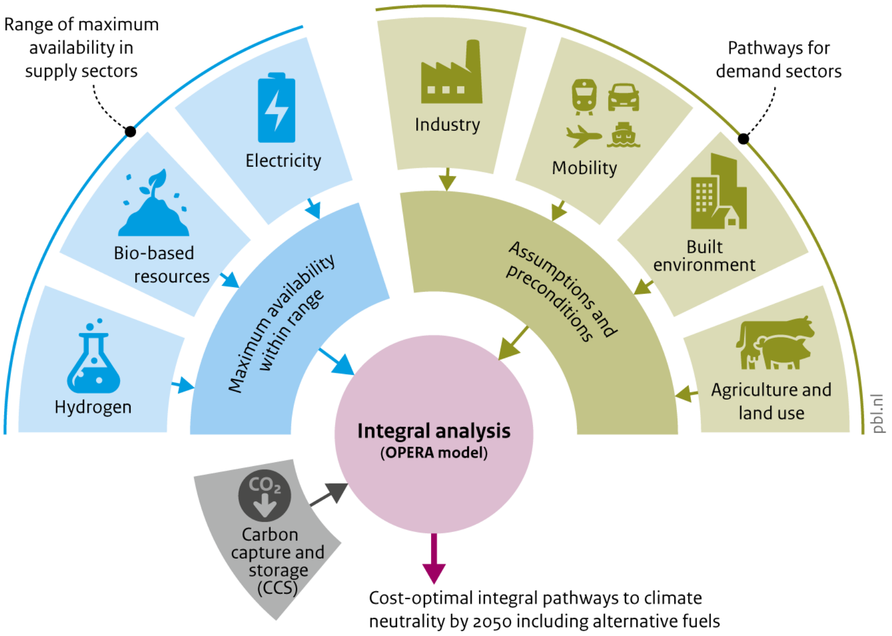
Changes may be necessary in economic structure, and in production and consumption

In reality, the economic structure and economic growth will of course develop differently from the assumptions we make in this study, but how they change and how much they change is highly unpredictable. We made a deliberate choice not to introduce variations in this regard. As a result it is possible to compare the more than 30 calculated pathways with each other and with the findings of the Climate and Energy Outlook. To be clear, we are *not* claiming that becoming climate neutral in 2050 would not entail changes in the economic structure and in production and consumption. The chosen approach serves to clarify the circumstances under which such changes will really be necessary for a climate-neutral Netherlands in 2050. The *Reflexive Evaluation of Dutch Climate Policy* (PBL & VU, 2024), for instance, takes a closer look at the question of how climate policy can win over society and thereby ensure that the necessary techno-economic measures are more than just potentially *achievable*, and can actually be *put into practice*.

To determine the pathways along which the Netherlands can become climate neutral, we conducted detailed analyses of the supply and demand sectors (see Figure F.1). Thereupon we used the OPERA model to produce an integral analysis. The first step involved making an inventory of the maximum availabilities of hydrogen, bio-based resources and electricity from the supply sectors. It is based on, among other things, a roll-out rate of the required extraction and conversion technologies that is found to be feasible. In addition, for each of the four demand sectors, we identified two to four possible pathways to becoming climate neutral. With the exception of agriculture, these demand sectors achieve net zero emissions in 2050.

Figure F.1

Method for determining integral pathways to climate neutrality by 2050



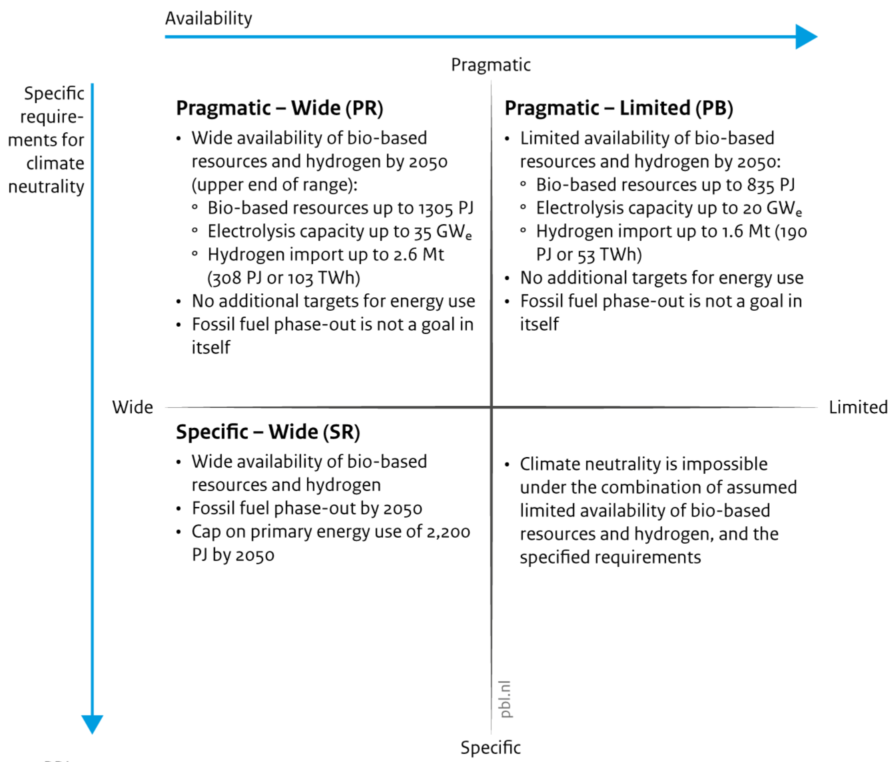
Source: PBL

The integral pathways differ as to availability of resources, specific climate neutrality requirements and use of technologies

The sectoral analyses have been used to perform an integral system analysis that focuses on the lowest national costs. National costs are the balance of direct costs and benefits to society as a whole for achieving climate neutrality (CE Delft, 2023; PBL & CPB, 2020). The analysis shows which technologies are needed in which sectors, and also those which are just not suitable for a given sector. In the pathways, there are variations in the assumptions about issues such as the availability of bio-based resources, CO_2 storage, nuclear power or wind power.

The different pathways are classed according to two axes, as shown in Figure F.2. One axis shows availability of bio-based resources and hydrogen, and ranges from *Wide* to *Limited*. The other shows the requirements of the approach to reaching climate neutrality, and ranges from *Pragmatic* to *Specific*. The *Specific* requirements — a complete phasing out of fossil energy carriers by 2050 and a cap on primary energy consumption in 2050 — are based on the current Energy Efficiency Directive (EED) definition.

Figure F.2
Classification principle for the integral pathways in three quadrants



Source: PBL

This arrangement results in four quadrants labelled Pragmatic-Wide (PR), Pragmatic-Limited (PB), Specific-Wide (SR) and Specific-Limited (SB). The fourth quadrant (SB) is empty because climate neutrality is impossible under the combination of assumed limited availability of bio-based resources and hydrogen, and the specific requirements mentioned above. This arrangement means the PB and SR quadrants contain the outermost limits within which climate neutrality is still possible.

Within the three quadrants, we introduced further variations into the assumptions, which ultimately lead to over 30 distinct pathways. To illustrate our main findings, we use a single pathway from each quadrant. These are labelled PR40, PB30 and SR20, where the number stands for the CO_2 storage cap in 2050 in megatonnes. These pathways provide a proper illustration of the corners of the playing field explored in this study.

The techno-economic content of the pathways takes precedence in this study. The relationships with other tasks are only discussed indirectly

The focus of this study is on the technical content of a climate-neutral energy and resource system, which adheres to the triangle 'clean' (climate neutrality), 'affordable' (at the lowest national cost) and 'reliable' (availability of energy carriers). Other public interests, such as security and fairness — the National Energy System Plan (NPE) lists eight points (EZK, 2023c) — are not explicitly included in the analysis. There are also other major transition tasks in the living environment that are directly or indirectly related to the energy transition. These include biodiversity and nature restoration, the creation of a fully circular economy and changes in the use of space in the Netherlands.

The relationship with these transition tasks is not examined in this study, but is of course relevant, and one of the determining factors in the way the transition to a climate-neutral Netherlands can take place. This study can be a good starting point for follow-up studies addressing such matters.

All findings presented below should be interpreted in the light of the setup, assumptions and preconditions discussed so far. Further information on the assumptions, the OPERA model and the results of the calculations can be found on the PBL website[1]. The comprehensive analyses of the demand and supply sectors are recorded in seven background reports (PBL, 2024d, 2024e, 2024c, 2024a, 2024b; PBL & TNO, 2024; TNO, 2024b) which are also available on the website.

F.2 The transition to a climate-neutral energy system

While climate neutrality by 2050 is technically feasible, it requires deploying all the available, but also scarce, 'building blocks' for emission reduction

From a technical point of view, it is possible for the Netherlands to be climate neutral by 2050. The available building blocks on the production side are CO_2-free electricity production, bio-based resources, green hydrogen, biogenic and synthetic fuels, and biogenic and synthetic resources the chemical industry (hereafter referred to as *feedstocks*). On the use side, the building blocks are reduction of energy use, electrification of traditional fuel applications for road traffic, electrification of heat production and industrial processes, and use of local heat. Capture of CO_2 for use or underground storage has a role to play in both energy production and energy use. In a climate-neutral energy system, the flexibility of the electricity system must be ensured much more than it is now in both the supply and demand sectors. Outside the energy domain, the CO_2 emissions from peatlands must be reduced, as well as the emissions of other greenhouse gases, particularly from agriculture.

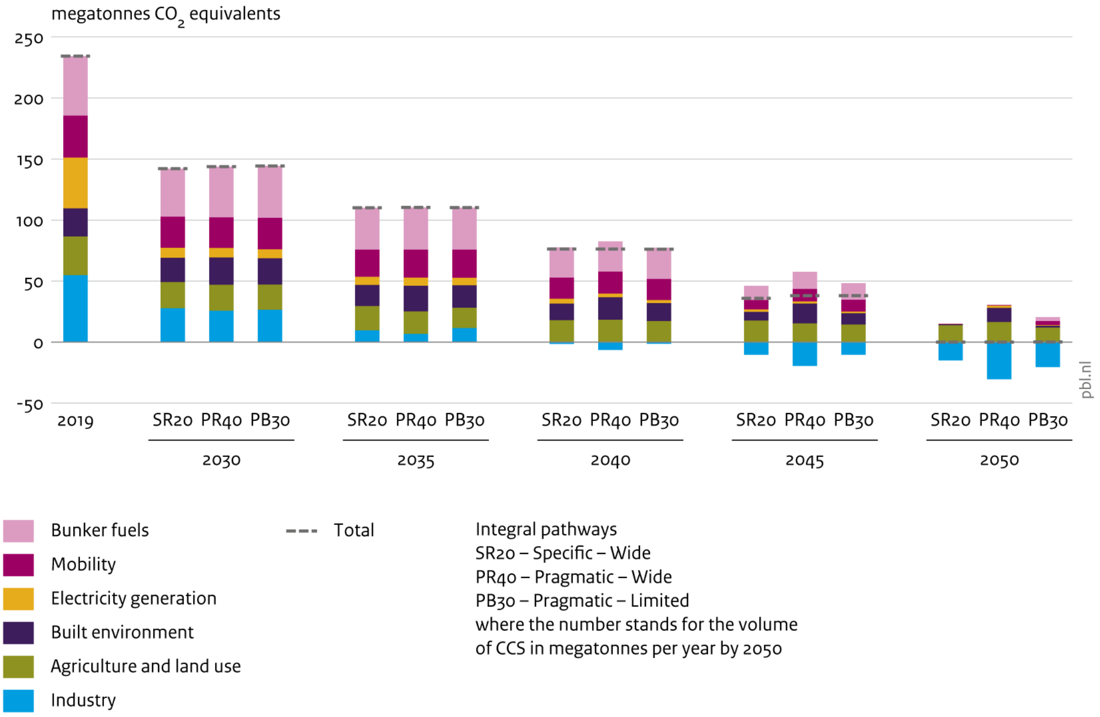
All these building blocks are limited in terms of their potential and they all have different functions in a climate-neutral energy system. For instance, bio-based resources and CO_2 storage are necessary because they are the only elements that can provide non-fossil carbon and produce negative emissions. On balance, all building blocks are necessary to achieve climate neutrality. At best, there may be room to do without specific technologies comprised within these building blocks, such as the use of ammonia engines in maritime shipping.

Figure F.3 shows how in the integral pathways greenhouse gas emissions decrease towards climate neutrality, in agreement with the linear reduction path described in Section F.1. Up to 2035, there is relatively little variation between the pathways with regard to sectoral emissions. After that, emissions start to diverge more, which means that from then there are more and more differences among the pathways in the roll-out of measures and technologies..

[1] https://www.pbl.nl/publicaties/trajectverkenning-klimaatneutraal-2050

Figure F.3

Greenhouse gas emissions per sector



Source: PBL

The transition to climate neutrality involves a complex trade-off between costs and risks regarding the availability of energy sources and technologies

All integral pathways express a cost-optimal trajectory, that is, the trajectory that, given the respective assumptions, leads to climate neutrality at minimal national cost. The higher the costs, the more drastic the required interventions in the energy system and the more complicated it becomes to achieve climate neutrality. The range of the net present value of the additional costs of all integral pathways for the period 2026 to 2050 spans over EUR 180 billion.

Wide availability of energy sources and supply technologies often goes hand in hand with relatively low cumulative additional costs to achieve climate neutrality. This is because there are more degrees of freedom to design the climate-neutral energy system as inexpensively as possible. However, it is risky to assume such wide availability beforehand, because it is very uncertain whether energy sources and technologies can be scaled up sufficiently or imported in sufficient amounts. Conversely, limited use of energy sources and technologies often goes hand in hand with higher cumulative additional costs, but at the same time it is a safer strategy since the required energy sources and technologies are more likely to be available. In short, this is a case of a complex trade-off between the costs of pathways towards climate neutrality and the risks around the availability of energy sources and technologies.

The pathways with the highest additional costs are also those that often have high CO_2 shadow prices[2], up to well above 1,000 euros per tonne of CO_2 in 2050. These pathways — mostly falling within the quadrant with limited availability of hydrogen and bio-based resources and with a 20 megatonne CO_2 storage cap in 2050 — are illustrative of a situation in which the practical feasibility of climate neutrality is highly doubtful.

But even without considering the level of additional costs of the various approaches, the majority of the pathways foresee the cost structure of the Dutch energy system changing significantly in the coming decades. Imports of fossil energy carriers (oil and natural gas) will be replaced, especially by domestic production of sustainable energy, which will cover more than half of the foreign supply, and also by smaller imports — in terms of energy content — of mainly biofuels and hydrogen. As a result, in most pathways, on balance, the costs of purchasing energy carriers decrease, and capital costs and other fixed costs increase. The Dutch energy supply thereby becomes less sensitive to the price fluctuations of energy carriers.

Climate neutral is not synonymous with fossil-free. Making fuels and feedstocks fossil-free requires specific policies and will not be completed by 2050

All integral pathways to climate neutrality involve a sizeable decrease in the use of fossil fuels and fossil feedstocks. This is clearly illustrated in Figure F.4 and the flow charts in Figures F.5 to F.9 which show the energy flows in, respectively, 2019, 2030 and 2050; there are three charts for the latter year, showing the energy flows for the three illustrative pathways (see Text box F.3 for further details on Figures F.4 to F.9). But this does not mean that climate neutrality by 2050 is synonymous with a fully fossil-free energy and resource system. This can be seen in the energy flow charts in Figures F.8 and F.9 where natural gas and oil still play a role.

Completely phasing out fossil fuels and feedstocks by 2050 is only possible if there is sufficient availability of bio-based resources (especially imports) and hydrogen (especially domestic production, but also imports). Even when phasing out by 2050 is possible, it is not necessarily the most obvious policy choice. It may, in fact, lead to substantial additional costs. Moreover, the demand for scarce climate-neutral energy carriers may make emission reductions in other countries more difficult. After 2050, emission reduction options will continue to develop and probably decrease in cost. Then it will become easier and cheaper to phase out the residual use of fossil energy carriers. Apart from that, for a long time after the phase-out there will still be a large amount of fossil carbon in the system in the form of plastics. It is important to continue to make high-quality use of this carbon for as long as possible through recycling.

[2] The CO_2 shadow price is equal to the cost-effectiveness of the most expensive measure that still needs to be implemented to achieve the greenhouse gas emission reduction target of the year in question after all the cheaper measures have already been taken.

Text box F.3 Notes on energy flow diagrams and national consumption balance
Figures F.5 to F.9 are Sankey diagrams that give an overview of the origin, volume and destination of the various energy flows in the energy system. The series shows energy flows for 2019, the PR40 pathway in 2030 and the three illustrative pathways SR20, PR40 and PB30 in 2050.

In the diagrams, the width of the lines represents the volume of the respective energy flow. On the left are the various energy sources by origin (e.g. imports, extraction), and on the right are exports and consumption by the different demand sectors of each energy carrier. Energy losses are shown separately.

The balance of imports, extraction, exports and losses is the national consumption balance as shown in Figure F.4. Extraction of energy — solar energy by household PV systems, ambient heat by heat pumps — is always shown on the left, and separately from the sectors in which extraction physically takes place.

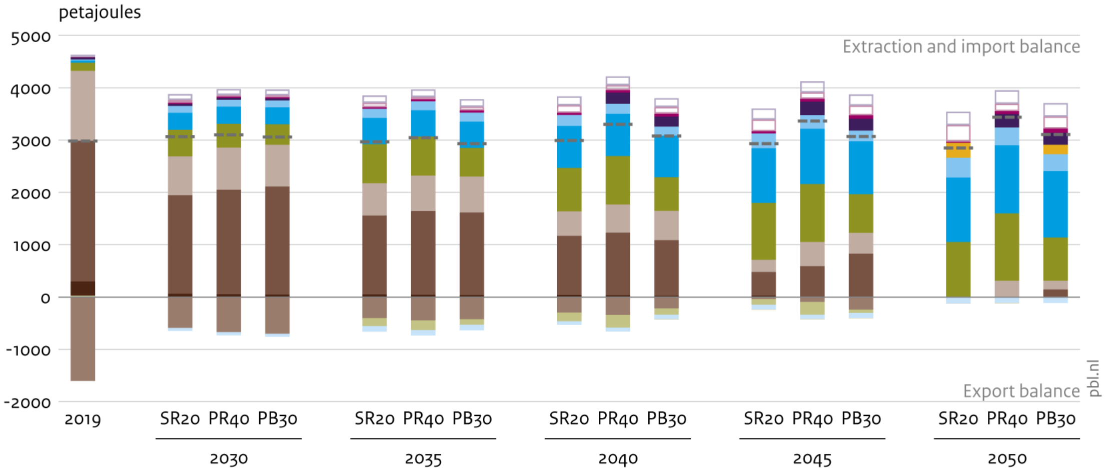
Different colours are used for crude oil as a primary energy source and for products derived from crude oil. Re-exports of energy carriers, such as the delivery of imported crude oil to the German hinterland, have been omitted because they are not essential to the Dutch energy system. In contrast with customary energy statistics, plastic waste is also included, as an alternative raw material for plastic. Ambient heat is an important heat source, particularly for the built environment, but EU energy statistics do not count it as an energy carrier. For these reasons, Figure F.4 shows both plastic waste and ambient heat as transparent segments.

The conversion sectors appear between the origin and destination of energy: power plants, waste treatment, hydrogen production and fuel production. Combined heat and power (CHP) is placed in the demand sector it produces heat for. The energy flows to the demand sectors are therefore not entirely defined in the same way as the final consumption according to Statistics Netherlands, but the difference is very small, especially towards 2050, as the role of CHP decreases significantly.

Fuel production comprises all liquid fuels and feedstocks, including methanol and ammonia, regardless of the origin of the energy (fossil or bio-based resources or hydrogen). Outbound fuel streams are subdivided into fossil, biogenic and synthetic, based on the contribution of the various sources to the energy content. Ammonia — as a carbon-free energy carrier, not as an industrial product — is shown separately, and is always of synthetic origin.

Figure F.4

National consumption balance of energy sources and energy carriers, including feedstocks



Extraction, import and export balance

- Plastic waste
- Ambient heat
- Geothermal energy
- Nuclear energy
- Hydrogen
- Solar energy
- Wind energy
- Bio-based resources
- Natural gas
- Oil
- Coal
- Oil products
- Biofuels
- Electricity
- Total consumption balance including feedstocks and excluding ambient heat and plastic waste

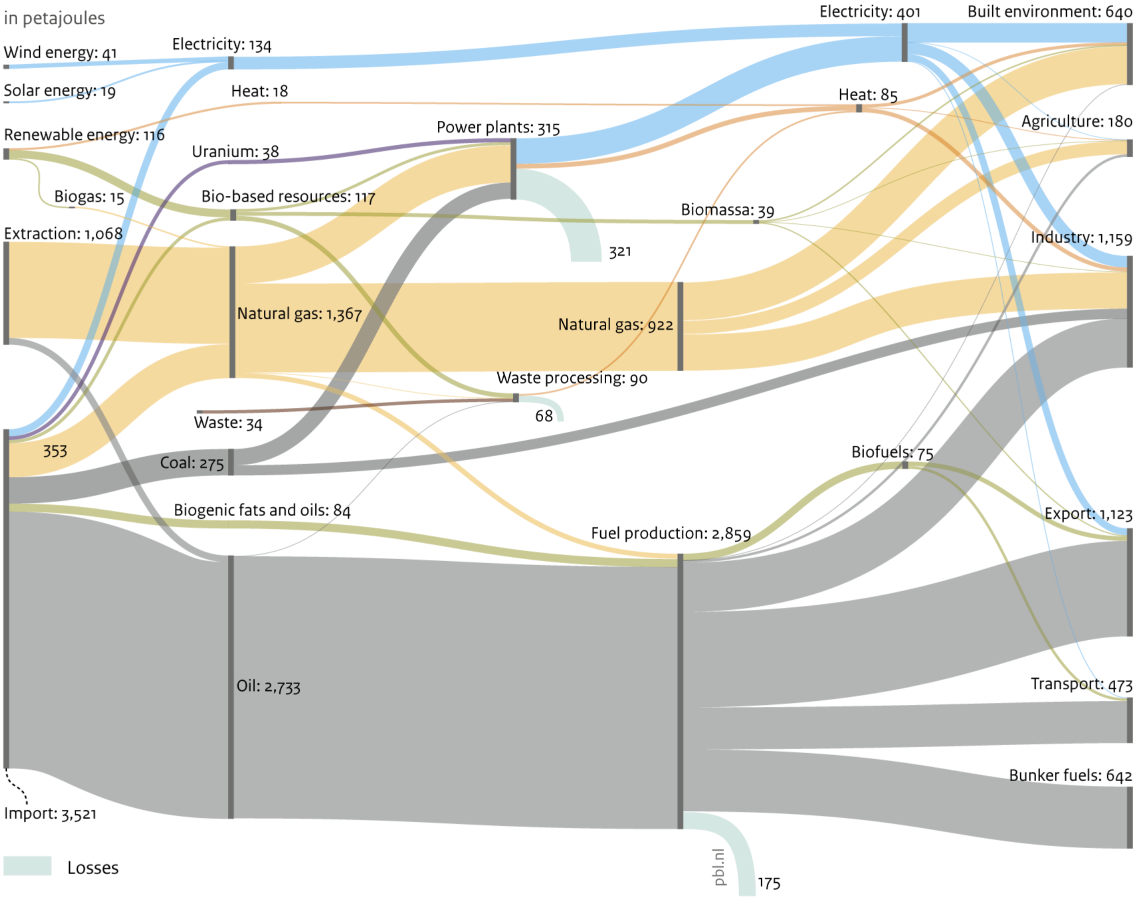
Integral pathways
SR20 – Specific – Wide
PR40 – Pragmatic – Wide
PB30 – Pragmatic – Limited
where the number stands for the volume of CCS in megatonnes per year by 2050

Source: PBL

Figure F.5

Energy flows Netherlands 2019

in petajoules

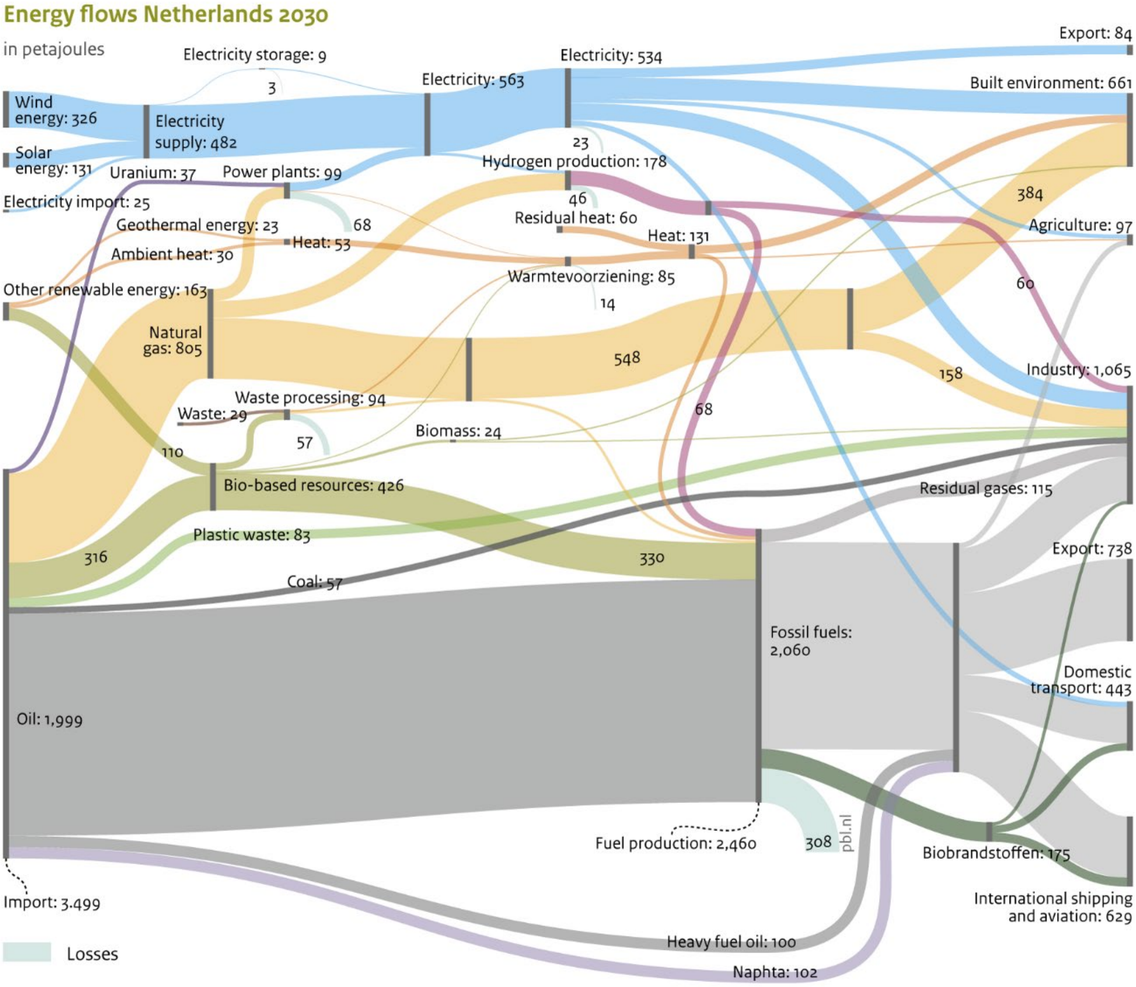


Source: PBL

Figure F.6

Energy flows Netherlands 2030

in petajoules

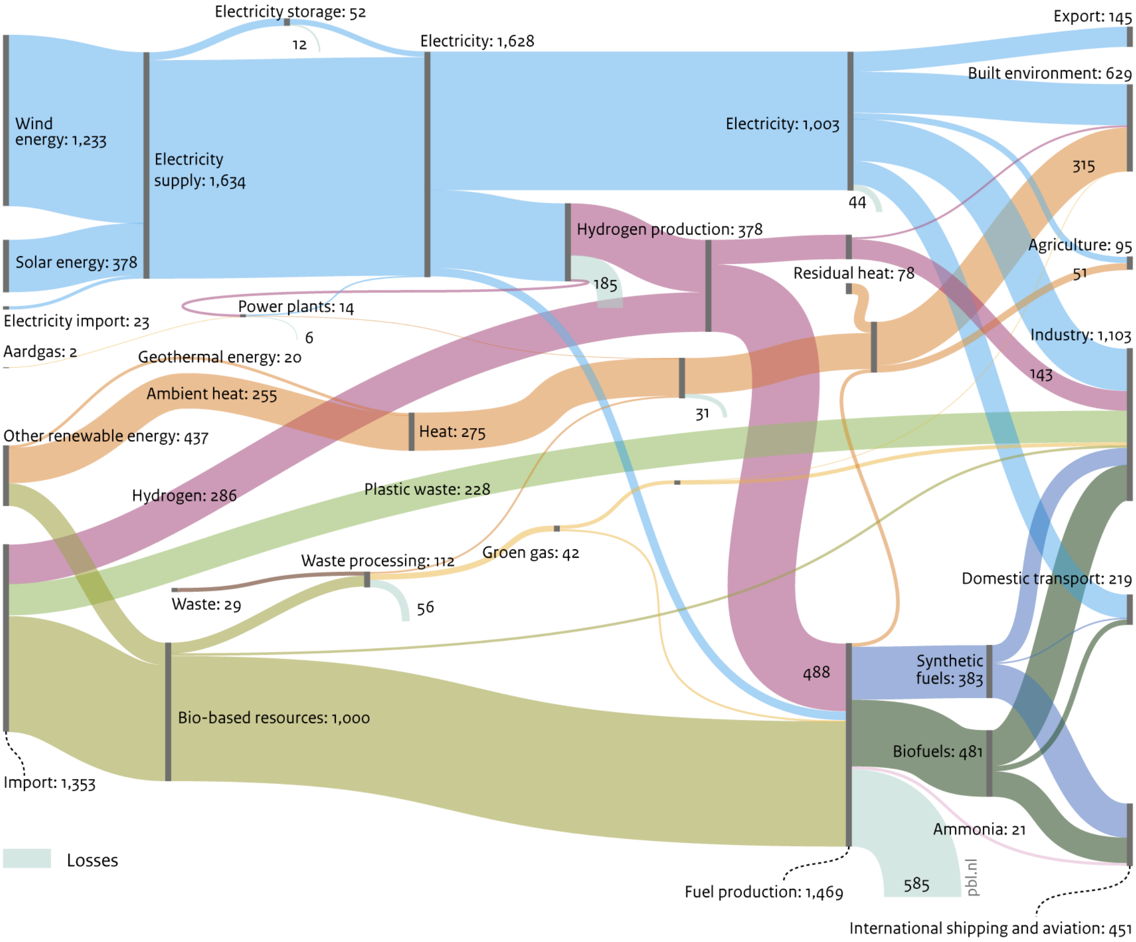


Source: PBL

Figure F.7

Energy flows Netherlands 2050, Specific-Wide pathway with CCS up to 20 Mt/yr (SR20)

in petajoules

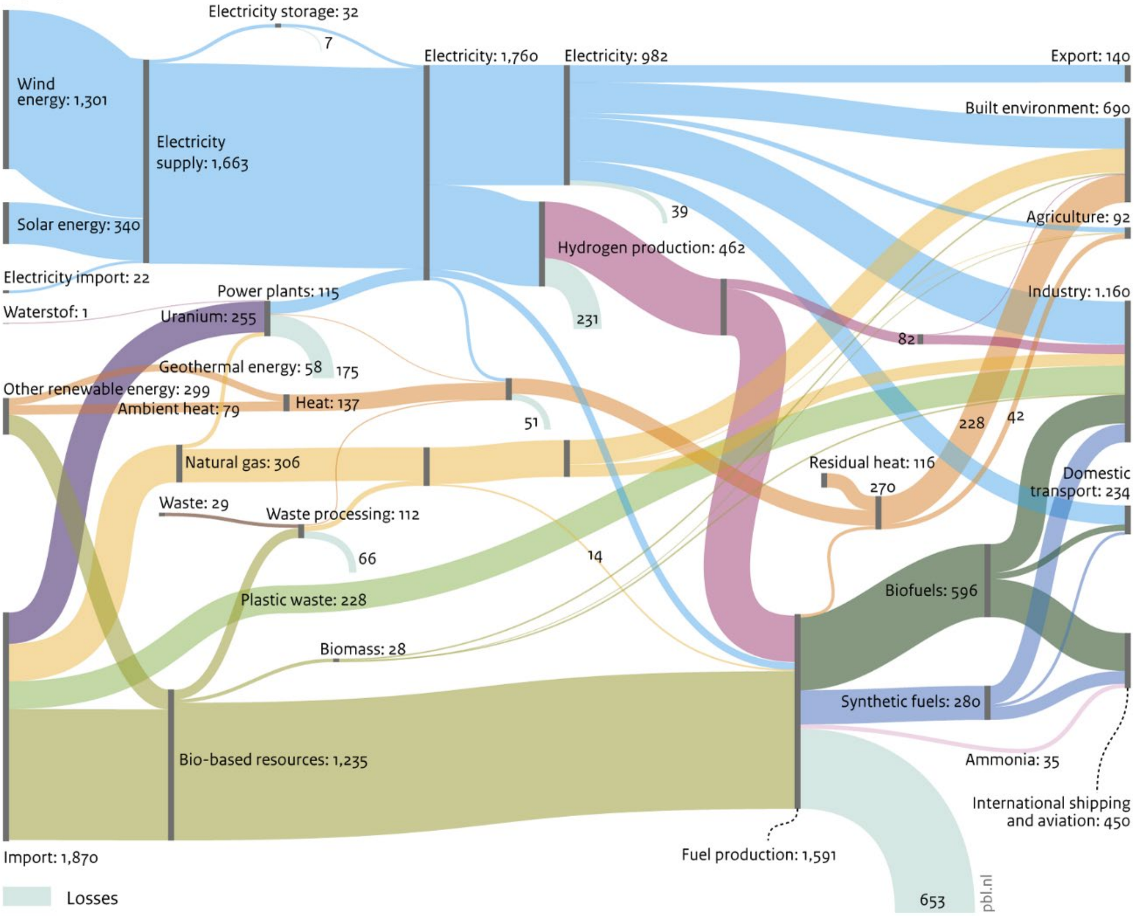


Source: PBL

Figure F.8

Energy flows Netherlands 2050, Pragmatic-Wide pathway with CCS up to 40 Mt/yr (PR40)

in petajoules

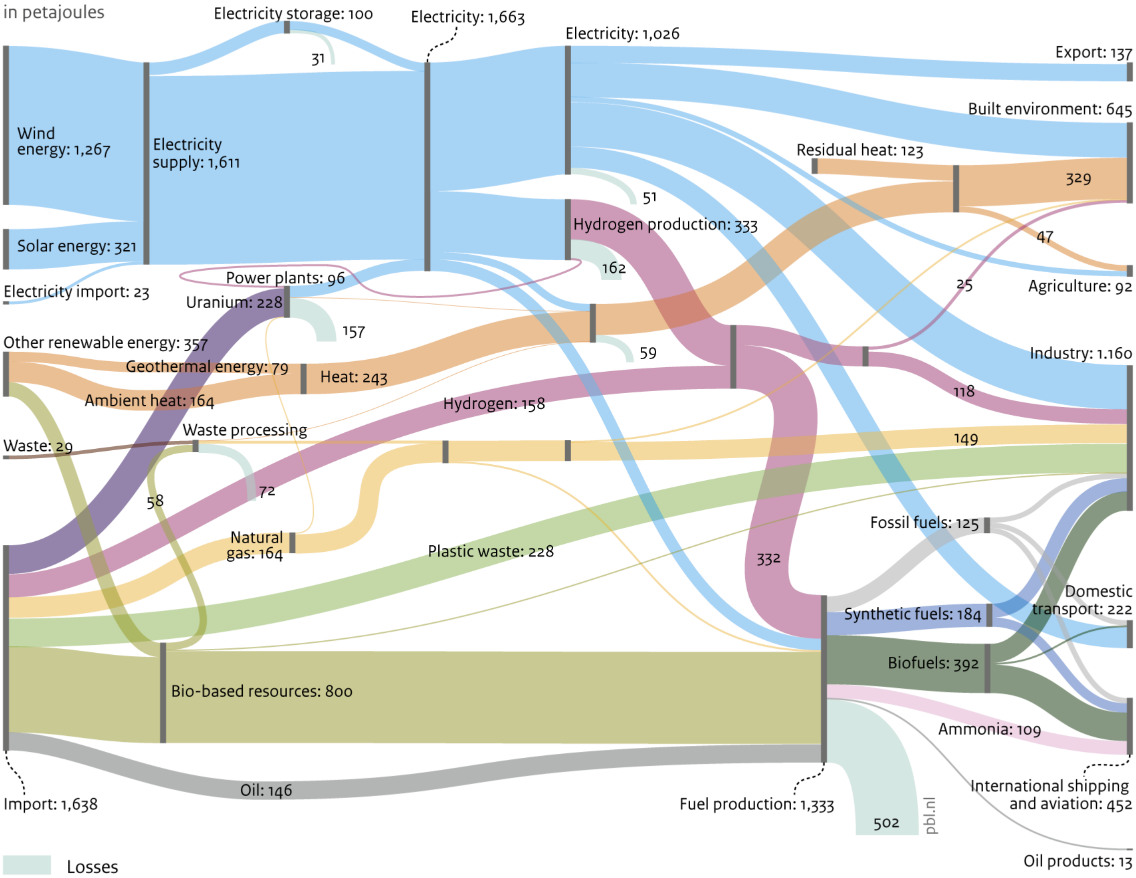


Source: PBL

Figure F.9

Energy flows Netherlands 2050, Pragmatic-Limited pathway with CCS up to 30 Mt/yr (PB30)

in petajoules



Source: PBL

Electrification is the driver of the energy transition. While emissions from electricity generation are dropping fast, they will not reach zero by 2040

In 2050, a share of 50% to 60% of the energy going to the demand sectors will come directly or indirectly from electricity, mainly from wind, solar and nuclear power. In 2019, the figure was just a little over 3% and in the various pathways it rises to around 14% by 2030. Most of this is direct use of electricity in the demand sectors. This strong growth is driven by *direct electrification* — the use of electricity instead of fuels for heating and mobility. On balance, energy use falls because the demand for electricity will not increase as rapidly as the use of fuel declines. This is because conversion losses in electric motors are much lower than in internal combustion engines, because heat pumps use a relatively small amount of electricity to produce a larger amount of useable heat through the upgrading of ambient heat or waste heat, and also because electric heating does not release combustion gases that cause heat losses. *Indirect electrification* involves using electricity to produce green hydrogen and synthetic fuels. On balance, this increases energy consumption because the conversion losses during production are greater than for fossil fuels.

In the pathways, greenhouse gas emissions from electricity production do not yet reach zero in 2040. This differs from the 2035 target of the Netherlands and the 2040 target of the European Union. Greenhouse gas emissions from electricity generation do fall to low levels relatively early, but many pathways indicate that even in 2050 there will still be limited residual emissions, offset by negative emissions. The final part of emission reduction mainly needs to be achieved through the use of hydrogen and green gas rather than through measures in the electricity sector itself. Enforcing net-zero emissions within the electricity sector may lead to additional costs.

Use of fuels and feedstocks declines and import dependence on oil and gas decreases greatly

In addition to electrification, measures such as insulation, efficiency enhancements and use of local heat (ambient and geothermal) contribute to the decline in fuel use. This is especially notable in road traffic and in heat production in industry and the built environment. The fewer bio-based resources and hydrogen are available or the less use is made of CCS, the greater the decrease in fuel use (compare Figures F.8 and F.9). For the built environment in particular, the differences between the pathways are relatively large in 2050. The integral analysis shows that in this sector it is usually cheaper to use fuels, including fossil fuels, if there is room for them.

As for the resources drawn upon in organic chemistry (feedstocks) and in aviation and shipping, the use of liquid energy carriers remains relatively high in the integral pathways. The differences between the pathways with regard to volume of use in 2050 are relatively small. In addition, in several industrial processes — such as the production of steel and fertilisers — there are no alternatives that can completely replace fuels.

The assumptions are made that, in maritime shipping, less fuel will be bunkered in the Netherlands and that, in organic chemistry, the use of primary feedstocks will decrease due to expanding recycling of plastics. Even so, the use of fuels and feedstocks will remain substantial, compared to that in other EU Member States, because it is assumed that the production of fuels for aviation and maritime shipping will continue to take place in the Netherlands and the chemical industry will also remain.

With the decline in the use of fuels and feedstocks, import dependence on oil and natural gas will also decrease sharply. In 2019, about 90% of all energy was imported, including that for international aviation and shipping as well as for feedstocks (see Figure F.5). Pathway calculations show that, in 2030, energy imports will still be 85% (see Figure F.6), mostly oil and natural gas. All pathways indicate that, by 2050, more than half of the energy will be sourced from the Netherlands itself, as illustrated in Figures F.7 to F.9. The remainder of imports in 2050 will consist mainly of bio-based resources, along with plastic waste, hydrogen and uranium. As a result, the origin of imports will also shift; in 2030, they will mainly come from outside the European Union, whereas by 2050 most will originate from within the European Union.

Bio-based resources and hydrogen are mainly used for the production of fuels and feedstocks. Use of plastic waste is also important

In all pathways, bio-based resources are the second-largest energy stream after electricity. Moreover, they are the only significant source of non-fossil carbon, given that extracting carbon from the air through Direct Air Capture (DAC) plays a very limited role, if any, in all pathways because of its assumed high cost and high energy consumption. Direct combustion of bio-based resources for heat and electricity is very limited in all pathways because they are more urgently needed for biofuel and feedstock production. In the production process, about half of the energy and a third of the carbon from the bio-based resources ends up in the fuels. The remaining carbon is for the most part converted into a relatively pure stream of CO_2. With the use of additional hydrogen, part of this is can still be converted into fuel, in the form of hydrocarbons or methanol. This part is referred to as synthetic fuels, since the energy comes from the added hydrogen. Whatever CO_2 remains can be stored underground, producing negative emissions. Even under the most pessimistic assumptions about the available amount of biofuels, it is possible to meet almost the entire demand for carbon, provided sufficient hydrogen is added to the production process.

Additional use of hydrogen is also still needed under the most optimistic assumptions about the availability of bio-based resources. This hydrogen is used not only to convert sufficient amounts of carbon from bio-based resources into fuel, but also to produce carbon-free fuels, such as ammonia — especially for use in shipping. Direct use of hydrogen is mainly limited to various industrial processes. And, though reduced in scale, it is important in load-following power plants that provide back-up power.

Another important element in the pathways is the import of plastic waste. All pathways foresee plastic waste becoming an important resource for plastic production, thereby limiting the demand for scarce bio-based resources and hydrogen. Since the Netherlands — as a major exporter of plastics — produces much more plastic than plastic waste becomes available domestically, this leads to large volumes of imports of plastic waste. This is clearly visible in the energy flow diagrams. Plastic waste can also be imported in the form of pellets or pyrolysis oil.

Text box F.4 Comparison with other studies

We have compared the results of the integral pathways with a select number of other studies. Making comparisons is complicated, due to differences in energetic, spatial or sectoral scope, differences in definitions, different assumptions on full-load hours, costs, preconditions, and whether the focus is on optimisation or simulation (Quintel & Witteveen en Bos, 2023). In addition, data are often not available or not unambiguously recorded. Therefore the comparison focuses mainly on the technical interpretation of the energy system, and not on exact figures.

Comparison with national studies: use of bio-based resources and hydrogen
The two studies selected on the Netherlands are the only recent studies that offer a complete and detailed picture of Dutch energy use by carrier and by sector. They are the 2nd edition of Integral Infrastructure Exploration *2030 – 2050* (II3050) (Netbeheer Nederland et al., 2023) and *Towards a sustainable energy system for the Netherlands in 2050* (TNO, 2024a, 2024b)).

The most notable differences from the pathways study can be found in the use of bio-based resources and hydrogen. In the other studies, the use of bio-based resources in particular is not as great. This is largely because bunker fuels are only considered partly or not at all. In addition, in a number of scenarios the assumed size of industry is smaller. This is important because industry and the production of renewable bunker fuels make a large claim on bio-based resources and hydrogen. After correcting for these differences, in most of the scenarios in the other studies the use of bio-based resources and hydrogen can reach, or even exceed, the upper limit of the range identified in our study.

Comparison with international studies: sources of negative emissions
The two international studies we considered are the *European Impact Assessment*[3] (EC, 2024b) and a study conducted in the United States (Williams et al., 2021). They differ from this pathway study mainly with regard to the relative volume and the source of negative emissions achieved through underground CO_2 storage. The US publication coincides with the present study in that the combination of biofuel production with CCS is seen as the main source of negative emissions within the energy system.

The Impact Assessment provides insight into EU perspectives on how to design the pathway to climate neutrality by 2050. It sees CO_2 storage from Direct Air Capture (DAC) as by far the largest source of negative emissions in the energy system, followed by BECCS in electricity generation. Capturing CO_2 during the production of liquid biofuels is not discussed and not even mentioned as a possibility. However, based on the reported volume of EU biofuel production, there is enough potential for BECCS to render unnecessary both the amount of DAC in the assessment scenarios and a substantial portion of CO_2 capture in electricity generation.

[3] The Impact Assessment is part of the 'Communication' of the European Commission regarding the 90% emission reduction target for 2040. Here, we are limiting the comparison to the results for 2050.

F.3 The transition of the fuel supply: bio-based resources, hydrogen and CO_2 storage

In the Netherlands, fuel and feedstock production based on sustainable bio-based EU resources plays an important role in the transition

Fuel use will decrease substantially, but even in 2050 the use of liquid and gaseous fuels will still be unavoidable for many applications. Climate neutrality in the fuel supply requires a sizeable amount of sustainable bio-based resources, green hydrogen and — especially if those two prove to be insufficient — CO_2 storage. Sustainable bio-based resources are obtained from agriculture, forestry, the wood sector and tertiary streams. The Netherlands sources them mainly from other EU Member States, but also from domestic production. This study does not take imports from countries outside the European Union into account. This is in accordance with the European Commission's Impact Assessments (EC, 2020, 2024b) which stipulate that more than 93% of bio-based resources are to come from the European Union itself. There are also major geopolitical, socio-economic and regulatory barriers that complicate imports from outside the European Union (Mandley et al., 2022). Furthermore, other world regions also need to become more sustainable and will therefore be requiring large amounts of bio-based resources themselves. Based on studies that provide estimates of global availability, it would even be possible to argue that, according to a *fair-share* outlook, the European Union would have to be a net exporter. This suggests that a global approach does not necessarily lead to a higher potential, neither for the European Union nor for the Netherlands.

Renewable bio-based resources are mainly needed for the production of fuels for maritime shipping, aviation and a number of industrial processes. They are also used to produce feedstocks for organic chemistry and as materials, particularly in construction. For all these applications, there are only limited alternatives available, if at all. Therefore, the fuels themselves need to be made climate neutral. This also means that bio-based resources, along with hydrogen, are used with priority for the production of fuels and feedstocks. The integral pathways in this study assume that the Netherlands will continue to produce relatively large amounts of fuels and will maintain a large chemical sector; this implies that a comparatively large share of the available bio-based resources in the European Union will be used in the Netherlands. Relocating the production of fuels and feedstocks to other countries — which means that the Netherlands would have to import them — does not necessarily make it easier for the country to bring the emissions from its own territory down to zero. This is because both the required bio-based resources and the related options to realise negative emissions would then also go to the countries where these fuels and feedstocks are being produced.

The pace of scaling up production and import of green hydrogen and changes in costs are highly uncertain

Electrolysers are needed to produce hydrogen. This study makes the assumption that all currently known project plans are realised to calculate the upper limit of electrolyser capacity installed in the Netherlands in 2030 (9 GWe) and 2040 (22 GWe). The assumption is, however, highly uncertain because more than 96% of those plans are 'feasibility studies' or 'concepts'. Given the pace offshore wind is being rolled out and the energy needs for direct electrification, an electrolysis capacity of 4 GWe in 2030 is already considered 'very ambitious' (EZK, 2023f). For long-term projections, this study puts investment costs for large-scale electrolysers at over EUR 600 per kWe. This corresponds to a decrease of more than 70% compared to 2024 (PBL, 2024). A decrease of this kind requires worldwide large-scale investment in electrolysis plants over the next 10 to 15 years combined with a major expansion in their scale of operations. It is true that around the globe, considerable numbers of large-scale projects have been announced for the next 15 years, but the number of plans for which a final investment decision has actually been made is still rather modest.

Reliable estimates for potential imports of green hydrogen in the period up to 2050 are not available, partly because thus far hardly any concrete projects have been realised. If all projects around the world aimed at export were realised on time, around 5 megatonnes (600 petajoules) of hydrogen would come to Europe by 2030 (IEA, 2023). However, by the end of 2022, final investment decisions had only been made on 0.3 megatonnes (36 petajoules). As other countries in Europe are also counting on large-scale imports, it seems likely that only a small share will go to the Netherlands. Based on Fraunhofer (2023) and Odenweller et al. (2022), we assume maximum imports of 310 petajoules in 2050.

The expected cost of imported hydrogen covers a wide range. The literature is not particularly clear-cut, especially with regard to the cost of imports via pipelines. The cost of imports by ship, which are based on ammonia as a hydrogen carrier, are more unambiguous and these have been used as a starting point.

In most integral pathways, domestic hydrogen production — which requires 25% to 40% of all electricity produced in the Netherlands — covers most of the consumption. This is not only because imports are relatively expensive under the assumptions made here, but also because domestic hydrogen production contributes to the consumption of relatively cheap electricity for which there would otherwise be no use.

The availability of bio-based resources is also uncertain, meaning alternatives such as fuel use cutbacks and CO_2 storage are required

The availability of sustainable bio-based resources is uncertain and national policies can only act upon it to a limited extent. Therefore, in the transition to climate neutrality, CO_2 storage and fuel use reductions are also part of a robust strategy. It is possible to achieve fuel use cutbacks through electrification, local heat and energy saving. Where use of fuels is inevitable, carbon-free fuels such as ammonia and hydrogen offer significant advantages because they do not require bio-based resources.

The use of carbon-free fuels is also important with a view to the period after 2050 because it is doubtful whether it will then be possible to further expand the available amount of bio-based resources within the applicable sustainability criteria. In the case of hydrogen production and import, there is uncertainty mainly about the pace of scaling up in the shorter term, but, compared to bio-based resources, there is more perspective for further scaling up after 2050. As for the use of ammonia, it should be mentioned that external safety is a major point of concern. Another important advantage of carbon-free fuels is that, unlike in the production of synthetic hydrocarbons and methanol, no CO_2 is needed for their production. This means there is more residual biogenic CO_2 that can be stored, which then leads to negative emissions.

A climate-neutral Netherlands requires negative emissions. These emissions arise from fuel production rather than electricity generation

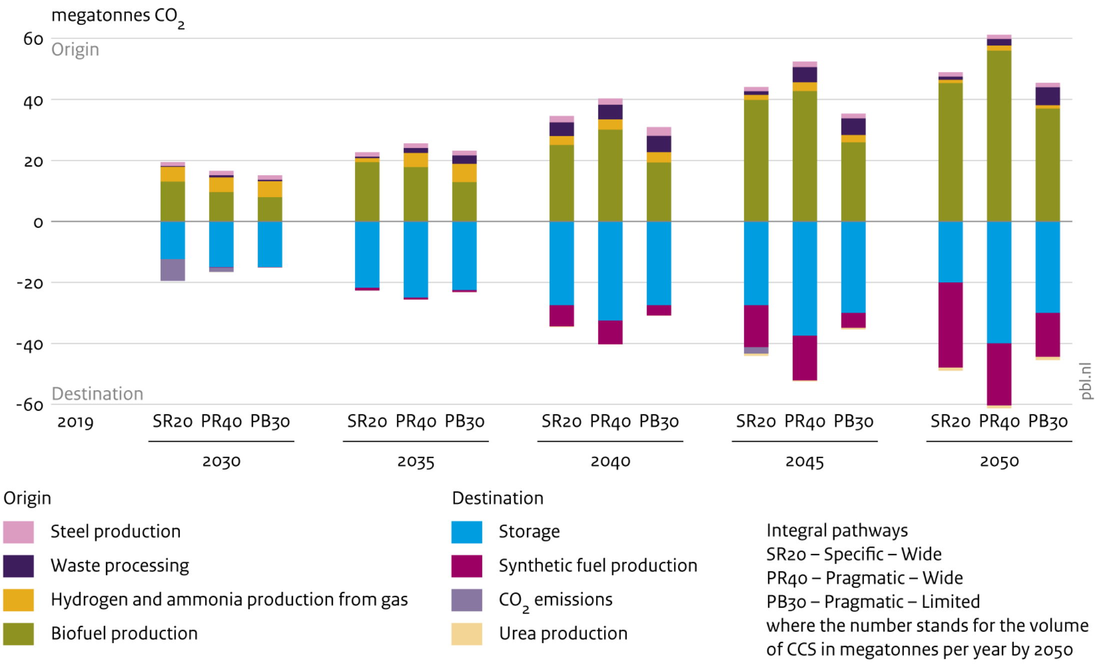
In the integral analysis, CO_2 capture and storage (CCS) is a key technology to reduce CO_2 emissions from fossil sources in the short term and reach interim emission targets. Up to 2030, the CO_2 that can be captured and stored will mainly originate from the existing ammonia and hydrogen production from natural gas, and from residual gases from refining and the chemical sector. Residual gases will continue to play a role after 2030, with the sources becoming more and more biogenic. In the longer term, negative emissions, achieved through capture and storage of CO_2 with a biogenic origin, will become increasingly important (see Figure F.10).

Without negative emissions, it will not be possible for the Netherlands and the European Union to reach net zero in the EU ETS1 sectors (energy-intensive industry, power generation, and part of aviation and maritime shipping) in just over 15 years; nor will this be possible for all territorial emissions in just over 25 years. By 2050, negative emissions will offset residual emissions, from agriculture in particular, and also emissions from other sectors that will still be using fossil fuels as an energy source. However, this requires that the advancement of negative emissions through CO_2 storage be regulated in EU policy. This is currently not the case.

As mentioned above and illustrated in Figure F.10, in the pathways, a major part of the relatively pure CO_2 released in biofuel production is used in combination with hydrogen to produce synthetic fuels. The remaining part is stored, resulting in an important source of negative emissions for the Netherlands. In the fields of electricity generation and heat production, negative emissions, and CO_2 capture in general, barely feature in the integral pathways. Removing CO_2 from combustion gases requires heavy investments and a great deal of energy. In fuel-fired power plants, there is the additional consideration that such investments are unprofitable due to the rather limited number of full-load hours in 2050.

Figure F.10

Origin and destination of captured CO_2



Source: PBL

To achieve efficient use of CO_2 storage, it may be sensible to set a CO_2 cap and introduce storage auctions

Insufficient CO_2 storage capacity means that climate neutrality will not be achievable or that the costs of achieving it will rise sharply. On the other hand, having more capacity than strictly necessary increases the likelihood of a lock-in on fossil energy carriers — a situation that could be avoided with relatively little additional cost. It is therefore sensible to pursue the use of CCS with great care to ensure that storage capacity is used as efficiently as possible, up to and also beyond 2050.

A well-balanced strategy could be setting a cap on annual CO_2 storage capacity that is in line with the amount of fossil fuels that has been agreed upon or that is unavoidable given the limited availability of alternatives. If necessary, that amount may be adjusted based on updated knowledge.

To accomplish this, it is important that companies that are weighing CCS against other ways of cutting their emissions are intensely aware of the deficiency. This may be done by linking a higher CO_2 storage cap to tighter emission reduction targets, actively pursuing the phasing out of fossil fuels, or by limiting and putting a price on CO_2 storage through, for instance, auctions of the limited storage capacity, preferably in an EU context.

F.4 The transition of the electricity supply: CO_2-free electricity generation, electricity grids and flexibility

Electricity production and consumption increase sharply and become more dependent on the weather

Figure F.11 shows not only that the consumption of electricity will rise sharply, but also that the origin of electricity will change radically. Offshore wind power accounts for the largest share of electricity production. Patterns of production and consumption will also change. Due to the electrification of space heating, instantaneous electricity consumption will depend partly on the outside temperature. In addition, due to the growing share of wind and solar power, electricity production will also become much more dependent on the weather.

Figure F.11 shows there is only little variation between the different pathways towards climate neutrality, particularly on the production side. This is primarily because in all pathways and all years the volume of construction of offshore wind turbines is close to the upper limits assumed in this study. Small differences can also be seen on the consumption side. However, beneath the surface there are huge disparities in actual implementation, as explained elsewhere in this study.

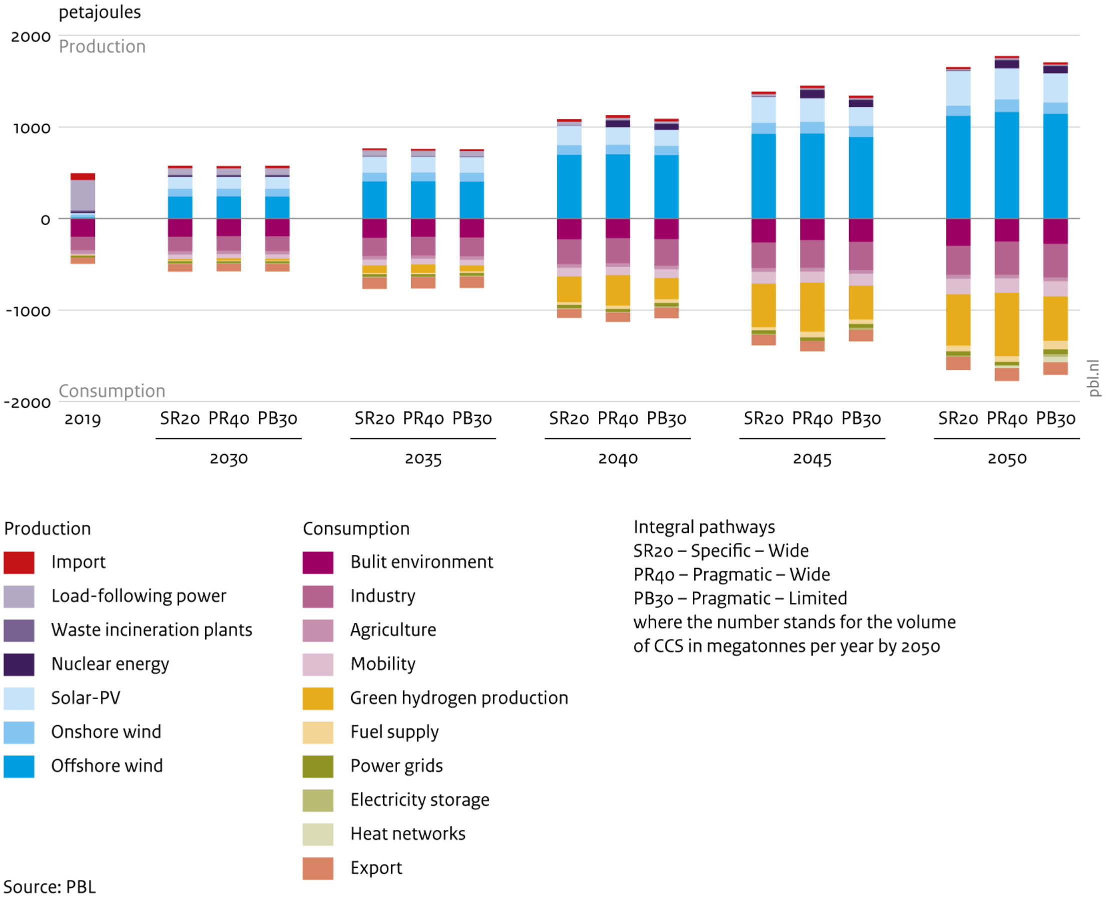
New CO_2-free electricity generation — from wind, solar and nuclear power —primarily covers the growing consumption of electricity. It contributes less to further reductions in greenhouse gas emissions in electricity generation itself. Those emissions are low compared to those in most other sectors, particularly in 2040, but they do not reach zero. However, CO_2 emissions from power generation will gradually decline because peak-load power plants make fewer and fewer full-load hours. Also, an increasing share of the fuel input at these power plants will consist of climate-neutral fuels.

All flexibility options are needed, but there is uncertainty as to where, when and how widely each will be used

In the current energy system, electricity production (supply) is aligned with electricity consumption (demand). This is primarily achieved by upward and downward adjustments of output power in fuel-fired power plants (load-following power) and by national or international electricity exchange between areas with surpluses and deficits. In the future, aligning electricity consumption and production will become an increasingly complex task. Accomplishing this will require making use of additional and diversified flexibility options, such as electricity storage, demand-side management or curtailment — the shutting down of wind farms or solar panels in cases of surplus electricity production. Each of these options has several specific characteristics and features as to cost, potential, length of time during which flexibility can be offered, availability and reliability, and the related energy losses. Some options are suitable for surplus situations, others for deficit situations and yet others for both. This explains why all flexibility options are needed and are included in all the calculated pathways.

Figure F.11

Electricity balance



Source: PBL

The scope of the various flexibility options varies greatly between the calculated integral pathways and, as has been observed in other studies, does not show a well-defined picture. For instance, in pathways that feature a relatively high electrolysis capacity, switching off hydrogen-producing electrolysers plays a major role as an option for demand-side management. But when hydrogen is in short supply, electrolysers cannot properly perform that role, as they then have to make more full-load hours to meet demand. That means there is less margin for downward adjustments if the situation calls for it. In that case, electricity storage has a bigger role to play, both to absorb surpluses and to supply the electricity that enables electrolysers to operate more hours. Demand-side management in the industry sector becomes more important with that.

Electricity grids need to be scaled up drastically

The increase in electricity production and consumption poses a major challenge for scaling up power grids. The challenge will be even more daunting due to fluctuating production from wind and solar. In addition, higher peaks in electricity consumption will occur, partly because of the electrification of heat production in the built environment. Up to 2050, the required capacity of the electricity grids will rise sharply, compared to 2030. In the various pathways, capacity increases by an average factor of 1.5 to 2.5 in typical low-, medium- and high-voltage grids and by a factor of 2.5 to 4 in offshore grids. Heavy investments in power grids will therefore continue to be needed for a long period.

More wind power and more nuclear power might make climate neutrality feasible and less costly, but degree of uncertainty is substantial

In line with the policy of the Rutte IV government, in this study we assume maximum capacities of 70 GW for offshore wind power and 3.5 GW for nuclear power in 2050. While this is sufficient for a climate-neutral system, the results indicate that higher capacity could lead to lower costs.

This is because additional capacity guarantees that instantaneous production is more often sufficient. That then means that flexibility options such as electricity storage and demand-side management require smaller investments, and electrolysers for green hydrogen production can be used more optimally. Opportunities for direct electrification are then also more favourable. This applies more strongly to nuclear power than to wind power, because nuclear power plants also produce when solar and wind power are insufficient — even over longer periods of time. Additional capacity of nuclear power in particular therefore contributes to the robustness of the system, but it is not necessarily essential (see, for example, Figure F.7). Under current policy assumptions, just realising sufficient wind and nuclear power capacity will already require a huge effort that has a bearing on, for instance, the necessary power grids, the available space, and also public support. It is therefore very doubtful whether even more capacity from nuclear and wind power is feasible.

In addition, it is important to highlight that the cost assumptions used in this study are highly uncertain, especially with regard to nuclear power. To give an example, the cost overruns in recent nuclear power plant construction projects are much higher than the system-wide benefits to expenditure obtained from increased nuclear capacity. Further developments in the cost of construction will therefore largely be the decisive factor in decisions on new nuclear power plants (TNO, 2022; Witteveen en Bos, 2022). And the estimated costs for offshore wind farms have now also undergone a drastic upwards revision from the figures this study is based on. In the evaluation of the cost increases in the supply chain and for the offshore grid, there is considerable uncertainty about the extent to which these increases are structural or temporary (EZK, 2023a).

F.5 The transition in the demand sectors: industry, mobility, built environment, agriculture and land use

Industry

A climate-neutral industry requires large-scale use of biofuels, green hydrogen, CO_2-free electricity and recycled plastics

Emissions from existing industrial activities need to be brought down considerably. At the same time, the greater part of the production of non-fossil fuels and feedstocks still needs to be developed. On the other hand, fossil fuel production will decrease sharply and eventually disappear. This may have profound consequences for the structure and spatial distribution of industry in the Netherlands.

There is a large number of different production processes available to produce non-fossil fuels and feedstocks. Bio-based resources and plastic waste can be used as sources of carbon. In addition, hydrogen plays an important role as a resource. New production processes will, in some measure, make use of existing installations, such as crackers in the chemical industry or refineries, but new plants and installations will also be needed.

Recycling of plastics is important to limit the demand for scarce bio-based resources and green hydrogen. This also aligns with the goal of achieving circularity. Recycling can be done by either mechanical means (sorting, grinding and melting) or chemical means (e.g. through pyrolysis). This requires a policy that aims for high-grade use of recyclate, applies the principles of design-for-recycling and conducts research into optimal sorting techniques.

In all pathways towards climate neutrality, industry undergoes large-scale electrification through the use of heat pumps and electric boilers for low- and medium-temperature heat, and — in the somewhat longer term — high-temperature furnaces. As illustrated in the energy flow charts (Figures F.5 to F.9), this leads to an increase in electricity consumption in industry by a factor of at least 2.5 compared to 2019. If electricity for green hydrogen and the synthetic fuels produced from it is added to the calculation, consumption could undergo a six-fold increase.

Importing products based on green hydrogen may make more sense than importing green hydrogen itself

All the integral pathways make the assumptions that the industrial sector will be internationally competitive and that its volume will remain similar to current levels. Many energy-intensive industries ended up in the Netherlands because of its inexpensive energy, but it is by no means clear that this will still be the case in the future. To the extent that energy-intensive industry can use bio-based resources and domestically produced green hydrogen, or fossil energy with CCS, it is quite conceivable that industrial production in the Netherlands will be competitive and stay at the same level. But in the pathways where hydrogen imports are required, that situation might change.

Transporting hydrogen to the Netherlands comes with a great deal of energy losses and high costs, which depend partly on place of origin and mode of transport. Alternatively, the choice could be made to import semi-finished or intermediate products from countries where cheap green hydrogen is available, and then further process them in the Netherlands. This requires less energy and might be cheaper.

Ammonia is a prime example. It can be produced in the Netherlands from hydrogen, but it is also seen as a relatively cheap medium to transport hydrogen. So if hydrogen imports are needed for ammonia production in the Netherlands, it probably makes more sense to import the ammonia itself.

A key concern around the import of hydrogen or hydrogen-based products, is whether and when enough green hydrogen will be produced to meet global demand. Until that moment, and to the extent that own hydrogen production is not sufficient, it may be justifiable to keep the relevant Dutch industrial production operating on the basis of fossil energy and CCS. This would probably be more beneficial in terms of cost and prevents demand of scarce hydrogen that is also needed in other countries for CO_2 emission reductions.

Reducing industrial production by relocating the energy-intensive industries abroad is unlikely to contribute to global emission reductions

Relocating existing energy-intensive industries (e.g. fertilisers, steel, chemicals) abroad — regardless of whether this is motivated by business considerations or policy decisions — is unlikely to contribute to achieving global climate goals in the years up to 2050. It could even be counterproductive if production elsewhere causes more emissions. Relocation of industries because emission-free production is cheaper and more efficient elsewhere is probably something that will only be contemplated in the longer term.

In addition, if the development of new industries related to the production of renewable fuels does not take place in the Netherlands, the associated negative emissions will not be assigned to the country either, while these do play a role in all integral pathways to achieve zero emissions from Dutch territory by 2050.

What actually happens will depend on decisions made by companies themselves. Of course, this in turn depends on policies adopted in the European Union and the Netherlands, for instance those aimed at strategic independence or quality of the local human environment.

Mobility

Electrification is the pertinent solution for climate-neutral road transport in 2050, but the European Union has not yet adopted enough policies to achieve full electrification

Both the sectoral and the integral analysis show that electrification is the preferred option for climate-neutral road traffic. Electrification offers significant advantages: it comes with large efficiency gains, it has the highest supply chain efficiency compared to other sustainability options (biofuels and synthetic fuels), it does not require bio-based resources and green hydrogen, and it is also expected to become the cheapest option over the entire life cycle of vehicles. If the development of battery-electric propulsion systems lags behind, then hydrogen remains relevant as an option for a part of heavy freight traffic, especially for long distances.

The pace of road traffic electrification is mainly dictated by EU policy. Looking at the expected phase-out rate of cars with combustion engines, electrification in 2050 will not yet be 100%. This should not be a problem: by 2050 fuel consumption will not be high anymore and shortly after 2050 full electrification will still be achieved. Cars still running on fuels in 2050 can use climate-neutral fuels, or — probably a cheaper option — fossil fuels whose emissions are offset by negative emissions.

In aviation and maritime shipping, fossil fuels are being replaced by non-fossil alternatives. The use of methanol and ammonia in maritime shipping is uncertain

Efficiency gains can still be made in both aviation and shipping, but sustainability improvements will mainly be the result of replacing fossil fuels with biodiesel, bio-kerosene, synthetic diesel, synthetic kerosene, methanol and ammonia. Aviation will continue to rely largely on kerosene. Sustainability in maritime shipping may be achieved through the use of biogenic or synthetic hydrocarbons, methanol and ammonia.

Climate-neutral methanol and ammonia for maritime shipping can be produced with slightly better supply chain efficiency than climate-neutral hydrocarbons. This means that for a given energy consumption, methanol and ammonia require less use of bio-based resources and hydrogen than hydrocarbons. However, the use of methanol and ammonia requires adjustments to a vessel's engine and to fuel storage installations. It is not certain how fast maritime shipping can make these adjustments. The development of ammonia-fuelled vessels is about 10 years behind the technology using methanol. Even so, focusing on ammonia as a carbon-free fuel seems more robust from the perspective of the system as a whole: the availability of hydrogen is likely to continue to grow in the longer term, beyond 2050, and because ammonia production requires only hydrogen, less of the CO_2 captured in biofuel production needs to be used for synthetic fuel production (CCU), leaving more to go to CO_2 storage.

The lower energy density of methanol and ammonia means the range of maritime vessels is lower, unless their fuel tanks are enlarged. Methanol and ammonia can, in principle, be used with even higher efficiency in fuel cells, but large-scale implementation is not foreseen before 2050.

The production costs of climate-neutral fuels are substantially higher than those of fossil fuels. The scarcity of bio-based resources and hydrogen may push prices up even further. Especially in aviation, it is the energy costs that determine a large part of the ticket price. This will therefore affect the volume of aviation.

In maritime freight transport, costs of shipping and energy represent only a minor part of the prices of the goods. As a result, volume effects are not so likely to occur. On the other hand, displacement effects — that is, refuelling or bunkering outside the Netherlands or the European Union — are actually quite conceivable here.

Built environment

Insulation, district heating and heat pumps are the most important options for climate neutrality in the built environment. Large-scale use of green gas and hydrogen is unlikely

There are wide variations in the costs and benefits of technologies that can make the built environment climate neutral. This is due to local conditions, physical differences between buildings and differences in heating practices. As a result, there is no single natural gas-free heating system that is the cheapest option in all locations. Rather, climate neutrality is achieved through a combination of insulation, standard and hybrid heat pumps, district heating, green gas and hydrogen.

Considering the issue from the sector of the built environment only, the large-scale use of hydrogen and green gas in boilers and hybrid heat pumps seems, at first, to be the most attractive option. The use of these gases is associated with relatively low investments, minimal inconvenience for residents and building occupants, and relatively low production costs, especially in the case of green gas. However, the integral analysis shows that hydrogen and bio-based resources will be so scarce by 2050 that they will be used for other applications for which there are no alternatives, such as the production of liquid fuels and feedstocks and for industrial processes.

Due to the scarcity of hydrogen and green gas, their prices are driven up to above, or even well above, production costs, which means that for most buildings the integral analysis does not find any cost advantage over other sustainability options. District heating, insulation and electric heat pumps to take advantage of ambient heat therefore come into view as the most important sustainability options, despite the higher investments they come with.

Certainty on district heating locations is needed soon to avoid the transition in the built environment becoming even more complex and expensive

Adapting the built environment requires a great deal of time. It involves many actors, and both costs and inconveniences mean it is important to link to natural investment moments, as much as possible. As a result, it is not possible to wait until there is more clarity on technical developments. It is sensible to first focus on actions that are reasonably likely to fit into a robust pathway towards climate neutrality by 2050, or take advantage of any additional replacement moments before 2050. Robust actions include developing promising district heating networks, using standard and hybrid heat pumps that rapidly lower natural gas consumption, taking up post-insulation of the worst-insulated homes and buildings and using natural investment moments for post-insulation.

In many cases, municipal plans to make the built environment more sustainable have not yet been worked out in specific terms. As long as it is not clear which heating technologies will be used in which neighbourhoods, there will be no certainty as to the best sustainability measures property owners can take and how infrastructure requirements will develop. This makes it difficult for citizens, property owners, heat companies and grid operators to take investment decisions. To develop promising district heating networks, it is crucial to have certainty on their locations in the very short term. If achieving certainty takes a long time, it will become more difficult to build those networks because some buildings will already have been adapted for sustainability with insulation and partial or full electrification.

As for hybrid heat pumps, there will be another replacement moment before 2050. In some cases they may be the definite solution if the availability of hydrogen or green gas eventually turns out better than expected, or if new generations of hybrid heat pump systems consume considerably less gas. Otherwise, they can be replaced by fully electric heat pumps. It is also conceivable that part of gas consumption in 2050 will still be covered by natural gas (see for example Figure F.8). In that case there need to be prospects of further gradual reductions of that natural gas use by replacing it with hydrogen or green gas, or by switching to heat pumps.

Agriculture and land use

Greenhouse gas emissions in the agriculture and land use sector are declining, but their ongoing presence in 2050 is inescapable. Offsetting in other sectors is necessary

In the pathways for agriculture, greenhouse gas emissions in the agriculture and land use sector will range between 9 and 12 megatonnes of CO_2 equivalents by 2050, compared to the current volume of almost 23 megatonnes. In 2050, emissions will consist mainly of methane (from animals and manure), followed by nitrous oxide (from manure, fertilisers and soils) and CO_2. In addition, the drainage of peatlands now and in the future will lead to more CO_2 emissions than can be captured and stored in forests and agricultural land within the Netherlands. Agriculture and land use is therefore the only sector where it has become certain beforehand that greenhouse gas emissions cannot be reduced to net zero. It would only be possible if even more substantial interventions in livestock numbers and land use were made than those already assumed in this study. Those emissions must therefore be compensated for elsewhere. For this, we are counting on achieving emission offsets in other sectors, industry in particular, while ensuring they occur *within* the Netherlands.

Achieving substantial emission reductions requires a combination of measures that are employed consistently over a long period of time

A mix of interventions is needed to bring down greenhouse gas emissions from agriculture and land use. These include reductions in the livestock population, changes in land management and fertilisation practices, management measures, such as precision fertilisation and adjustments to dairy cattle rationing, and technical measures, such as modifications to stables. Changes in land use and soil management can only contribute to emission reductions to a limited extent, unless they involve alternative uses of peatlands. Land-use changes in peatlands can prevent further soil subsidence and thereby reduce CO_2 emissions.

The interventions mentioned above lead to improved soil quality through carbon sequestration in agricultural soils. Afforestation can also be beneficial for biodiversity. Both the reduction of the livestock population and the creation of forests and other natural areas require substantial changes in the structure of agriculture. A smaller dairy herd may mean more farming land becomes available for agricultural produce, such as food crops or crops for bio-based resources. Given the nature of many of these measures, it will take a long time to achieve significant reduction effects. It is therefore important to implement consistent long-lasting policies that are based on a clear long-term perspective for agriculture and land use.

Greenhouse horticulture can become more sustainable by combining energy conservation with renewable heat and electrification. Geothermal energy and heat pumps with thermal energy storage provide a heat supply that does not require fuels. This also means that greenhouse horticulture will no longer contain any sources of CO_2. For crops that require CO_2 fertilisation, the CO_2 will have to come from outside the sector.

F.6 Implications for policy

No major contradictions between the integral pathways to climate neutrality in 2050 and EU policy

Until now, relatively few quantitative targets and instruments have been detailed for the period beyond 2030, but broadly speaking we do not see any major contradictions between the cost-optimal implementation of most of the integral pathways and the paths towards solutions that EU policy is focusing on. The pathways with the lower CO_2 storage caps (maximum 30 megatonnes per year by 2050) align most closely with policy. They do not lean that heavily on residual emission offsetting through negative emissions, which is in line with many EU policies that aim to achieve emission reduction within the sectors themselves. In addition, in the early stages, many pathways employ relatively expensive technologies, such as the production of green hydrogen and synthetic fuels. This, too, is consistent with the EU's scaling-up policy, which focuses heavily on these options.

According to the calculations made in this study, the combined greenhouse gas emissions from industry and power generation will be around net zero by 2040 (see Figure F.3), which is in line with the Emissions Trading System (EU ETS1). This does, however, depend in part on offsetting with negative emissions, in areas such as biofuel production. EU policy does not yet have provisions for negative emissions. The reduction in greenhouse gas emissions from aviation and maritime shipping by 2040 calculated in this study is probably large enough to meet the reduction target for the share of emissions covered by the EU ETS1.

The EU ETS2 is the emissions trading system for the built environment, light industry and road traffic. Under the scheme, emissions must reach zero shortly after 2044, when the last allowances are issued. However, the pathways still foresee substantial CO_2 emissions in 2045 from road traffic and especially from the built environment[4] (see Figure F.3). It is unclear whether offsetting with negative emissions from sectors outside the EU ETS2 will be possible, or, if possible, how it would be achieved.

An integral consideration of policies is needed to avoid unnecessarily high costs or delays in the transition to climate neutrality

This study performs an analysis of possible sectoral pathways to climate neutrality that have been examined in an integral analysis of all sectors combined. The analysis presented here shows that formulating policy goals and developing policy instruments for the transition to climate neutrality

[4] It is not possible to make a full one-to-one comparison because the EU ETS2 reduction pathway has been developed on the basis of a European target that is more ambitious — 90% emission reduction by 2040 — than the target set in this study. If we were to develop a more ambitious reduction pathway, the difference would become smaller, but not disappear entirely.

require careful integral consideration. This is important when it comes to, for example, making international aviation and maritime shipping more sustainable and ensuring a timely start of the associated production of climate-neutral fuels. These sectors are currently not included in the national emission targets, but they are a major factor in the formulation of emission reduction policies.

The choices that are made in the agricultural sector determine the volume of its residual emissions and thereby the required volume of negative emissions from the industry sector to compensate for them. The choices are also very important for the amount of bio-based resources that can be supplied nationally. Hydrogen and green gas are needed for applications for which there are no alternatives, and therefore their use in the built environment is not logical, even if it seems attractive from the perspective of the sector itself. The rate at which production and infrastructure for CO_2-free electricity is scaled up is one of the factors in determining how fast road traffic can become climate neutral. These and other examples illustrate the importance of integral consideration.

The uncertainties associated with the transition require flexible and adaptive policies

The transition to a climate-neutral Netherlands in 2050 requires flexible and adaptive policies. It can be counterproductive to strictly adhere to partial or absolute targets, such as a climate-neutral electricity supply by 2035 or a phase-out of all fossil energy by 2050. For instance, imposing a separate target for the electricity sector might lead to the use of BECCS there at the expense of cheaper (BE)CCS projects elsewhere, or it might lead to the use of scarce climate-neutral fuels in the electricity sector.

Flexible and adaptive policies are especially required if the feasibility of meeting targets also depends on factors over which Dutch policy has only limited influence or none whatsoever. These factors include the concrete development of the economic structure, the availability of bio-based resources in the European Union and the scaling up of green hydrogen imports.

In the short term, additional policy is needed to develop markets for climate-neutral energy sources and technologies in a timely manner

The decreasing EU ETS1 and EU ETS2 emission caps are likely to cause the price for CO_2 emissions to rise. While this is a necessary condition for achieving the emission reduction targets, it is not sufficient. Moreover, without additional policy, the CO_2 price might rise to the point of producing damaging secondary effects. For instance, companies may choose to move their operations abroad, or undesirable revenue effects may occur.

A substantial scaling up of energy sources and technologies is needed in the short term. However, such efforts have barely begun in the field of green hydrogen and advanced biofuels, especially those based on woody resources, such as woody crops and woody residues. A market for green hydrogen has yet to be created and the market for advanced bio-based resources, including the associated supply chains, needs to be scaled up substantially.

As for CO_2 storage, the Porthos project[5] is scheduled to be operational by 2026. No investment decision has been taken yet for the much larger Aramis project[6], which should be operational in 2028 or 2029. In addition, CO_2 storage needs to be regulated to ensure optimal use of scarce capacity. In connection with this, an EU policy framework is required to manage negative emissions. Cooperation with neighbouring Member States is advisable in this regard, whether or not in preparation for the formulation of EU policy.

An extensive scale-up relative to current volumes is also required for other energy sources and technologies, such as CO_2-free electricity, plastics recycling and the use of ambient heat. In the case of CO_2-free electricity, the question is whether the current market design and regulatory framework are sufficiently robust to ensure the necessary investments in generation capacity, electricity grids and flexibility options are made in a timely manner, and to distribute their costs fairly.

Many national policies are being carried out for, for example, new nuclear power plants (EZK, 2024), grid reinforcement (EZK, 2023d), construction of district heating networks (EZK, 2023e), CO_2 infrastructure (EZK, 2023b) and scaling up the production of bio-plastics and advanced biofuels (EZK and IenW, 2022; PBL et al., 2024). This study does not explicitly examine the extent to which current and planned policies contribute to achieving climate neutrality by 2050. It is, however, clear that additional policies are needed in the short term to get on track and maintain a steady course. This study provides starting points for further analysis in this regard.

[5] 2.5 megatonnes CO_2 per year; see CO2-reductie door opslag onder de Noordzee - Porthos (porthosco2.nl)

[6] Up to 22 megatonnes CO_2 per year; see Over | Aramis CCS (aramis-ccs.com)

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