Towards a sustainable energy system for the Netherlands in 2050

Impacts of real-world obstacles to transition pathways

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TNO 2025 R12614 – December 2025

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Classification report	
	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	77 (excl. front and back cover)
Number of appendices	0

Executive summary

Motivation

Constructing energy scenarios is a key method for exploring possible transition pathways toward a sustainable, climate-neutral energy system. In 2024, TNO published a study presenting two energy scenarios for the development of the Dutch energy system towards 2050: ADAPT and TRANSFORM. These scenarios were modelled using OPERA, an energy system model that represents the entire Dutch energy system. Based on a limited set of assumptions – kept minimal to avoid excluding potential pathways – the OPERA model calculates the configuration with the lowest societal costs for each scenario.

In practice, however, the energy transition faces numerous obstacles that are often difficult to overcome. These constraints limit the feasibility of the modelled scenarios and raise an important question for this follow-up study: What alternative pathways to a sustainable energy system by 2050 are available if significant obstacles arise during the transition?

Approach

This study assesses the impact of six potential obstacles to the ADAPT and TRANSFORM energy scenarios and explores alternative transition pathways that maintain the lowest possible societal costs for the energy system:
⟩ Inability to deploy or scale-up low-TRL technologies within the energy system, as they are unlikely to mature in time.
⟩ Spatial limitations for renewable energy production, particularly solar and wind.
⟩ Scarcity of critical minerals used for the production of photovoltaic systems, wind turbines, electrolysers and batteries.
⟩ Labour market and/or financial constraints hindering energy efficiency improvements of existing buildings in the built environment.
⟩ Uncertainty about energy, material, and technology costs leading to delays in the energy transition, in particular in the energy and industrial sectors.
⟩ Insufficient progress in implementing flexibility measures in the electricity system, such as demand response.

The study followed the following steps:
⟩ *Translation of constraints*: For each potential obstacle, the limitations were reflected in adjustments to model parameters, e.g. excluding a technology, increasing technology costs, restricting deployment volumes, or modifying capital cost calculations.
⟩ *Scenario recalculation*: The ADAPT and TRANSFORM scenarios were recalculated using the adjusted parameters (the "what-if" cases).
⟩ *Comparison*: The outcomes related to energy supply, consumption and technology deployment from the what-if cases were assessed against the ADAPT and TRANSFORM baseline scenarios.
⟩ *Synthesis*: General findings and conclusions were drawn based on these comparisons.

Because of current limitations in the OPERA model, potential constraints related to the expansion and reinforcement of the electricity grid have not been analysed. TNO is working on improving the model to provide a more accurate representation of grid infrastructure.

Findings

The what-if analyses reveal several valuable insights:

⟩ **Achieving a sustainable Dutch energy system by 2050 requires the availability of innovative technologies and the ability to produce sufficient sustainable energy.** The future Dutch sustainable energy system relies heavily on TRL 6, TRL 7[1], and several essential TRL 5 technologies, which still require further development and scaling-up. If the renewable electricity production is limited a sustainable Dutch energy system, under the given demand assumptions, will only be viable if supplemented by alternative renewable sources, such as imported biofuels.

⟩ **Future technology costs remain uncertain, and altering cost assumptions in a cost-optimized energy system results in different transition pathways.** Three what-if analyses illustrate this, sometimes producing similar outcomes, but also notable differences:

  ▪ Higher capital costs across all technologies particularly impact capital-intensive options such as nuclear energy, favouring less capital-intensive alternatives and reshaping the final energy mix.

  ▪ Increased investment costs for renewable electricity, hydrogen, and batteries, primarily influence electricity and hydrogen production and, consequently, end-user energy mixes.

  ▪ Higher flexibility costs raise electricity costs, prompting diversification toward lower-cost supply options.

In all these what-if analyses changes in electricity and hydrogen costs also affect import and export volumes.

⟩ **There are cascading effects caused by the strong interdependency between the subsystems electricity, hydrogen, sustainable fuels and carbon.** For example, in one scenario, limiting biofuel production leads to an increase in synthetic fuel production, which subsequently demands more hydrogen and electricity. At the same time, limited biofuel production reduced the amount of CO_2 captured from the process, which makes the system more reliant on direct air capture (DAC) of CO_2. In another case, limiting renewable electricity production reduces domestic hydrogen production, which lowers synthetic fuel production and shifts the mix toward biofuels, fossil fuels, and ammonia as marine fuel.

⟩ **Constraints on renewable electricity supply or available technologies drive greater reliance on renewable heat and more efficient energy use.** For instance, limiting renewable electricity production leads to a shift toward renewable heat sources. Similarly, the shift of electricity usage toward hydrogen production results in increased renewable heat use in buildings, supported by energy-efficient heat pumps.

⟩ **Different boundary conditions for the scenarios lead to varying, and sometimes contradictory, responses to imposed constraints.** The ADAPT scenario, with its less ambitious sustainability goals, allows more flexibility for alternative transition pathways compared to the more ambitious TRANSFORM scenario. For example, the systemic sensitivity to critical mineral constraints is higher in a more CCS and fossils reliant scenario (ADAPT) and lower in higher renewable strongly electrified system (TRANSFORM), indicating that deep electrification can mitigate, but not eliminate, costs increases due to mineral supply scarcity. Conversely, TRANSFORM's higher sustainability ambitions can amplify some of the responses observed in ADAPT.

⟩ **Constraints in end-user sectors primarily affect the composition of the final energy mix**. For instance, higher energy demand caused by less home insulation can be offset through more efficient energy use (such as increased adoption of heat pumps) thereby reducing its impact on overall energy supply.

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[1] IEA TRL scale 1-11

Conclusions

The following key conclusions can be drawn from this study:

〉 To enhance the policy relevance of scenario studies, it is essential to account for real obstacles to the energy transition. Transition pathways toward a climate-neutral energy system, derived from exploratory scenarios with a limited number of preconditions and based on cost-optimisation modelling, may overlook real-world bottlenecks. Introducing additional constraints uncovers alternative pathways to a climate-neutral energy system in 2050, while also identifying technologies and supply options that are critical for achieving climate neutrality. In some cases, policy measures can address the bottleneck (e.g. spatial limitations), but in other cases (e.g. scarcity of critical minerals), insight into possible alternative transition pathways may be relevant for energy and climate policy.

〉 Scenarios outline possible futures that combine societal and political preferences with external factors such as the international context. A scenario where the transition to a sustainable energy system progresses more slowly (e.g., ADAPT) tends to be more resilient to emerging obstacles (e.g. critical minerals scarcity or spatial limitations) than one where the transition occurs more rapidly (e.g., TRANSFORM).

〉 If obstacles emerge during the energy transition and the objective remains to achieve a cost-optimized sustainable energy system, it must be acknowledged that such limitations will require adjustments across multiple subsystems.

〉 Energy supply constraints may necessitate adjustments in demand sectors, such as implementing energy efficiency measures. The reverse effect, i.e. constraints on end-user technologies, has a less pronounced impact on energy supply, as end-user sectors often have alternative solutions of their own to mitigate constraints.

Contents

1 Introduction

Context and motivation

The Dutch government has set ambitious targets for reducing greenhouse gas emissions and transitioning the national energy system, as outlined in the Climate Act (Ministry of EZK, 2019a) and Climate Agreement (Klimaatakkoord, 2019). The Ministry of Climate and Green Growth has also developed a strategy to transition towards a climate-neutral energy system (Ministery of KGG, 2023). However, the energy transition is confronted with several obstacles, such as cost-increase of off-shore wind and electrolysis for green hydrogen production. Additionally, it faces setbacks including rising investments in energy infrastructure, as well as delays in the scaling-up of technologies for producing green hydrogen, green methane, biofuels, and e-fuels. As a result, the emission reduction targets may become unattainable (PBL, 2025).

In 2024, TNO published an update of the ADAPT and TRANSFORM scenarios (Scheepers, et al., 2024). These scenarios outline transition pathways toward a climate-neutral energy system for the Netherlands by 2050. The transition pathways have been calculated based on assumptions regarding technological availability and anticipated future costs using the OPERA model. However, they do not explicitly account for obstacles that may emerge during the implementation phase. This raises the question of whether the climate targets are still achievable when such constraints are considered. Or are there alternative transition pathways to a climate-neutral energy system by 2050?

Objective and approach

As a follow-up to the 2024 scenario study, TNO examined the effects of various constraints and limitations on the feasibility of achieving a climate-neutral energy system. The central question guiding this study is: What alternative pathways to a sustainable energy system by 2050 are available if significant obstacles emerge during the energy transition?

This study was conducted by performing six what-if analyses for the ADAPT and TRANSFORM scenarios using the OPERA model. The following constraints and limitations were examined in the study:
1. Inability to deploy or scale-up low-TRL technologies within the energy system, as they are unlikely to mature in time.
2. Spatial limitations for renewable energy production, particularly solar and wind.
3. Scarcity of critical minerals used for the production of photovoltaic systems, wind turbines, electrolysers and batteries.
4. Labour market and/or financial constraints hindering energy efficiency improvements of existing buildings in the built environment.
5. Uncertainty about energy, material, and technology costs leading to delays in the energy transition, in particular in the energy and industrial sectors.
6. Insufficient progress in implementing flexibility measures in the electricity system, such as demand response.

Due to limitations in the OPERA model, no what-if analyses were conducted for increased grid costs or insufficient expansion and reinforcement of the electricity infrastructure. TNO is currently working on enhancing the model to better represent grid infrastructure.

Report structure

This report is structured as follows: Chapter 2 explains the methodology. It describes the Dutch energy and greenhouse gas systems, as well as the OPERA model applied. The two baseline scenarios are also introduced in this chapter. Chapter 3 discusses the rationale behind the what-if analyses explored in this study and the parameterisation of the real-world obstacles. Chapter 4 presents and discusses the results of the what-if analyses in detail. Chapter 5 provides a general discussion of the findings and methodological limitations and concludes with several key observations.

2 Methodology

This study builds upon the findings of the TNO energy scenario report (Scheepers, et al., 2024) to explore alternative what-if scenarios considering additional constraining factors surging in the real world. For that, the OPERA model is used to find the characteristics of these potential Dutch energy systems, and analyse the differences with the baseline ADAPT and TRANSFORM scenarios of the previous scenario study. This Chapter is structured as follows: Section 2.1 provides a description of the scope of the Dutch energy and greenhouse gas (GHG) emission systems considered in the study. These systems are modelled in the OPERA model, a brief description of which is given in Section 2.2. In the 2024 scenario study the Dutch energy system is calculated using the OPERA model for two baseline scenarios: ADAPT and TRANSFORM. These are explained in Section 2.3, including their parameterization.

2.1 Dutch energy system

This study examines the Dutch energy and GHG emission systems, including energy production and CO_2 storage in the Dutch part of the North Sea as well as GHG emissions related to land use. The energy system considered is schematically shown in **Figure 2.1**. This energy system includes energy production (e.g. electricity and fuel production), but not the extraction of fossil fuels. Primary fossil fuels (oil, natural gas, coal) are provided externally from domestic and foreign sources.

Various end-use sectors are distinguished within the energy system: industry, built environment, agriculture and transport. The energy system also includes the demand for hydrocarbon feedstock, as well as demand for bunker fuels used for international aviation and shipping. All techniques used for production, conversion, transport & storage, and use of energy, such as industrial production installations, heating installations and transport vehicles, but also CO_2 pipelines and energy saving technologies are part of the energy system. However, aircraft and seagoing vessels for international aviation and shipping are not included as technologies within the system boundary; only their fuel demands and related emissions are considered.

The Netherlands can import various hydrocarbon feedstocks and commodities via seaports, such as fossil fuels, biomass[2], plastic waste, biofuels, ammonia and bio-naphtha. Energy imports and exports are also possible from neighbouring countries via pipelines and interconnectors of the electricity network. Fossil fuels, biomass and electricity are used for the production of hydrocarbons and hydrogen which are ultimately utilised as feedstocks in manufacturing fertilisers, chemicals and plastics. It should be noted that the Dutch energy system produces liquid fuels for international aviation and shipping that are refuelled in the Netherlands (bunker fuels) and for export to other countries around the world. Based on international agreements, the Netherlands is currently responsible for greenhouse gas emissions from the subsectors within the energy system and from land use, but not for greenhouse gases from international aviation and shipping to and from the Netherlands. For this analysis however, separate targets for these bunker fuel greenhouse gas emissions are

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[2]   In this report, the term 'biomass' is used for primary energy and in case of direct energy use, the term 'biofuel' is used when biomass is converted into a liquid fuel and the term 'bio-feedstock' when biomass is used for production of chemicals and plastics.

included.
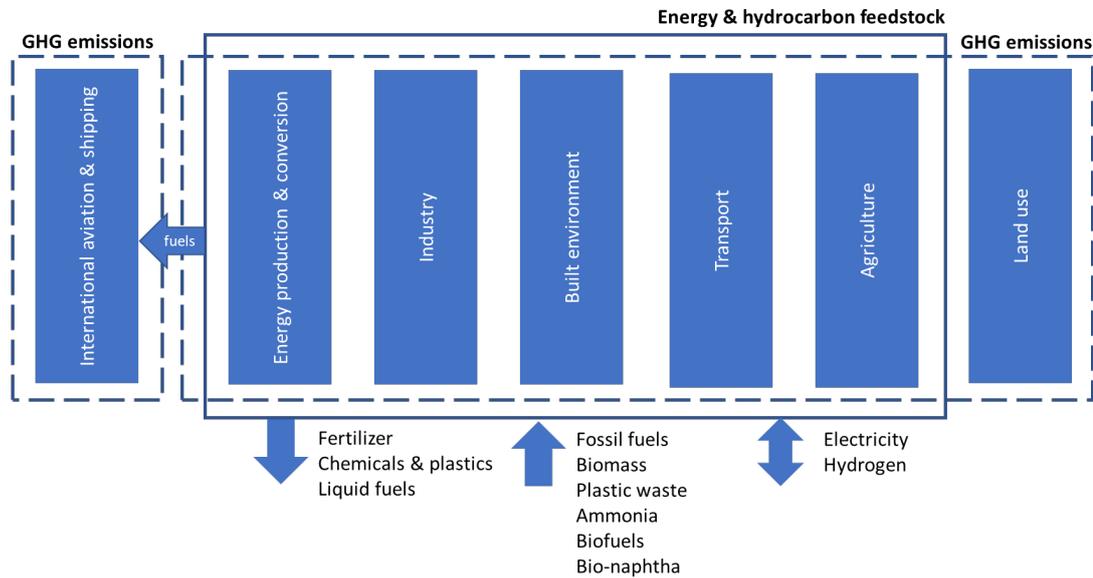
Figure 2.1: Schematic representation of the energy and greenhouse gas emissions system.

2.2 OPERA model

The OPERA model is an integrated energy system optimisation model for the Netherlands. It optimises the Dutch energy system for a given year for the lowest system cost, while meeting the energy demand and realizing industrial production under certain preconditions (e.g. maximum GHG emissions), see **Figure 2.2**.
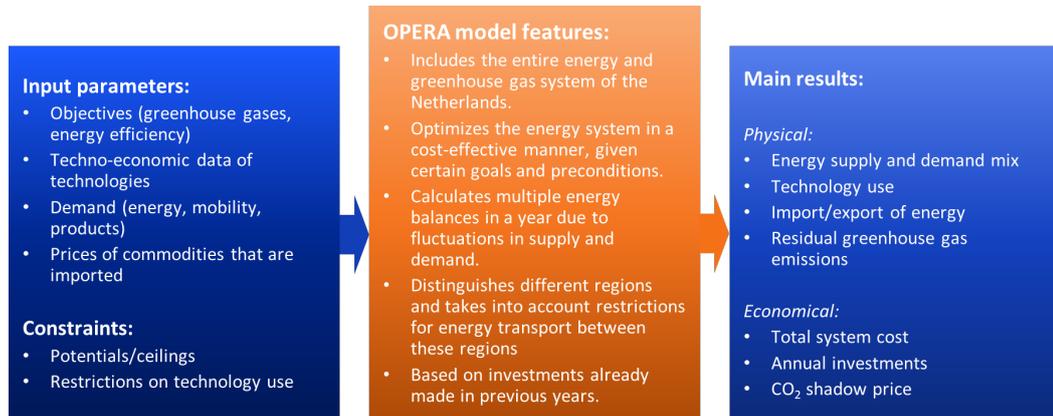
Figure 2.2: Inputs, outputs and model features of the OPERA model.

The model calculates endogenously the technology deployment and energy mix (both supply and demand), determined by the model's optimisation algorithm. The model uses social costs based on investment and operating costs for the entire energy system (excluding subsidies and taxes) and the cost balance of energy imports and exports[3].

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[3]   In practice, market parties will want to pursue their own maximum benefit when making investment and operational decisions and not the desired optimum for society as a whole. Good market design, regulation and

The main input parameters that OPERA uses are:
- ⟩ Scenario boundary conditions: e.g. maximum GHG emissions and/or maximum energy use.
- ⟩ Annual demand for energy and mobility and annual production of certain industrial products.
- ⟩ Techno-economic data (costs, technology performance) for technologies and options, including mitigation and saving options..
- ⟩ Availability and price of imported feedstocks and commodities.
- ⟩ Certain restrictions on the use of technologies.
- ⟩ Hourly curves for supply (wind, solar) and demand (electricity, heat and, hydrogen).
- ⟩ Exogenous assumptions on import and export of electricity and hydrogen.

The model is a representation of the energy system as described in Section 2.1. The model distinguishes different regions in the Netherlands: 7 regions on land (each of the national industry clusters falls in a separate region) and 7 regions on the North Sea with distinctive wind regimes and distances to the coast (see **Figure 2.3**). The model also accounts for fluctuations in energy demand and supply. For each subsequent year for which an energy system is calculated, the model accounts for existing assets from the previous period based on the technical lifetime of these assets. The model determines whether additional capacity needs to be invested in to meet demand[4]. A more detailed description of the OPERA model can be found in (Stralen, Dalla Longa, Daniëls, Smekens, & Zwaan, 2021).
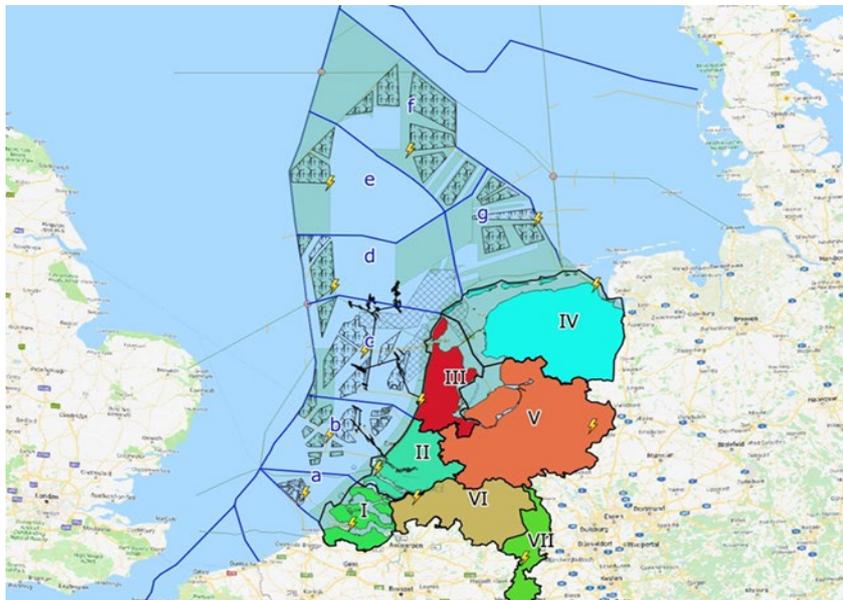
Figure 2.3: Regions distinguished by the OPERA model.

Large industry in the Netherlands is concentrated in five industrial clusters, see **Table 2.1**. These industrial clusters largely coincide with the regions in the model, with the exception of Noord-Brabant. The industry in West-Brabant around Bergen op Zoom is included in the

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policy can provide guidance, but there will never be perfect information and coordination. As a result, the energy system that is calculated for the lowest social costs will be difficult to realise in practice.

[4] It is possible to have investments determined by the OPERA model at the lowest social costs over the entire period (i.e. 2030-2050), i.e. with perfect foresight. However, in practice, the future for investors is uncertain. In this study, the energy system is optimized per year and not over the entire period (myopic). In principle, this will lead to higher system costs.

Zeeland region and the industry in Moerdijk in the Zuid-Holland region. Other end-use sectors (built environment, agricultural sector, mobility) are also distributed across these regions.

Table 2.1: Industry clusters in the OPERA model

Region	Indicated in OPERA	Industry cluster[5]
I	Zeeland	Zeeland-West Brabant
II	Zuid-Holland	Rotterdam-Moerdijk
III	Noord-Holland	Noordzeekanaal
IV	Noord-Nederland	Noord-Nederland
V	Midden-Nederland	-
VI	Noord-Brabant	-
VII	Limburg	Chemelot

The model produces physical and economic results of the future energy system:
› Physical results:
  − Mix of energy supply and demand (total and per sector).
  − Technologies used (e.g. installed capacity, full load hours).
  − Import and export of energy (e.g. fossil energy, biomass, electricity, hydrogen).
  − Residual greenhouse gas emissions.
› Economic results:
  − System costs (total and per sector).
  − Annual investments (total and per sector).
  − Sadow prices (based on marginal costs for CO_2 reduction and production of electricity and hydrogen).

For the 2024 scenario study, the exchange of electricity and hydrogen between the Netherlands and eight countries in Northwest Europe (Belgium, Denmark, France, Germany, Ireland, Sweden, Norway and UK) was determined with the energy market model COMPETES-TNO (Sijm, Morales-Espana, & Hernández-Serna, 2022).The resulting electricity and hydrogen demand and production capacities of relevant options from OPERA were fixed in COMPETES-TNO to model the European flow trade dynamics. COMPETES-TNO produced hourly import and export flows and border prices for electricity and hydrogen, which were then used in the OPERA model.

2.3 Scenario analysis

Possible transition pathways to a sustainable Dutch energy system are analysed in the following steps:
› First, the base scenarios ADAPT and TRANSFORM are recalculated using some updated parameters and model improvements from the 2024 study.
› Next, what-if analyses are conducted by changing assumptions and preconditions (see Chapter 3 for a detailed explanation).
› Finally, the outcomes of the what-if analyses are compared to the base scenarios, with results presented in Chapter 4.

This section describes the base scenarios and the assumptions underlying them.

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[5] As indicated in Cluster Energy Strategies (CES) 2022.

ADAPT and TRANSFORM
The Netherlands has the ambition to reduce greenhouse gas emissions by 55% by 2030 and to achieve greenhouse gas neutrality by 2050. In the TNO 2024 scenario study (Scheepers, et al., 2024), two different future transition scenarios for the Dutch energy system are drawn to achieve these goals: ADAPT and TRANSFORM.

The assumed population growth and the development of the overall Dutch economy, with an annual GDP growth of 1.7%, are equal in both scenarios. The differences reside in the intrinsic motivation and support for the energy transition among governments, citizens, and companies. Box 1 summarizes the fundamental divergences between ADAPT and TRANSFORM.

Box 1 – Visions for the future (storylines)

ADAPT
- *The Netherlands and EU will meet 2030 and 2050 GHG reduction targets.*
- *Society values the current lifestyle.*
- *EU countries have their own policies for achieving GHG reductions.*
- *Industrial production and the economic structure remain basically the same.*
- *National and local governments take the lead.*
- *Adapting and optimising the energy system and industrial processes.*
- *There is a planning for structural change post 2050.*
- *To abate CO_2 emissions, fossil fuels are expected to be utilised in combination with carbon capture and storage (CCS).*

TRANSFORM
- *The Netherlands and EU will meet 2030 and 2050 GHG reduction targets.*
- *Society values environmental awareness and has a sense of urgency.*
- *The Netherlands and EU want to become an innovative power house.*
- *Individual and collective action by civilians.*
- *Civilians take significant actions, while the government has a stimulating and enabling role.*
- *There is an ambitious transformation of energy system and the energy-intensive industry.*
- *Demand reduction due to lifestyle changes results in lower industrial production, animal husbandry, international travel and energy use.*
- *A limited use of CO_2 storage.*

Scenario parameters
The scenarios are parameterised across four main categories: energy demand, commodity prices, techno-economic characteristics of technologies, and boundary conditions. The following paragraphs outline these parameters for the ADAPT and TRANSFORM scenarios. A more detailed description of the parameterisation for both scenarios is available in (Scheepers, et al., 2024).

Energy demand
One key aspect of the scenarios is the future energy demand. The energy demand for various end-user sectors is determined by the OPERA model based on the size of activities (i.e. service demand), such as the number of homes, the floor area offices and commercial buildings, passenger and freight kilometres and production of industrial products. This

information is supplemented with energy demand data for a number of other activities. The input parameters are derived from projections of the Climate and Energy Outlook 2022 (Klimaat en Energieverkenning, 2022).

To reflect the assumed behavioural changes in the TRANSFORM scenario, a decrease in mobility demand, a lower industrial production in most energy-intensive industrial subsectors, and a lower agriculture production are assumed compared to ADAPT. To compensate for lower economic activity in industrial and agricultural sectors, TRANSFORM assumes that the service sector will become larger than in the ADAPT scenario.

Energy imports, exports and prices
With the exception of some natural gas in 2030 and possibly in 2035[6], fossil fuels are imported. The prices for fossil fuels are based on advice from the European Commission (European Commission, 2022). Prices for different types of biomass are taken from the Climate and Energy Outlook 2022 (Klimaat en Energieverkenning, 2022). Prices used for biofuels (biodiesel and bioethanol) are assumed to be constant over the period considered and correspond to data from the AdvanceFuel project[7].

Electricity can be imported or exported based on the electricity price determined by the OPERA model for the Dutch energy system, compared to prices in neighbouring countries connected via interconnectors, as calculated by the COMPETES-TNO model. These exchanges can vary hourly but are constrained by the interconnector's capacity, which is expected to increase in the coming years. It is assumed that an international hydrogen market will develop, enabling imports and exports through transport pipelines with Germany and Belgium. These flows will depend on market price differences between the Netherlands and its neighbouring countries. The OPERA model determines the hydrogen price for the Dutch system, while prices in neighbouring countries are calculated using the COMPETES-TNO model. In the ADAPT and TRANSFORM scenarios, limited imports of ammonia and e-methanol via seaports are allowed, but no imports of biofuels or hydrogen are assumed. Prices for green ammonia and e-methanol are derived from a HyDelta study (Hajonides van der Meulen, Scaric, Tyraskis, & Verstraten, 2022).

Boundary conditions
For both scenarios, two different types of conditions are defined:
〉 GHG emissions constraints. In both scenarios, the same GHG reduction targets are defined (see Table 2.2), with a reduction target of 55% in 2030 and carbon neutral by 2050 (Ministry of EZK, 2019a). Some characteristics of this boundary condition are:
  − The GHG of international aviation and shipping are out of scope of the Dutch domestic reduction target. The extent to which sustainable fuels are part of bunker fuels in the Netherlands is influenced by GHG reduction measures for these sectors. TRANSFORM assumes that GHG emissions in 2050 for international aviation and shipping are reduced by 100%, with a 2040 reduction target of 53% for international aviation and 70% for maritime shipping. ADAPT assumes a less ambitious GHG reduction: 50% in 2050 and a reduction target in 2040 of 30% for international aviation and 45% for maritime shipping.
  − To make carbon in feedstocks more sustainable, a target for the share of sustainable carbon (i.e. biogenic or atmospheric carbon) is imposed. This share is 5% in 2030 for

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[6] The OPERA model considers imported and domestically produced natural gas as exogenous supply to the energy system and does not distinguish between them.
[7] See: http://www.advancefuel.eu/

both scenarios. In TRANSFORM it increases to 80% in 2050. In ADAPT, the target is abandoned after 2030.

- In TRANSFORM the GHG emissions of the Dutch ETS sector are zero form 2040 onwards, as a result of the tightening of allowances proposed by the European Commission (European Commission, 2023). For ADAPT no specific target is applied for the ETS sector.

› Technology restrictions representing limitations on the deployment for certain technologies (see Table 2.3). This are comprised in the scenarios as:

- Deployment restrictions for wind onshore, wind offshore, solar PV and geothermal energy. These restrictions relate to when a technology becomes available, a realistic growth rate, and physical or policy limitations.
- In accordance with current policy, CO_2 storage can be used to a limited extent in 2030 in both the ADAPT and the TRANSFORM scenarios. In the ADAPT scenario an increase in CO_2 storage is permitted. In the TRANSFORM scenario, CO_2 storage is permitted to be used for carbon removal (negative emissions) to compensate for emissions of activities that are difficult to reduce (e.g. emissions from non-CO_2 greenhouse gases, non-energy CO_2 emissions and GHG emissions of land use).
- The amount of domestically available biomass is insufficient to meet the demand for biofuels and bio-based feedstocks. Therefore, in addition to the domestically available biomass, biomass import is assumed at a maximum. This maximum is based on a study of various potential estimates, see (Scheepers, et al., 2024).
- From 2030, coal-fired power plants can no longer be used (Ministry of EZK, 2019b).

Techno-economic parameters
The OPERA model has a technology portfolio with approximately 600 technology options for production, conversion, transport, and use of energy; techniques for capturing, transporting and storing CO_2, and other CO_2 sequestration technologies; and energy saving options. The techno-economic data for these options are retrieved from a database containing current data and projections for parameter values in 2030 and 2050. A full list of this data can be found in (Scheepers, et al., 2024). The performance and cost parameters for 2030 and 2050 take into account technology learning in an exogenous manner, i.e. cost reduction and performance improvement as results of R&D and technology deployment. For technologies with learning potential for which the learning rate is unknown, an investment cost reduction of 20% is assumed between 2030 and 2050. It is assumed that the technology costs and development are the same in both scenarios. Given this, OPERA calculates a cost-optimal energy system selecting from this technology catalogue.

Parameter updates and model improvements
For this study, the base ADAPT and TRANSFORM scenarios from (Scheepers, et al., 2024) have been updated regarding the following aspects:

› Cost parameters and the inputs/outputs for the stand-alone Direct Air Capture (DAC) technology have been updated.
› The option 'Aromatics production via biomass' has been updated for both costs and the inputs/outputs. This option no longer has an output of captured CO_2.

Table 2.2: GHG emissions constraints

	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
GHG reduction target (wrt 1990)	%	55% [a]	70%	80%	90%	GHG neutral[a]	55%[a]	70%	80%	90%	GHG neutral[a]

GHG emissions international transport
    Aviation (% reduction wrt 2005)
    Shipping (% reduction wrt 2008)
	Mt CO_2eq	10.7[b]
		
		34.4[b]
			9.4
			
			32.5
				8.1
				
				30.5
					6.2
					
					28.6
						5.5 (50%)
						26.7 (50%)
							9.2[b]
							
							31.2[b]
								6.9
								
								23.4
									4.6
									
									15.6
										2.3
										
										7.8
											0 (100%)
											0 (100%)

Circular carbon target for production of chemicals	%	5%[c]	0%	0%	0%	0%	5%[c]	20%	40%	60%	80%

[a] Climate Act 2023

[b] Based on a 6% share of renewable and low-carbon fuels (European Commission, 2023), (European Commission, 2021)

[c] This non-fossil criterium is added in line with policy described in (Ministerie van Infrastructuur en Waterstaat, 2023)

Table 2.3: Technology restrictions

	Unit	ADAPT					TRANSFORM				
		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
Wind energy potential Onshore Offshore	GW	7.8 16[a]	7.8 26	7.8 36	7.8 38	7.8 40	7.8 16[a]	8.9 30.5	10 45	11 57.5	12 70[c]
Solar energy potential (PV)	GW	36.6[b]	52.7	68.6	88.8	109.0	42.9[b]	64.7	83.6	107.7	132.1
Nuclear capacity Borssele[d] New nuclear power potential Large Gen III SMR	GW	0.5	0.5 1.5	0.5 3 0.45	 4.5 0.9	 6 2.1	0.5	0.5 1.5	0.5 3 0.45	 4.5 0.9	 6 2.1
CO$_2$ storage potential Industry Power generation	Mt	9.7[e] 3[e]	24	35	40[f]	40[f]	9.7[e] 3[e]	12.7	12.7	12.7	15[g]
Geothermal potential[h]	PJ	50	88	125	163	200	50	88	125	163	200
Biomass potential Domestic Import [i]	PJ	164 83.4	183 225	202 366	221 508	241 650	164 83.4	175 225	186 366	198 508	209 650

[a] 6 GW additional to Climate agreement.

[b] Monitor RES 1.0 (PBL, 2021).

[c] 70 GW wind offshore is based on (Matthijsen, Dammers, & Elzinga, 2018). An other study by Taminiau and Van der Zwaan calculates a physical potential up to 99 GW (Taminiau & van der Zwaan, 2022).

[d] For Borssele a long term operation (LTO) of 10 years is assumed after 2033.

[e] Climate agreement, 2.5 Mt additional for industry (2022). However, the subsidy ceiling in the SDE++ expired in 2023, i.e., de facto there is no maximum.

[f] The potential is derived from the total available storage capacity of 1,600 to 1,700 Mt in the Dutch part of the North Sea (Joint Fact Finding CO$_2$-afvang en -opslag, Klimaattafel, 2018).

[g] Potential needed for sufficient negative emissions.

[h] Based on (Platform Geothermie, 2018).

[i] TNO own assessment based on the recent DG RTD study (EC, 2024). The assessment approach can be found in (Scheepers, et al., 2024)

3 What-if scenarios

To assess the impact of potential bottlenecks in the transition of the Dutch energy system, six distinct what-if scenarios have been selected for this study. These scenarios enable the exploration of alternative pathways that may diverge from the ADAPT and TRANSFORM scenarios, taking into account possible constraints and limitations. This chapter outlines the rationale behind the what-if analyses and explains the parameterisation of each scenario. A comparison of the what-if results with the ADAPT and TRANSFORM scenarios is presented and discussed in Chapter 4.

3.1 Limited availability of innovative technologies

For a technology to be adopted at scale within the energy system, it must reach a certain level of maturity. This can be assessed using the Technology Readiness Level (TRL), either according to the EU scale (TRL 1 to 9) or the ETP Clean Energy Technology Guide (TRL 1 to 11) (IEA, 2020), (IEA, 2024), see **Figure 3.1**. If the technology has a low TRL at present, there is a risk that this technology will not be fully developed and ready to be scaled up in time for its expected deployment between 2030 and 2050. Both the EU and IEA scales go from level 1 (initial idea) to 9 or 11: proof of stability reached, and has become a mature commercially deployed technology for which a growth path can be predicted.
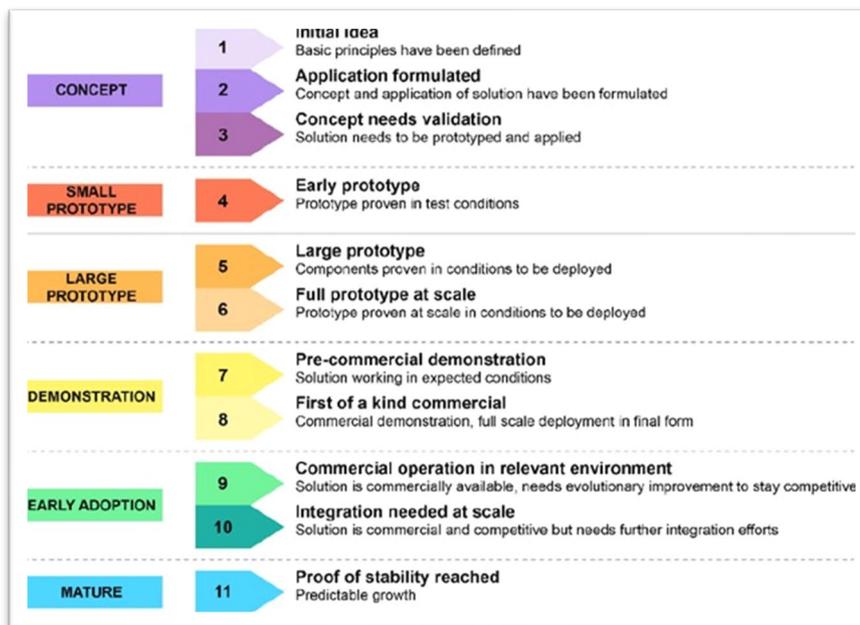
Figure 3.1: Technology readiness level (TRL) scale applied by IEA (IEA, 2020).

In this study, the IEA ETP Clean Energy Technology Guide (edition 2024) is used to assess the TRL of innovative energy and emission reduction technologies in the OPERA technology database because the IEA provides TRLs for individual technologies. The focus of the technologies was on those applied in industry, energy supply, and fuel conversion sectors.

Even though the IEA Technology Guide also contains TRLs for technologies in end-use sectors such as the built environment and transport, these TRLs were not part of this study.

To determine which technologies (options) in the existing OPERA database are not yet market ready or sufficiently developed to make a substantial contribution to the transformation of the energy system (i.e. TRL 5 or less), a comparative analysis is made with the IEA Clean Energy Technology Guide based on the latest year that a TRL is reported (IEA, 2024). This is executed in a two-step approach:
1. A match is made between the OPERA technology database and the IEA Clean Energy Technology Guide to determine which of the OPERA technologies have a TRL of 5 or less, and those with a TRL between 6 and 7. This match is based on the sector defined and technologies listed both in the Guide and in OPERA.
2. The matched technologies are reviewed as the technology description by IEA does not always correspond one-to-one to the OPERA database nomination. Some background reports in the Guide served as basis for this review to better understand what is covered by the technologies listed in both databases. However, any bias in the linking of technologies in both databases cannot be fully excluded.

In the first what-if scenario, technologies that have a TRL of 5 or less on the IEA scale are excluded from 2030 onwards. It is assumed that these technologies do not become fully mature in time for full-scale deployment before 2050. Also, technologies with a TRL of 6 or 7 on the IEA scale that appear in the what-if scenario results as installed technologies for the years 2030 and 2035 are identified. These technologies are classified as 'critical technologies' and are subject to a qualitative assessment only; no additional what-if analyses are conducted for them.

The above exercise results in the technologies listed in **Table 3.1** with low TRL (i.e. 5 and lower), and in **Table 3.2** with TRL 6 or 7.

Table 3.1: Technologies in OPERA database with TRL 5 or lower, based on the IEA scale (IEA, 2024)

Sector	Type	Technology name	TRL 2024 IEA scale[a]
Industry – Cross-cutting industry	Industrial heat – High temperature heating	Electric arc and plasma arc furnaces (high temperature heating)	3
Industry – Iron and steel	Blast furnace	Chemical absorption – Process gas hydrogen enrichment and CO_2 removal for use or storage (blast furnace)	5
Industry – Iron and steel	Ore electrolysis	Low temperature electrolysis (<110 ºC)	4
Industry – Iron and steel	Ore electrolysis	High temperature molten oxide electrolysis (>1500 ºC)	5
Industry – Chemicals and plastics	Ethylene	Lignocellulosic gasification (ethylene)	5
Industry – Chemicals and plastics	High value chemicals	Steam cracker electrification (high value chemicals)	5
Industry – Aluminium production[b]	Primary smelting	Primary smelting with multipolar cell	5
Industry – Aluminium production	Primary smelting	Primary smelting with CCUS	3
Electricity generation	Biomass with CCUS	Pre-combustion: physical absorption (biomass with CCUS)	3
Hydrogen production	Biomass with CCUS	Biomass-waste gasification with CCUS	5
Hydrogen production	Methane reforming	Sorption enhanced steam reforming with CCUS (methane)	4
Hydrogen production	Methane reforming	Single reformer (methane)	5
Hydrogen production	Thermochemical water splitting	Solar (water splitting)	4
Hydrogen production	Photocatalytic water splitting	Photocatalytic water splitting	5
Hydrogen production	Ammonia cracking	Ammonia cracking	4
Refining	Fluid catalytic cracker	Post-combustion carbon capture (cracking)	4
Refining	Process heater	CCUS using post-combustion capture (process heater)	4
Biofuels production	Bioethanol	Enzymatic fermentation with CCUS (lignocellulosic bioethanol)	5
Biofuels production	Biodiesel and biokerosene	Gasification and Fischer-Tropsch with CCUS (biodiesel)	5
Biofuels production	Bioethanol	Lignocellulosic ethanol production	5
Biofuels production	Bioethanol	Lignocellulosic ethanol production with CC	5

[a] The highest level is utilized when a range is provided in the TRL 2024 IEA scale.

[b] The OPERA model contains processes and technologies related to the aluminium industry in both ADAPT and TRANSFORM scenarios, however there is no production demand for aluminium in the Netherlands after 2030.

Table 3.2: Technologies in OPERA database with TRL 6 and 7, based on the IEA scale (IEA, 2024)

Sector	Type	Technology name	TRL 2024 IEA scale[a]
Industry – Cross-cutting industry	Industrial heat – High temperature heating	Hydrogen (high temperature heating)	7
Industry – Iron and steel	Direct reduced iron	Based on 100% electrolytic hydrogen (DRI)	6
Industry – Iron and steel	Smelting reduction	CCUS (smelting)	7
Industry – Iron and steel	Direct reduced iron	Improved ore refining methods (DRI)	6
Industry – Chemicals and plastics	High value chemicals	Chemical absorption (high value chemicals)	7
Industry – Chemicals and plastics	Methanol production	CO_2- and electrolytic hydrogen-based produced with variable renewables (methanol)	7
Industry – Aluminium production	Primary smelting	Primary smelting with inert anode	7
Electricity generation	Coal with CCUS	Pre-combustion: physical absorption (coal with CCUS)	7
Electricity generation	Biomass with CCUS	Post-combustion: chemical absorption (biomass with CCUS)	7
Electricity generation	Hydrogen	Pure hydrogen	7
Electricity generation	Nuclear	Light water reactor-based small modular nuclear reactor	7
Hydrogen consumption	Hydrogen blending in natural gas network	Hydrogen blending in natural gas network	7
Hydrogen production	Biomass	Biomass-waste gasification without CCUS	6
Hydrogen production	Methane reforming	High capture rates (steam reforming)	6
Hydrogen production	Partial oxidation with CCUS	Partial oxidation with CCUS	6
Hydrogen production	Methane pyrolysis-cracking	Catalytic decomposition (methane)	6
Biofuels production	Biodiesel and biokerosene	Pyrolysis and upgrading (biodiesel)	7
Biofuels production	Biodiesel and biokerosene	Alcohol-to-jet (biodiesel)	7
Liquid fuels production	Synthetic hydrocarbon fuels	CO_2 reduction	6
CO_2 capture	Direct air capture	Solid DAC (S-DAC)	7

[a] The highest level is utilized when a range is provided in the TRL 2024 IEA scale.

3.2 Spatial limitations

In the Netherlands, where available land is scarce and densely utilized, expanding renewable energy generation often competes directly with other critical land-use functions, such as housing, agriculture, and nature conservation. Wind and solar PV technologies require substantially more surface area compared to conventional power generation sources. Although innovative co-location approaches (e.g., agrivoltaics or integrating solar PV into existing infrastructure) can partially alleviate spatial pressure, these solutions alone cannot fully resolve the land-use constraints facing renewable expansion. Furthermore, environmental and societal factors can further constrain the expansion of these technologies.

Therefore, this what-if scenario aims to assess how spatial scarcity could limit future wind and solar PV deployment in the Netherlands and the subsequent impact on the broader energy system. To quantify these effects, four scenarios for the spatial development of the Netherlands in 2050 (PBL, 2023) were consulted These scenarios indicate the spatial area that may be available for wind and solar energy, see **Table 3.3**.

Table 3.3: Potentials for installed capacities of solar and wind in the Netherlands in 2050 (PBL, 2023).

[GW]	Mondiaal Ondernemend	Snelle Wereld	Groen land	Regionaal Geworteld
Wind offshore	70	40	70	25
Wind onshore	8	8	12	9
Solar PV	200	70	200	100

The available potential for wind and solar energy is higher in the TRANSFORM scenario than in ADAPT. For this wait-if scenario, the two lowest values from **Table 3.3** were used for ADAPT and TRANSFORM. This results in the new parameterization shown in Table 3.4.

Table 3.4: Potentials for installed capacities of solar and wind in the Netherlands for 2050 for the base case and the what-if scenarios.

[GW]	ADAPT Base case	ADAPT What-if	TRANSFORM Base case	TRANSFORM What-if
Wind offshore	40	25	70	40
Wind onshore	7,8	8	12	9
Solar PV	109	70	132	100

These new potentials are translated into OPERA in two ways: spatially, by splitting the total maximum potentials per Dutch regions; and determining a growth path for the period 2030-2050.

Geographical distribution
To enable regional optimisation within OPERA, the distribution of onshore wind and solar PV across regions is based on the methodology from (Stralen, Janssen, Koornneef, Scheepers, & Zwaan, 2025). For offshore wind, the distribution reflects existing and planned offshore wind areas as of 2024. Using power density data for both onshore and offshore wind, as well as various solar PV technologies, regional distribution factors are calculated to estimate the spatial requirements per technology and region. These factors are then used to allocate the newly considered potentials. **Table 3.5** summarises the spatial distribution factors for onshore wind, offshore wind, and solar PV potentials across OPERA regions.

Table 3.5: Geographical distribution of the wind and solar-PV potentials in the modelled regions of OPERA.

Region OPERA map	Region OPERA name	Solar	Wind On shore/ Offshore
I	Zeeland	4%	10%
II	South Holland	11%	12%
III	North Holland	10%	11%
IV	North-NL	22%	28%
V	Mid-NL	32%	30%
VI	North Brabant	13%	8%
VII	Limburg	6%	2%
A	Offshore Borssele	-	2%
B	Offshore South-West	-	12%
C	Offshore Hub West	-	21%
D	Offshore Hub North	-	9%
E	Offshore North-West	-	9%
F	Offshore Top-North	-	33%
G	Offshore Hub-East	-	14%
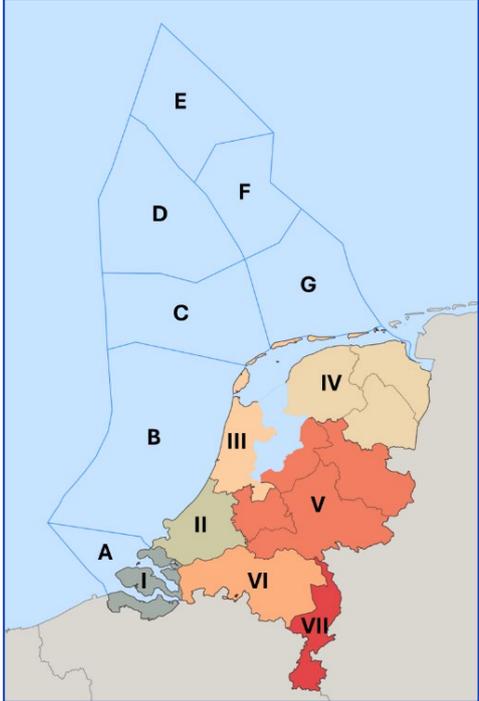
Growth path

The potentials for wind and solar are processed to have a logical and realistic evolution between 2030 and 2050. For the base cases of ADAPT and TRANSFORM, this progression of the potentials across the years is based on the policy targets and ambitions, such as the 70 GW of offshore wind by 2050. The same trends were applied for obtaining the new yearly potentials of the Space limitation what-if scenario. **Figure 3.2** shows the growth path for the wind offshore potential for the what-if scenarios compared with the base case scenarios.
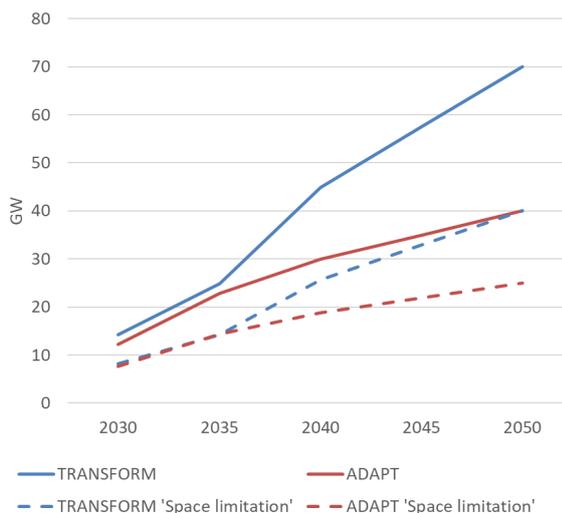
Figure 3.2: Potential for offshore wind evolution between 2030 and 2050 for the base case scenarios of ADAPT and TRANSFORM and the Spatial limitation what-if scenarios.

3.3 Critical minerals

Sustainable technologies such as wind turbines, solar panels, batteries, and electrolysers rely heavily on rare minerals. A future global shortage of these minerals, potentially driven by geopolitical tensions, could significantly impact the availability of these technologies. Without viable alternatives, the deployment of such technologies may be limited, and their costs could rise substantially.

Figure 3.3 provides an overview of the dependence on critical minerals for a number of clean energy technologies. Rare earth elements, a group of 17 chemical elements, are crucial for permanent magnets used in wind turbines and EVs. Lithium, nickel and cobalt are critical for battery performance. Electricity networks need a significant amount of aluminium and copper. Lithium and copper are more exposed to supply and volume risks, while the other key energy transition minerals face more geopolitical risks.

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	High	Low	Low	Low	Low	Low	Low	Low	High
Wind	High	Low	Moderate	Low	High	Moderate	High	Low	Moderate
Hydro	Moderate	Low	Low	Low	Low	Moderate	Moderate	Low	Moderate
CSP	Moderate	Low	Moderate	Low	Low	High	Moderate	Low	High
Bioenergy	High	Low	Low	Low	Low	Low	Moderate	Low	Moderate
Geothermal	Low	Low	High	Low	Low	High	Low	Low	Low
Nuclear	Moderate	Low	Moderate	Low	Low	Moderate	Low	Low	Low
Electricity networks	High	Low	Low	Low	Low	Low	Low	Low	High
EVs and battery storage	High	High	High	High	High	Low	Low	Low	High
Hydrogen	Low	Low	High	Low	Moderate	Low	Low	High	Moderate
Importance			High ●			Moderate ●		Low ●	

Figure 3.3: Critical mineral needs for clean energy technologies (IEA). CSP = concentrating solar power. PGM: platinum group metals.

While studies have examined the reliance of clean energy technologies on critical mineral resources (IEA, 2025) (IRENA, 2025), there is no research known on how mineral scarcity might affect the availability and cost of these technologies. To explore the sensitivity of the future Dutch energy system to such scarcity, a what-if analysis was conducted. This analysis assumes a cost increase of 100% due to limited mineral availability for four technology groups (i.e. solar PV, wind, green hydrogen production, and batteries).

3.4 Limited energy quality of buildings

This what-if scenario limits the extent to which both residential and service-sector buildings can upgrade to higher energy-efficiency labels over time. Constraints such as shortages of skilled labour, supply-chain bottlenecks, and the high complexity of deep renovations restrict the ability to reach labels A and A+, especially for buildings starting from low initial performance. As a result, most improvements converge toward mid-efficiency levels, while high-performance upgrades grow only moderately.

Residential buildings

The ADAPT and TRANSFORM base case scenarios assumes that the Dutch building sector can continue to improve insulation and energy-efficiency performance in line with long-term cost-optimal pathways. This includes the ability to upgrade buildings to high-performance labels (A and A+) and to make large jumps from low-performing categories (GFE or DC) to B or higher. These pathways require substantial renovation depth, skilled labour, supply-chain capacity, and stable investment conditions.

The what-if scenario explores a future in which these conditions cannot be met. Several factors could limit large-scale retrofit progress in the Netherlands: shortages of qualified personnel, supply-chain constraints for insulation materials and heat-system components, financial barriers for deep renovation, planning bottlenecks, or slow uptake by building owners. As a result, the scenario restricts pathways that require major construction efforts or deep efficiency upgrades. Only transitions involving moderate improvements remain available. **Table 3.6** shows the availability of improvements to residential buildings in the base case and what-if case.

Table 3.6: Residential building improvements

Dwelling type	Start → Target label	Base case	What-if case
Apartments	B/DC → B	Available	Available
Other dwellings	B/DC → B	Available	Available
Terraced houses	B/DC → B	Available	Available
Apartments	GFE → DC	Available	Available
Other dwellings	GFE → DC	Available	Available
Terraced houses	GFE → DC	Available	Available
Apartments	GFE → B (deep upgrade)	Available	Restricted
Other dwellings	GFE → B (deep upgrade)	Available	Restricted
Terraced houses	GFE → B (deep upgrade)	Available	Restricted
Apartments	DC/B → A (major renovation)	Available	Restricted
Other dwellings	DC/B → A (major renovation)	Available	Restricted
Terraced houses	DC/B → A (major renovation)	Available	Restricted
Apartments	A → A+ (high-performance standard)	Available	Restricted
Other dwellings	A → A+ (high-performance standard)	Available	Restricted
Terraced houses	A → A+ (high-performance standard)	Available	Restricted

Service buildings

The service-building trajectory assumes that only moderate improvements in high-performance labels (A and A+) can be achieved between 2030 and 2050. Similar to the residential sector, constraints arise from limited availability of skilled personnel, restricted supply-chain capacity for deep renovation measures, investment hurdles, and practical constraints related to upgrading large and diverse service-building stock. Buildings that

already have label A or A+ in 2030 remain in the stock and show a small increase over time, reflecting incremental improvements in new constructions and limited high-quality refurbishments. **Table 3.7** shows the shares of labels in 2030 and 2050 for different service-building types in the what-if case.

Table 3.7: Service building improvements

Service-build-ing type	Label	2030 share	2050 share	Change 2030→2050	Interpretation
Education	GFE	2%	2%	~0%	Stable low share
	DC	53%	10%	−80%	Strong reduction in low-efficiency stock
	B	7%	46%	+>500%	Major growth in mid-efficiency stock
	A	8%	9%	+9%	Mild increase
	A+	30%	33%	+9%	Moderate increase
Hospitals	GFE	1%	2%	+74%	Slight increase
	DC	57%	20%	−65%	Reduction in low-efficiency stock
	B	4%	53%	+>1100%	Major shift to B label
	A	7%	5%	−32%	Gradual decline
	A+	30%	20%	−32%	Decline from large initial share
Industrial halls	GFE	5%	11%	+114%	Rising share of outdated stock
	DC	79%	30%	−62%	Moderate upgrades reduce DC share
	B	4%	49%	+>1200%	Large shift to B label
	A	1%	1%	−20%	Slight decrease
	A+	11%	9%	−20%	Minor reduction
Offices	GFE	0%	0%	0%	No GFE stock assumed
	DC	29%	10%	−66%	Decline in low-performing buildings
	B	11%	32%	+204%	Strong increase
	A	13%	13%	−4%	Very small decline
	A+	47%	45%	−4%	Stable high share
Rest of services	GFE	1%	2%	+59%	Slight increase
	DC	35%	20%	−43%	Decline in low-efficiency share
	B	8%	25%	+202%	Strong increase in mid-efficiency stock
	A	16%	15%	−4%	Stable with minor reduction
	A+	40%	38%	−4%	Very small decline

For the majority of existing service buildings, especially those in low-performing categories (GFE and DC), reaching A or A+ by 2050 would require substantial structural renovation, advanced insulation measures, and replacement of technical systems. Under the what-if conditions, such deep upgrades cannot be implemented at the required scale. Therefore, outdated buildings in 2030 are assumed to improve only to the mid-efficiency level (label B). This leads to a strong rise in the B-label share across all service-building categories, representing a scenario where moderate renovations remain feasible, but widespread deep renovation cannot be achieved.

Lower labels (GFE and DC) gradually decline but do not fully disappear, as the renovation rate remains constrained. High-performance shares (A and A+) show only limited growth beyond their 2030 levels.

3.5 Financing cost uncertainty

In recent years, geopolitical events, such as the Russian invasion of Ukraine and the instability in the Middle-East, combined with remanent economic and supply chain effects from the global COVID-19 pandemic, have led to high volatile and unpredictable dynamics in European energy markets. This instability has increased the perceived risk of investors for energy projects, resulting in project delays and financing challenges.

The offshore wind sector has been particularly affected, as evidenced by recent tenders in the UK, Denmark and Germany, where no bids were submitted (The New York Times, 2023) (Offshorewind.biz, 2024) (4C Offshore News, 2025). Recently, the Dutch Nederwiek I-A wind site has also closed without bids from developers (Offshorewind.biz, 2025). Nuclear power projects face comparable difficulties, with the latest European developments (e.g. Hinkley Point C in the UK or Flamanville in France) encountering significant financing and scheduling obstacles (Profundo, 2024). Similarly, the hydrogen sector is struggling with unforeseen economic barriers hindering project development (Fuelcellsworks.com, 2024).

This uncertainty is reflected in the increase of the weighted average cost of capital (WACC) for private investors. Under conditions of high perceived risk, investors raise discount rates to account for the greater uncertainty (The Brattle Group, 2018). This increase in WACC penalizes capital-intensive assets, such as nuclear power plants or offshore wind, favouring technologies with lower upfront capital costs instead (OECD, 2021).

The OPERA model minimizes the total discounted system costs of the Dutch energy system utilizing a social discount rate. This discount rate is applied equally across all technologies and sectors, and maximizes social welfare. However, this disregards the interests and real-world investment decisions of private investors.

Therefore, for this what-if scenario on financing cost uncertainty, we assume a discount rate increase from the default social rate in OPERA of 2.25% to a more market-based WACC of 6.5%. With this approach, higher risk for investors and its effect on the technology mix of the future Dutch energy system is investigated.

3.6 Limited flexibility options

This what-if analysis examines how higher-than-expected flexibility costs could affect the development of the future energy system. Flexibility options, such as battery storage, electrolysers, and demand response are essential for integrating variable renewable energy (i.e. wind and solar energy), but their future costs are highly uncertain. To assess the impact

of this uncertainty, flexibility-related costs are uniformly increased over time: by 10% in 2030, 30% in 2040, and 50% in 2050 (see **Table 3.8** and **Table 3.9**). The +50% value for 2050 is based on average cost ranges reported in recent literature on electrolyser and battery technologies, hydrogen production, and national cost assessments. While individual technologies sometimes show even higher variability, applying a uniform cost increase across all flexibility technologies avoids bias and allows a clear system-level interpretation (Weeda & Eblé, 2024) (IRENA, 2024) (IEA, 2025).

Table 3.8: Electricity and hydrogen storage option investment cost

Technology[a]	Jaar	Investment costs [mln €$_{2015}$/PJ]	
		Base case	What-if case
CAES	2030	€ 23,148	€ 25,463
	2040	€ 21,991	€ 28,356
	2050	€ 20,833	€ 31,250
A-CAES	2030	€ 72,222	€ 79,444
	2040	€ 69,445	€ 89,722
	2050	€ 66,667	€ 100,001
Pb battery	2030	€ 63,333	€ 69,667
	2040	€ 59,722	€ 76,917
	2050	€ 56,111	€ 84,167
NiCd battery	2030	€ 78,125	€ 85,938
	2040	€ 70,313	€ 89,844
	2050	€ 62,500	€ 93,750
Li ion battery	2030	€ 48,889	€ 53,778
	2040	€ 42,778	€ 54,389
	2050	€ 36,667	€ 55,000
VRB battery	2030	€ 148,611	€ 163,472
	2040	€ 148,611	€ 193,194
	2050	€ 148,611	€ 222,917
ZnBr battery	2030	€ 93,750	€ 103,125
	2040	€ 84,375	€ 107,813
	2050	€ 75,000	€ 112,500
H$_2$ underground storage	2030	€ 50	€ 55
	2040	€ 50	€ 65
	2050	€ 50	€ 75

[a] CAES = conventional compressed air energy storage; A-CAES = adiabatic compressed air energy storage; Pb battery = lead-acid battery; NiCd battery = nickel–cadmium battery; Li-ion battery = lithium-ion battery; VRB battery = vanadium redox flow battery; ZnBr battery = zinc–bromine flow battery; H$_2$ underground storage = hydrogen stored in underground caverns or reservoirs

In each milestone year, the model is run with adjusted CAPEX values for all flexibility options, while operating costs and all other system assumptions remain identical to the base case. This isolates the effect of more expensive investments without conflating it with changes in efficiency, fuel, or operational behaviour. The resulting system configurations are compared to the base case to examine shifts in technology deployment, reliance on alternative options,

total system cost, curtailment levels, and emissions. This reveals the sensitivity of long-term decarbonisation pathways when flexibility options become more capital-intensive.

Table 3.9: Electrolytic hydrogen for flexibility - investment cost increase in this what-if

Technology[a]	Year	Investment costs [mlnEUR2015/GWe-in]	
		Base case	What-if case
SOEC small-scale	2030	€ 5,100	€ 5,610
	2040	€ 3,530	€ 4,589
	2050	€ 2,382	€ 3,574
H$_2$ Alkaline small-scale	2030	€ 3,753	€ 4,128
	2040	€ 2,872	€ 3,734
	2050	€ 2,193	€ 3,289
H$_2$ Large-scale electrolyser	2030	€ 1,770	€ 1,947
	2040	€ 1,416	€ 1,841
	2050	€ 1,133	€ 1,699
H$_2$ PEM small-scale	2030	€ 3,616	€ 3,977
	2040	€ 2,721	€ 3,538
	2050	€ 2,039	€ 3,059

[a] SOEC small-scale = small-scale solid oxide electrolyser cell; H$_2$ alkaline small-scale = small-scale alkaline electrolyser; H$_2$ PEM small-scale = small-scale proton exchange membrane electrolyser

Using a uniform CAPEX increase across all flexibility technologies improves transparency, avoids complex technology-specific assumptions, and makes results easier to compare. It also allows straightforward extrapolation to other cost levels and saves time by not requiring detailed uncertainty ranges for each technology. The drawback is that real cost trajectories differ across technologies, so this approach does not reflect technology-specific uncertainty. However, since the aim is to evaluate system-level effects of a pessimistic cost outlook, this simplification is justified and provides a clear and policy-relevant perspective.

Industrial flexibility is included by considering major energy-intensive sectors and their main production activities: chlorine, ammonia (NH$_3$), olefins and methanol production in the chemical and fertilizer industries; steel production in the basic ferrous metals sector; and ceramics and glass production in the general industry sector. For each of these sectors, flexibility is represented through process overcapacity, which allows production levels to vary around the annual demand requirement within a defined range. This overcapacity enables short-term adjustments in operation, such as shifting production to periods of lower energy prices or higher renewable availability. In this what-if case, the maximum overcapacity threshold is reduced by 10% in 2030, 30% in 2040, and 50% in 2050. For example, the steel sector, which initially allows production capacity to reach up to 30% above the annual demand level, has this margin reduced proportionally in each period. For more details about industrial flexibility, see (Scheepers, et al., 2024).

4 Results

This Chapter contains the results for the six what-if scenarios described in the previous Chapter. The what-if scenario results are compared to the base cases ADAPT and TRANSFORM.

4.1 Limited availability of innovative technologies

Technologies with TRL 5 and lower

Based on the ADAPT and TRANSFORM base cases, technologies deployed with low TRL (<5) were first identified[8], see **Table 4.1**. With a few exceptions, these technologies were excluded from the what-if scenarios.

Excluding all technologies with a TRL 5 or lower results in infeasible model runs for both the ADAPT and TRANSFORM what-if scenarios in 2030, 2040, and 2050. To understand the cause of this infeasibility, a deeper analysis was conducted. It revealed that lignocellulosic ethanol production with CO_2 capture and bio-ethylene via bio-ethanol (TRL 5) are essential from 2030 onwards in both scenarios, due to the requirement of bio-ethanol demand in road transport as defined in the demand inputs for road transport obtained from (PBL, 2022). Since the current OPERA database lacks alternative supply technologies, the absence of these specific technologies in the respective years makes the ADAPT and TRANSFORM what-if scenarios infeasible.

Critical technologies: TRL 6 and 7

In the what-if scenarios, a second assessment was conducted to identify technologies with a TRL of 6 and 7 that are deployed in 2030 and/or 2035. Technologies were classified as 'critical' based on their capacity levels in the model results. These technologies are listed in **Table 4.2**.

Table 4.1: Deployed, non-deployed and excluded technologies in ADAPT and TRANSFORM base scenarios and what-if scenarios with a TLR 5 or lower

Technology OPERA database[a]	Technology IEA guide	ADAPT base case	ADAPT what-if	TRANSFORM base case	TRANSFORM what-if
Lignocellulosic ethanol production - Refineries	Lignocellulosic gasification (ethylene) – Industry Chemicals and Plastics	Non-deployed	Excluded	Deployed	Excluded
ATR with CC – Hydrogen production	Single reformer (methane) – Hydrogen production	Deployed	Excluded	Non-deployed	Excluded
Post-combustion CCS - Refineries	Post-combustion carbon capture (cracking) - Refining	Deployed	Excluded	Deployed	Excluded

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[8] Appearance in the scenario solution in any given year with a capacity value of >0.01 unit (GWe or PJ)

Technology OPERA database[a]	Technology IEA guide	ADAPT base case	ADAPT what-if	TRANSFORM base case	TRANSFORM what-if
Hydrogen from photocatalysis PEC central – Hydrogen production	Photocatalytic water splitting – Hydrogen production	Non-deployed	Excluded	Deployed	Excluded
Electrification of steam crackers – Chemicals	Steam cracker electrification (high value chemicals) – Industry Chemicals and Plastics	Deployed	Excluded	Deployed	Excluded
Electric Direct Firing – Basic metal non-ferro	Electric arc and plasma arc furnaces (high temperature heating) – Cross-cutting industry	Deployed	Excluded	Deployed	Excluded
Direct Firing Electric 200-400 °C – Basic metal non-ferro	Electric arc and plasma arc furnaces (high temperature heating) – Cross-cutting industry	Deployed	Excluded	Deployed	Excluded
Direct Firing Elec 200-400 °C – Chemicals	Electric arc and plasma arc furnaces (high temperature heating) – Cross-cutting industry	Deployed	Excluded	Deployed	Excluded
Direct Firing Electric 200-400 °C - Industry	Electric arc and plasma arc furnaces (high temperature heating) – Cross-cutting industry	Deployed	Excluded	Deployed	Excluded
Lignocellulosic ethanol production with CC – Refineries	Enzymatic fermentation with CCUS (lignocellulosic bioethanol) – Biofuels production	Deployed	Deployed	Deployed	Deployed
Bio-DME production with CC - Refineries	Post-combustion carbon capture (cracking) - Refining	Deployed	Excluded	Deployed	Excluded
Biomass gasification + FT towards kerosene with CC – Refineries	Gasification and Fischer-Tropsch with CCUS (biodiesel) – Biofuels production	Deployed	Excluded	Deployed	Excluded
Bio-ethylene via bio-ethanol – Chemicals	Lignocellulosic gasification (ethylene) – Industry Chemicals and Plastics	Deployed	Deployed	Deployed	Deployed
Biomass gasification + FT towards diesel with CC – Refineries	Gasification and Fischer-Tropsch with CCUS (biodiesel) – Biofuels production	Deployed	Excluded	Deployed	Excluded

[a]   CC: CO_2 Capture CCS: CO_2 Capture & Storage; FT: Fischer Tropsch; PEC: Photoelectrochemical; ATR: autothermal reforming.

Table 4.2: Deployed and non-deployed technologies in ADAPT and TRANSFORM and what-if scenarios with a TLR of 6 and 7

Technology OPERA database[a]	Technology IEA guide	ADAPT base case	ADAPT what-if	TRANSFORM base case	TRANSFORM what-if
P2L FT pathway, external hydrogen, external CO_2 - Refineries	CO_2 reduction – Liquid fuels production	Deployed	Non-deployed	Deployed	Deployed
P2L FT pathway, high temperature electrolysis, external CO_2 – Refineries	CO_2 reduction – Liquid fuels production	Deployed	Deployed	Deployed	Non-deployed
Methanol from external hydrogen and external CO_2 – Chemicals	CO_2- and electrolytic hydrogen-based produced with variable renewables (methanol) – Industry Chemicals and Plastics	Deployed	Deployed	Deployed	Deployed
Hydrogen from SMR CC from shifted syngas low – Hydrogen production	Partial oxidation with CCUS- Hydrogen production	Non-deployed	Non-deployed	Deployed	Deployed
Hydrogen from SMR CC from PSA tail gas high – Hydrogen production	Partial oxidation with CCUS- Hydrogen production	Deployed	Deployed	Non-deployed	Non-deployed
CO_2 from air capture – Gas supply	Solid DAC (S-DAC) – CO_2 capture	Deployed	Non-deployed	Deployed	Non-deployed
Small modular reactor – electricity only modus – Electricity generation	Light water reactor-based small modular nuclear reactor – Electricity generation	Deployed	Non-deployed	Deployed	Non-deployed
Small modular reactor – max heat modus – Electricity generation	Light water reactor-based small modular nuclear reactor – Electricity generation	Deployed	Non-deployed	Deployed	Non-deployed
CCGT Hydrogen – Electricity generation	Pure hydrogen – Electricity generation	Deployed	Deployed	Deployed	Deployed
Hydrogen Direct Firing >400 °C – Basic metals non-ferro	Hydrogen (high temperature heating) – Cross-cutting industry	Deployed	Deployed	Deployed	Deployed
CO_2 capture add-on – Basic metals	CCUS (smelting) – Industry Iron and Steel	Deployed	Deployed	Non-deployed	Non-deployed
Steelmaking Direct Reduction with external hydrogen – Basic metals ferro	Based on 100% electrolytic hydrogen (DRI) – Industry Iron and Steel	Non-deployed	Non-deployed	Deployed	Deployed

Technology OPERA database[a]	Technology IEA guide	ADAPT base case	ADAPT what-if	TRANSFORM base case	TRANSFORM what-if
Hydrogen Direct Firing >400 °C – Basic metals ferro	Hydrogen (high temperature heating) – Cross-cutting industry	Deployed	Non-deployed	Non-deployed	Non-deployed
Hydrogen Direct Firing >400 °C – Industry	Hydrogen (high temperature heating) – Cross-cutting industry	Non-deployed	Non-deployed	Deployed	Non-deployed

[a] CC: CO_2 Capture CCS: CO_2 Capture & Storage; CCUS: CO_2 Capture Use & Storage; DAC: Direct air capture; P2L: Power-to-liquid; FT: Fischer Tropsch; SMR: Steam methane reforming; CCGT: Combined cycle gas turbine

Impacts on the energy system

Given that the specific TRL 5 technologies, i.e. lignocellulosic ethanol production with CO_2 capture and bio-ethylene production via bioethanol (see **Table 4.1**) are available to the system, the what-if cases yield feasible outcomes. **Figure 4.1** to **Figure 4.4** compare key indicators from the what-if scenarios with those from the ADAPT and TRANSFORM base cases, highlighting the main impacts of excluding low-TRL technologies from the Dutch energy system. The detailed analysis focuses on the year 2050, as this is expected to show the most significant changes.

Primary energy supply

Figure 4.1 shows that in 2050 in the what-if case of ADAPT, primary energy consumption increases by 268 PJ (6%). In TRANSFORM, the increase is 116 PJ (3%). This increase in energy consumption is primarily due to an increase in the production of electricity (renewable and nuclear) and renewable heat: in ADAPT by 107 PJ (11%) and 186 PJ (64%), respectively, and in TRANSFORM by 43 PJ (2%) and 118 PJ (33%), respectively.

Electricity balance

Electricity demand and production increase by 54 PJ (5%) and 16 PJ (1%) in 2050 in the what-if cases compared to the ADAPT and TRANSFORM base cases, respectively, see **Figure 4.2**. The sectors with increasing and decreasing electricity demand differ per scenario. In ADAPT, electricity demand decreases in industry, the built environment, and transport. Hydrogen production and fuel conversion, on the other hand, use more electricity in this scenario. In TRANSFORM, electricity demand decreases in industry and fuel conversion, while it increases in hydrogen production, the built environment, transport, and exports. Excluding a number of high-temperature electrification options above 200º C in the what-if cases of both scenarios explains the decline in industrial electricity demand.

Hydrogen balance

The hydrogen balance changes in both scenarios differently (see **Figure 4.3**): in ADAPT, because methane reforming with carbon capture is excluded, electrolysers play a larger role in production (in 2050 increases by 104 PJ, 41%), and combined with more import, it is used to produce synthetic fuels (power-2-liquid; 192 PJ) as replacement for biogenic bunker fuels. On the other hand, the external supply of hydrogen to produce fertilizer disappears. Changes in other uses are much smaller and the export remains unchanged. Overall, the volume of hydrogen in the system increases in 2050 by 138 PJ (33%). In TRANSFORM, electrolysers produce also more (in 2050: 37 PJ, 8%), but import decreases while export increases. Similar to ADAPT, in TRANSFORM, hydrogen is used to produce ammonia as a bunker fuel, but use for synthetic fuels decreases. In total, there is a somewhat lower volume of hydrogen in the system (-18 PJ, -3%).

Other	48	48	54	54	61	61
Nuclear	37	37	354	355	728	746
Synthetics	9	9	9	9	10	10
Rewew. heat	96	138	212	274	289	475
Renew. electricity	417	417	795	777	1094	1182
Biomass/biofuels	246	250	560	561	884	889
Fossil fuels	2384	2384	1825	1843	1165	1103
Hydrogen import	0	0	95	95	178	211

Other	48	48	52	52	51	51
Nuclear	37	37	364	364	740	765
Synthetics	8	8	6	6	5	5
Rewew. heat	92	114	152	173	363	482
Renew. electricity	468	469	1184	1192	1859	1878
Biomass/biofuels	235	237	556	548	862	862
Fossil fuels	2117	2151	1263	1272	215	213
Hydrogen import	0	0	46	59	238	201
Electricity import	201	196	35	32	61	55

Figure 4.1: Primary energy supply, including feedstock and international bunker fuels for the what-if scenarios with limited availability of innovative technologies compared to ADAPT (top) and TRANSFORM (bottom).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use transport	54	55	133	133	171	119
■ Use built environment	135	103	112	136	110	103
■ Use industry	252	247	198	189	294	221
■ Use fuel conversion	15	14	31	12	24	50
■ Use H2 production	61	42	58	54	397	556
■ Use export	143	169	215	215	102	102
■ Supply domestic	-472	-457	-714	-704	-1007	-1061
■ Supply import	-189	-174	-34	-34	-90	-90

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use transport	35	35	116	115	155	159
■ Use built envir.	134	133	81	78	88	100
■ Use industry	231	225	196	181	231	186
■ Use fuel conv.	15	15	25	21	46	14
■ Use H2 prod.	42	42	482	469	734	748
■ Use export	148	176	192	216	509	571
■ Supply domestic	-404	-431	-1057	-1049	-1702	-1723
■ Supply import	-201	-196	-35	-32	-61	-55

Figure 4.2: Electricity supply and demand balances for the what-if scenarios with limited availability of innovative technologies compared to ADAPT (top) and TRANSFORM (bottom).

Carbon balance

Figure 4.4 shows that in the ADAPT what-if case, CO_2 captured is 11 Mt (26%) higher in 2050 compared to the baseline scenario. Because bioprocesses with CO_2 capture are excluded, the CO_2 capture shifts to DAC, which in 2050 amounts to 43 Mt. In CO_2 storage, a shift also occurs from biogenic CO_2 to CO_2 captured from the air. The total amount of CO_2 stored remains at a maximum of 40 Mt. A similar shift is visible when comparing the TRANSFORM what-if case with the baseline scenario. The amount of CO_2 captured from the air (DAC) increases by 17 Mt to 21 Mt, while the amount of CO_2 captured from biogenic processes decreases by roughly the same amount. This shift is also visible in the use and storage of CO_2. The total amount of stored CO_2 in TRANSFORM remains at a maximum of 15 Mt in 2050.

Summary

The fact that the system cannot make use of certain carbon capture options, especially those producing bio-fuels for international transportation (kerosine and diesel) forces the system to seek other pathways to satisfy the unchanged demand for these fuels. In ADAPT this leads to the production of more synthetic fuels (i.e. power-2-liquid) and in TRANSFORM to more ammonia as marine fuel. In both ADAPT and TRANSFORM, bio-fuels are still produced through Fischer-Tropsch, but without carbon capture. Therefore, direct air capture (DAC) is deployed substantially in both ADAPT and TRANSFORM what-if cases and biogenic carbon capture almost disappears. This also has consequences for the compensation of the remaining greenhouse gas emissions to achieve climate neutrality in 2050, with the result that CO_2 from DAC is also used for this purpose. Consequently, this deployment of DAC increases the demand for renewable electricity (especially in ADAPT) and heat in the system.

When excluding direct electric heating for industrial applications with a heat demand above 200º C, this heat demand is supplied by natural gas and biomass direct firing in both scenarios.

Excluding bio-fuel technologies with carbon capture and direct electric heating technologies causes several shifts in the entire system, because the supply options to produce (renewable) electricity and heat are limited. Consequently, this extra energy demand for DAC and non-electric industrial heat supply must be compensated in other sectors by e.g. extra energy savings or the use of more efficient, but also more costly, alternatives.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use other	87	73	93	100	91	83
■ Use NH3 energy	0	0	0	9	65	72
■ Use NH3 fertiliser	0	0	0	0	52	0
■ Use feedstock	11	11	17	17	13	13
■ Use P2L	5	5	0	0	0	192
■ Use energy	0	0	0	1	1	0
■ Use export	41	46	113	113	215	215
■ Supply import	0	0	-95	-95	-178	-211
■ Supply process	-9	-8	-7	-1	0	0
■ Supply electrolyser	-41	-32	-38	-36	-250	-354
■ Supply SMR	-94	-95	-84	-109	-10	-11

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use other	86	86	101	170	75	58
■ Use NH3 energy	0	0	88	29	244	293
■ Use NH3 fertiliser	0	0	13	4	14	14
■ Use feedstock	9	9	13	13	9	9
■ Use P2L	9	9	58	59	225	139
■ Use energy	0	1	4	3	5	0
■ Use export	46	46	50	66	156	196
■ Supply import	0	0	-46	-59	-238	-201
■ Supply process	0	0	0	0	0	0
■ Supply electrolyser	-29	-29	-273	-277	-467	-504
■ Supply SMR	-122	-123	-8	-8	-24	-6

Figure 4.3: Hydrogen balances for the what-if scenarios with limited availability of innovative technologies compared to ADAPT (top) and TRANSFORM (bottom).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
CCS DAC	0,0	0,0	0,0	14,7	1,6	33,6
CCS bio	3,9	1,5	20,1	8,8	29,3	2,6
CCS fossil	8,8	11,2	14,9	11,6	9,1	3,8
CCU DAC	0,0	0,0	0,0	0,1	0,1	9,6
CCU bio	0,5	0,1	0,2	0,1	1,0	0,7
CCU fossil	1,8	1,0	0,1	0,1	0,3	1,6
CC DAC	0,0	0,0	0,0	-14,8	-1,7	-43,2
CC bio	-4,3	-1,6	-20,2	-8,8	-30,3	-3,3
CC fossil	-10,7	-12,2	-15,0	-11,7	-9,4	-5,4

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
CCS DAC	0,0	0,0	0,0	6,8	2,0	13,4
CCS bio	3,4	2,3	11,4	1,9	10,2	0,4
CCS fossil	6,2	7,4	3,6	6,4	2,8	1,2
CCU DAC	0,0	0,0	0,0	1,6	1,9	7,6
CCU bio	0,9	0,6	3,2	0,4	9,6	0,8
CCU fossil	2,0	2,7	3,4	2,5	2,7	0,6
CC DAC	0,0	0,0	0,0	-8,4	-3,8	-21,0
CC bio	-4,3	-3,0	-14,7	-2,3	-19,7	-1,2
CC fossil	-8,2	-10,1	-7,0	-8,9	-5,5	-1,8

Figure 4.4: CO$_2$ balances for the what-if scenarios with limited availability of innovative technologies compared to ADAPT (top) and TRANSFORM (bottom).

4.2 Spatial limitations

The what-if analysis of ADAPT and TRANSFORM, that assumes limited potential for wind and solar energy due to spatial constraints (see **Table 3.4**), was found to be unfeasible. This proves the critical importance of wind and solar availability for achieving an energy system aligned with stringent GHG reduction targets. To enable feasible outcomes, the following relaxations were introduced to provide the model with alternative pathways:
〉 Increase in the bandwidth for imports and exports for both electricity and hydrogen around the volumes taken from the energy market model is increased by 20% for all years by 20% for all years analysed in both scenarios ADAPT and TRANSFORM.
〉 Increase in the availability of imported synthetic and bio-methanol, synthetic and bio-kerosine, and ammonia in the TRANSFORM scenario.

Primary energy supply

As illustrated in **Figure 4.5**, changes in the total primary energy supply are more significant in the final year 2050. In that milestone year, the scenarios show a decrease of 121 PJ and 358 PJ of total primary energy in ADAPT and TRANSFORM, respectively. This decline in the primary energy supply indicates a decrease in the system's energy demand due to higher energy efficiency in energy conversion and energy use in the demand sectors.

There are commonalities between the scenarios regarding the impact on the primary energy supply, such as:
〉 Decrease in the share of renewable electricity in the system, as explained further in the electricity balance analysis below. In 2050, TRANSFORM experiences 660 PJ less renewable electricity compared to the reference and ADAPT renewable electricity production decreases by more than 300 PJ.
〉 ADAPT and TRANSFORM exhibit relative increases in electricity imports, renewable heat (i.e. deployment of more heat pumps and heat pumps with higher efficiency), and nuclear energy.

However, there are also divergences, such as:
〉 In ADAPT, hydrogen imports are lower in the what-if case compared to the base case by approximately 40 PJ and 50 PJ in 2040 and 2050, respectively. On the contrary, TRANSFORM experiences an increase of around 40 PJ in 2040 and 2050, showing opposite transition paths. This is explored in the hydrogen balance analysis below.
〉 Synthetic fuels are not affected significantly in ADAPT under the spatial what-if case. However, TRANSFORM exhibits a significant increase of 144 PJ in 2050. This is mainly explained by the increased application of synthetic energy carriers, which provide a feasible alternative path in TRANSFORM.
〉 Fossil energy (gas, oil, and coal) shows an important increase under ADAPT, reaching a positive difference in 2050 of 105 PJ in the what-if case compared to the base case. On the other hand, TRANSFORM shows a decrease of 52 PJ in that same year, demonstrating again the opposite behaviour between the scenarios. This is further explored in the following carbon balance analysis below.

Next, the relevant sub-sectors of the energy system are described in greater detail to explain the changes observed in the primary energy results. The analysis primarily focuses on the year 2050, when the differences between the reference scenarios and the what-if variant are most pronounced.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Other	48	48	54	54	61	61
■ Nuclear	37	37	354	367	728	764
■ Synthetics	9	9	9	9	10	10
■ Renew. heat	96	123	212	308	289	357
■ Renew. electricity	417	302	795	581	1094	786
■ Biomass/biofuels	246	250	560	570	884	884
■ Fossil fuels	2384	2397	1825	1949	1165	1271
■ Hydrogen import	0	0	95	56	178	129
■ Electricity import	189	210	34	37	90	117

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Other	48	48	52	52	51	51
■ Nuclear	37	37	364	365	740	767
■ Synthetics	8	8	6	162	5	149
■ Renew. heat	92	109	152	206	363	424
■ Renew. electricity	468	336	1184	774	1859	1199
■ Biomass/biofuels	235	240	556	566	862	941
■ Fossil fuels	2117	2252	1263	1208	215	163
■ Hydrogen import	0	0	46	90	238	276
■ Electricity import	201	211	35	38	61	66

Figure 4.5: Primary energy supply, including feedstock and international bunker fuels for the what-if scenarios with limited potentials for wind and solar energy compared to ADAPT (top) and TRANSFORM (bottom).

Electricity balance

Figure 4.6 shows the electricity balance for the base cases and Spatial limitations what-if scenarios. Both ADAPT and TRANSFORM show common trends in the demand and supply changes.

ADAPT

Limiting wind and solar energy potentials results in a decrease of output of these energy sources in 2050 of 245 PJ_e (~30%) and 63 PJ_e (~20%) respectively, compared to the reference scenario. This is partly compensated by increased domestic production from nuclear and biomass sources, along with a rise in electricity imports. In 2050, the Netherlands transitions from a net exporter in the base case to a net importer in the what-if scenario. The shortfall of electricity supply leads to an associated net decrease of the domestic electricity demand of 163 PJ_e (~16%) in 2050. The most affected sectors are the hydrogen sector (-194 PJ_e) and fuel conversion (-14 PJ_e). A demand increase (+49 PJ_e) is evident in the built environment, caused by the substitution of natural gas district heating for ground-source heat pumps.

TRANSFORM

The limited potentials of wind and solar energy have a bigger impact on TRANSFORM, with reductions in 2050 of 548 PJ_e (~40%) of wind and 113 PJ_e (~25%) of solar output. Similar to ADAPT, these reductions are compensated with higher production from nuclear, biomass and fossil fuels. The lower availability of electricity results in a decrease of demand across all sectors except for the built environment, which (like in ADAPT), deploys ground-source heat pumps to replace mainly district heating. In the what-if case of TRANSFORM, the electricity use decreases in 2050 by 480 PJ_e (-65%) for hydrogen production, by industry 33 PJ_e (-14%) for industry and by 34 PJ_e (-74%) for fuel conversion. The Netherlands is a net-exporter of electricity (448 PJe) in the TRANSFORM base case in 2050. In the what-if case, this net export decreases to 379 PJ_e (-15%).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use transport	54	56	133	129	171	167
■ Use built environment	135	128	112	152	110	159
■ Use industry	252	231	198	158	294	293
■ Use fuel conversion	15	13	31	21	24	10
■ Use H2 production	61	37	58	7	397	203
■ Use export	143	116	215	173	102	83
■ Supply domestic	-472	-371	-714	-603	-1007	-798
■ Supply import	-189	-210	-34	-37	-90	-117

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use transport	35	35	116	113	155	155
■ Use built environ.	134	149	81	111	88	150
■ Use industry	231	231	196	189	231	198
■ Use Fuel convers.	15	15	25	13	46	12
■ Use H2 prod.	42	42	482	159	734	252
■ Use export	148	120	192	169	509	445
■ Supply E-sector	-404	-381	-1057	-717	-1702	-1145
■ Supply import	-201	-211	-35	-38	-61	-66

Figure 4.6: Electricity balance for ADAPT (top) and TRANSFORM (bottom) for the what-if scenarios with limited potentials for wind and solar energy.

Hydrogen balance

Figure 4.7 illustrates the hydrogen balance across both the base case and the what-if scenarios. In general, hydrogen plays a less prominent role in the energy system in the what-if scenarios, due to reduced electricity availability. This directly impacts the domestic green hydrogen production, which in 2050 has a drop of 119 PJ (-47%) in ADAPT, and 300 PJ (-64%) in TRANSFORM.

ADAPT

Domestic hydrogen production (including imports) reduces by 168 PJ (-40%) in 2050 in the what-if scenario compared to the base case. In this year, the Netherlands is both importing and exporting hydrogen, resulting in a net import of hydrogen of 10 PJ compared to an export position in the base case of almost 40 PJ.

This decrease corresponds in its majority to an interrelated decrease of ammonia production in the industry sector and its end use in other processes; notably, there is a shift in the end-use fuels for navigation bunkers. In 2050, the system relies on methanol produced from fossil-based fuels to meet that demand in the what-if scenario, resulting in lower hydrogen demand use for methanol (-30 PJ) and for ammonia (-28 PJ) production. The alternative methanol route ultimately substitutes the role of ammonia and biofuels in the navigation bunkers sector.

TRANSFORM

In the TRANSFORM scenario, domestic hydrogen production is also significantly lower in the what-if case compared to the base case, amounting to 168 PJ compared to the 467 PJ of the base case in 2050 (a decrease of 60%). In the base case, the Netherlands is a net exporter of hydrogen in 2050 (81 PJ). However, in the what-if case, this net export shifts to a net import of 158 PJ.

The main factor behind the reduced domestic hydrogen demand is the decreased use of hydrogen for fuel conversion in end-use applications, particularly within international bunkering, reflected in the reduction in the power-2-liquid and ammonia energy use of 120 PJ compared to the base case in 2050. This is explained by the major shift in the navigation bunkers' supply mix. In 2050, there is a significant reduction of the use of ammonia (-76 PJ) compared to the base case. This ammonia is replaced mainly by biofuels, and marginally by synthetic fuels. Meanwhile, the aviation sector switches 30 PJ of synthetic kerosine by its bio alternative. Overall, the limited hydrogen availability is redirected to other pathways for fuel production for bunkers, relying on bio sources and imported synthetic fuels to solve that hydrogen shortage.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use other	87	74	93	59	91	61
■ Use NH3 energy	0	0	0	0	65	38
■ Use NH3 fertiliser	0	0	0	0	52	40
■ Use feedstock	11	11	17	17	13	13
■ Use P2L	5	5	0	0	0	0
■ Use energy	0	0	0	1	1	1
■ Use export	41	37	113	116	215	118
■ Supply import	0	0	-95	-56	-178	-129
■ Supply process	-9	0	-7	0	0	0
■ Supply electrolyser	-41	-29	-38	-5	-250	-132
■ Supply SMR	-94	-97	-84	-133	-10	-10

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use other	86	91	101	186	75	110
■ Use NH3 energy	0	0	88	0	244	139
■ Use NH3 fertiliser	0	0	13	0	14	14
■ Use feedstock	9	9	13	13	9	9
■ Use P2L	9	5	58	32	225	105
■ Use energy	0	4	4	0	5	0
■ Use export	46	46	50	35	156	118
■ Supply import	0	0	-46	-90	-238	-276
■ Supply process	0	0	0	0	0	0
■ Supply electrolyser	-29	-29	-273	-100	-467	-168
■ Supply SMR	-122	-126	-8	-77	-24	-51

Figure 4.7: Hydrogen balance for ADAPT (top) and TRANSFORM (bottom) for the what-if scenarios with limited potentials for wind and solar energy.

Carbon balance

Figure 4.8 presents the carbon balance for both the base cases and the what-if scenarios. The what-if scenarios show a clear divergence: while ADAPT sees a slight increase in carbon capture, TRANSFORM experiences a substantial decline.

ADAPT

The carbon balance for ADAPT shows an increase in direct air capture (DAC) and fossil carbon capture (CC). These changes are driven by a shift in the transition path from electricity to more fossil fuels. The increase of fossil energy in the system (more than 100 PJ in 2050, see Figure 4.5) results in the need for higher carbon removal (negative emissions) to meet the GHG reduction targets. Negative emissions increase in 2050 by 1.1 Mton, whereas total CO_2 storage remains at the maximum allowed storage of 40 Mton.

TRANSFORM

In the TRANSFORM scenario in 2050, non-fossil CO_2 storage decreases slightly by 0.6 Mton compared to the base case, whereas the total storage remains at the maximum of 15 Mton. This reduction results from increased imports of synthetic and bio-based fuels, introduced as a system relaxation measure to ensure feasibility of the model. These imports reduce biogenic carbon capture, as less biogenic carbon is needed for fuel production and for generating negative emissions. This effect is partially offset by a modest increase in DAC.

In summary

In the ADAPT scenario, limiting the potential for wind and solar energy production due to spatial constraints leads to a reduction of roughly 28% in renewable electricity generation by 2050, driving a cascade of system adjustments. The shortfall in domestic renewable supply is compensated partly by modest increases in electricity generation from nuclear and fossil fuels, as well as greater reliance on electricity imports. Electrolysis activity is cut by almost half, reducing domestic hydrogen production and shrinking both imports and exports, leading to a smaller overall hydrogen system. Demand shifts, e.g. to more renewable heat use, relieve pressure on the power system. In the international transport sector, aviation fuels remain unchanged, but navigation fuels shift toward greater fossil use as ammonia and biofuel availability declines. Carbon capture activity edges up slightly through more DAC and fossil-based capture/CCU, while biogenic capture remains stable.

In the more ambitious TRANSFORM scenario, limiting wind and solar energy potential causes a sharper loss in renewable electricity (about 35%) and this loss is not backfilled with fossil generation to the same extent as in ADAPT. Instead, the system pivots toward more renewable heat, higher hydrogen imports, and an increased share of synthetic fuels, while maintaining a low-fossil profile. Electrolysis drops by over 65%, freeing scarce electricity for direct use in buildings and industry but limiting domestic hydrogen output; imports rise to supply industrial hydrogen demand, while fuel conversion (P2L) is heavily reduced. In aviation, synthetic fuels decline sharply, replaced by biofuels; in navigation, ammonia use falls while biofuels rise, avoiding fossil fallback. Finally, the biogenic carbon capture falls significantly due to less demand for CCU.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ CCS DAC	0,0	0,0	0,0	0,0	1,6	2,4
■ CCS bio	3,9	3,6	20,1	23,0	29,3	29,6
■ CCS fossil	8,8	9,1	14,9	12,0	9,1	8,0
■ CCU DAC	0,0	0,0	0,0	0,0	0,1	0,1
■ CCU bio	0,5	0,2	0,2	0,1	1,0	0,7
■ CCU fossil	1,8	3,7	0,1	2,4	0,3	2,6
■ CC DAC	0,0	0,0	0,0	0,0	-1,7	-2,5
■ CC bio	-4,3	-3,8	-20,2	-23,1	-30,3	-30,3
■ CC fossil	-10,7	-12,8	-15,0	-14,4	-9,4	-10,6

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ CCS DAC	0,0	0,0	0,0	0,0	2,0	3,2
■ CCS bio	3,4	4,3	11,4	6,4	10,2	8,3
■ CCS fossil	6,2	5,1	3,6	8,6	2,8	3,5
■ CCU DAC	0,0	0,0	0,0	0,0	1,9	1,4
■ CCU bio	0,9	1,0	3,2	0,8	9,6	3,6
■ CCU fossil	2,0	4,1	3,4	2,1	2,7	1,5
■ CC DAC	0,0	0,0	0,0	0,0	-3,8	-4,7
■ CC bio	-4,3	-5,2	-14,7	-7,2	-19,7	-11,9
■ CC fossil	-8,2	-9,2	-7,0	-10,7	-5,5	-5,0

Figure 4.8: CO_2 balance for ADAPT (top) and TRANSFORM (bottom) for the what-if scenarios with limited potentials for wind and solar energy.

4.3   Critical minerals

The impact of critical mineral scarcity driven by geopolitical tensions, is explored through a what-if analysis, which assumes this scarcity leads to increased investment costs (see Section 3.3). Specifically, the analysis examines changes in the energy system when the investment costs of four technology groups are doubled at the same time: solar PV, wind energy, green hydrogen production, and batteries.

Primary energy supply

Overall, the effect on primary energy is limited in both ADAPT and TRANSFORM scenarios, but the shifts differ. In ADAPT, higher costs make renewable electricity supply less attractive. In 2040 and 2050, renewable electricity production falls by approximately 20%, partly compensated by a rise in renewable heat: 11% in 2040 and 25% in 2050 (see **Figure 4.9**). Also an increase in fossil fuels supply (14% in 2050) compensates the drop in renewable electricity production.

In TRANSFORM, renewable electricity supply is more resilient. It barely declines in 2030 and 2040, and even grows slightly by 2050 (+20 PJ, +1%) despite higher costs (see **Figure 4.9**). This contrast is due to TRANSFORM's stronger reliance on renewable electricity, with fewer alternatives like fossil fuels, CCS, or biomass. In ADAPT, such alternatives are available, enabling a shift away from costly critical mineral-intensive renewables.

Electricity balance

Zooming into electricity balances shows how demand sectors are affected by higher costs linked to critical mineral intensity (see **Figure 4.10**).

In ADAPT, total electricity demand remains relatively stable in 2030 and 2040, but declines by about 130 PJ_e (-10%) by 2050. The sharpest decline is in electricity demand for hydrogen production, which drops by 150 PJ_e (-40%), due to higher costs of renewable electricity production and electrolysers. Smaller demand decreases are seen in transport and fuel conversion, each falling by around 10 PJ_e. In contrast, electricity use in the built environment increases by 50 PJ (+48%), driven by greater adoption of heat pumps.

In TRANSFORM**,** end-use sectors are less affected. By 2050, electricity demand falls by 38 PJ_e in industry and 15 PJ_e in fuel conversion, while electricity use in the built environment increases by 50 PJ_e, similar to ADAPT. Despite higher renewable electricity production and electrolysers costs, electricity demand for hydrogen production rises by 45 PJ_e. Unlike ADAPT, the total electricity supply and demand volumes hardly change, illustrating that the TRANSFORM scenario relies heavily on electrification of the energy system and that there are no alternatives if renewable electricity production costs rise sharply.

Although the need for deep electrification remains unchanged, electricity storage choices shift as rising critical-mineral intensity raises lithium-ion battery costs. Li-ion battery capacity declines by 25% and is replaced by compressed-air energy storage (CAES) in TRANSFORM. In ADAPT, the effect is negligible: Li-ion battery capacity in the base case is already 85% lower than in the TRANSFORM base case, and this small volume remains essentially unchanged in this scenario despite the cost increase.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
		2030		2040		2050
■ Other	48	48	54	54	61	61
■ Nuclear	37	37	354	367	728	749
■ Synthetics	9	9	9	13	10	10
■ Rewew. heat	96	122	212	236	289	361
■ Renew. electricity	417	417	795	621	1094	878
■ Biomass/biofuels	246	250	560	516	884	893
■ Fossil fuels	2384	2397	1825	1879	1165	1327
■ Hydrogen import	0	0	95	103	178	196
■ Electricity import	189	174	34	34	90	85

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
		2030		2040		2050
■ Other	48	48	52	52	51	51
■ Nuclear	37	37	364	365	740	769
■ Synthetics	8	8	6	6	5	5
■ Rewew. heat	92	95	152	168	363	433
■ Renew. electricity	468	437	1184	1164	1859	1878
■ Biomass/biofuels	235	240	556	556	862	862
■ Fossil fuels	2117	2213	1263	1302	215	213
■ Hydrogen import	0	0	46	60	238	201
■ Electricity import	201	196	35	32	61	55

Figure 4.9: Primary energy supply, including feedstock and international bunker fuels for the what-if analysis considering critical mineral scarcity compared to ADAPT (top) and TRANSFORM (bottom).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
Use transport	54	54	133	129	171	160
Use built environment	135	103	112	168	110	163
Use industry	252	254	198	187	294	293
Use fuel conversion	15	14	31	18	24	11
Use H2 production	61	39	58	8	397	241
Use export	143	169	215	222	102	105
Supply domestic	-472	-459	-714	-697	-1007	-887
Supply import	-189	-174	-34	-34	-90	-85

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
Use transport	35	35	116	115	155	156
Use built env.	134	150	81	100	88	98
Use industry	231	223	196	186	231	193
Use Fuel conv.	15	15	25	30	46	21
Use H2 prod.	42	42	482	424	734	758
Use export	148	176	192	216	509	571
Supply domestic	-404	-445	-1057	-1040	-1702	-1742
Supply import	-201	-196	-35	-32	-61	-55

Figure 4.10: Electricity supply and demand balances for the what-if analysis considering critical mineral scarcity compared to ADAPT (top) and TRANSFORM (bottom).

Hydrogen balance

Since hydrogen production is affected in both ADAPT and TRANSFORM, it is useful to examine hydrogen balances in more detail (see **Figure 4.11**).

Hydrogen use in the Dutch energy system decreases significantly in ADAPT: -6% in 2040 and -18% in 2050; while in TRANSFORM, hydrogen use rises slightly (+1.5%) when critical-mineral constraints raise technology supply-chain costs. In ADAPT, electrolytic hydrogen drops by 40% (-100 PJ) in 2050 due to the higher capital costs of electrolysers. Hydrogen production from steam methane reforming (SMR) increases by 35% (+4 PJ), partially compensating for the reduced green hydrogen production. Demand decreases mainly in ammonia production (-96 PJ). The scenario relies less on electrification and alternative molecules, so higher renewable and electrolyser costs trigger a broad reduction in hydrogen use and system wide adaptation.

In TRANSFORM, strong dependence on renewables, electrolysis, and electrification leads to much higher electrolytic hydrogen: in 2050 467 PJ in the base scenario rises to 500 PJ (+36%) under the critical-minerals case. SMR production increases by 47% (+11 PJ) to support shifts in trade. Imports fall by 37 PJ (−15%), while exports rise by 40 PJ (+25%). Lower imports combined with higher export obligations require more domestic production. Changes in imports and exports are the result of hourly price fluctuations and complex market interactions that make exporting more attractive and imports less attractive despite higher costs.

Carbon balance

The impact on the carbon balance of increased technology costs resulting from mineral scarcity is limited in both scenarios. As shown in **Figure 4.12**, CCU in ADAPT increases by 2.5 Mton in 2050, while in TRANSFORM it decreases by 3.8 Mton. In ADAPT, the rise is linked to greater production of synthetic methanol for maritime bunkers, replacing ammonia as a marine fuel. Conversely, the decline in TRANSFORM is associated with reduced synthetic fuel production.

In summary

Rising costs for critical-mineral-intensive technologies moderately affect the energy system, with different impacts between ADAPT and TRANSFORM. Overall primary energy supply remains stable, but energy composition shifts. In ADAPT, higher costs reduce the competitiveness of renewable electricity, leading to substitution by fossil fuels, renewable heat, and hydrogen. In TRANSFORM, the system is more resilient due to its structural dependence on electrification and fewer fossil or biomass alternatives, maintaining renewable electricity use. Hydrogen plays a key balancing role: in ADAPT, domestic production declines, while in TRANSFORM, domestic production expands. Thus, systemic sensitivity to critical mineral constraints is higher in a more CCS-, industry- and fossils-reliant scenario (ADAPT) and lower in higher renewable strongly electrified systems (TRANSFORM), indicating that deep electrification can mitigate, but not eliminate, cost increases due to mineral supply scarcity.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use other	87	83	93	83	91	91
■ Use NH3 energy	0	0	0	0	65	11
■ Use NH3 fertiliser	0	0	0	0	52	11
■ Use feedstock	11	11	17	17	13	13
■ Use P2L	5	5	0	0	0	0
■ Use energy	0	0	0	5	1	0
■ Use export	41	46	113	107	215	233
■ Supply import	0	0	-95	-103	-178	-196
■ Supply process	-9	-13	-7	-4	0	0
■ Supply electrolyser	-41	-29	-38	-8	-250	-150
■ Supply SMR	-94	-102	-84	-97	-10	-14

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use other	86	85	101	134	75	90
■ Use NH3 energy	0	0	88	21	244	264
■ Use NH3 fertiliser	0	0	13	0	14	14
■ Use feedstock	9	9	13	13	9	9
■ Use P2L	9	9	58	86	225	166
■ Use energy	0	1	4	1	5	0
■ Use export	46	46	50	66	156	196
■ Supply import	0	0	-46	-60	-238	-201
■ Supply process	0	0	0	0	0	0
■ Supply electrolyser	-29	-29	-273	-252	-467	-503
■ Supply SMR	-122	-122	-8	-8	-24	-36

Figure 4.11 Hydrogen supply and demand balances for the what-if analysis considering critical mineral scarcity compared to ADAPT (top) and TRANSFORM (bottom).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
▦ CCS DAC	0,00	0,00	0,00	0,00	1,60	1,61
▦ CCS bio	3,85	3,31	20,06	22,65	29,32	30,30
▦ CCS fossil	8,85	9,39	14,94	12,19	9,09	8,09
▦ CCU DAC	0,00	0,00	0,00	0,00	0,05	0,02
▦ CCU bio	0,45	0,38	0,16	0,49	0,95	0,30
▦ CCU fossil	1,80	1,53	0,09	0,27	0,29	3,52
▦ CC DAC	0,00	0,00	0,00	0,00	-1,65	-1,63
▦ CC bio	-4,31	-3,70	-20,23	-23,14	-30,27	-30,60
▦ CC fossil	-10,65	-10,92	-15,03	-12,45	-9,38	-11,61

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
▦ CCS DAC	0,00	0,00	0,00	0,00	1,97	3,69
▦ CCS bio	3,38	3,54	11,43	8,29	10,18	9,10
▦ CCS fossil	6,15	6,13	3,57	6,71	2,84	2,23
▦ CCU DAC	0,00	0,00	0,00	0,00	1,85	2,51
▦ CCU bio	0,92	0,75	3,22	2,61	9,56	6,20
▦ CCU fossil	2,04	4,42	3,42	4,51	2,68	1,53
▦ CC DAC	0,00	0,00	0,00	0,00	-3,83	-6,20
▦ CC bio	-4,30	-4,28	-14,65	-10,90	-19,75	-15,30
▦ CC fossil	-8,19	-10,54	-6,99	-11,22	-5,53	-3,76

Figure 4.12 CO_2 balances for the what-if analysis considering critical mineral scarcity compared to ADAPT (top) and TRANSFORM (bottom).

4.4 Limited energy quality of buildings

This what-if case has only been performed for the TRANSFORM scenario. The what-if scenario limits the extent to which both residential and service-sector buildings can upgrade to higher energy-efficiency labels over time.

Effect on the energy system

The restriction in the built environment (residential and service sector buildings) to move to higher insulation levels, does not change the total building stock itself. For residential, there are almost 9 million dwellings in 2050 and for the service sector the ground floor area (GFA) remains at 501 million square meters.

Residential sector

In the what-if case the composition of energy labels changes compared to the base case. Where in the base case, level A and A+ residential dwellings account for about 36%, level B for 53%, and level C/D for 12%; in the what-if case we see an identical share for level A/A+ dwellings (36%), but level B decreases somewhat to 49%, and level C/D decline to 4%. The remaining part consists of level E/F/G dwellings (12%), which were not present in the base case. This change in composition also leads to a different provision of heat for dwellings, see **Figure 4.13**: in the base case heat is delivered for about 1% by solar thermal technologies, 80% by air and ground source heat pumps and 18% from district heating networks. In the what-if case, the total demand increases by 3% to 293 PJ in 2050. This mix also changes slightly: solar thermal accounts for 3%, heap pumps for 81% and district heating for 16%. In both cases there is hardly any gas used for heating.

Service sector

In the service sector the stock of buildings (industrial halls (43% of GFA), offices (16%), education (7%), health care (6%), other (28%)) also remains unchanged between the base case and the what-if case. The composition according to insulation level and energy consumption for heat do change. In 2050, due to the restriction on building improvement, the stock share of level A/A+ building moves from 65% to 38%, level B from 35% to 34%, level C/D from 0% to 22% and level E/F/G from 0% to 5%. As a consequence, total energy for heat demand increases with 27% to 98 PJ, see **Figure 4.13**. Heat supplied by heat pumps stays about the same (40 PJ), but contribution from solar thermal increases from 28 PJ to 40 PJ and district heating increased from 9 PJ to 17 PJ. In addition, 2 PJ from hydrogen boilers appears in the what-if case.

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use lower	0,0	29,5	0,0	60,1		55,5
■ Use CD	138,5	44,1	70,5	19,1	49,7	13,9
■ Use B	101,1	158,7	153,5	153,5	167,7	157,1
■ Use A/A+	47,9	51,2	60,3	60,3	66,0	66,0
■ Supply exter. heat	-28,5	-28,4	-31,8	-35,4	-52,2	-45,6
■ Supply H2	0,0	-0,1	0,0	0,0	0,0	0,0
■ Supply HP	-47,1	-47,2	-54,8	-57,8	-227,3	-237,9
■ Supply Gas	-209,9	-202,9	-196,4	-196,7	-0,1	-0,2
■ Supply solar ther.	-2,0	-4,7	-1,4	-3,2	-3,8	-8,7

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use lower	0,0	3,8	0,0	6,5		9,3
■ Use CD	15,0	53,0	0,0	39,8	0	25,4
■ Use B	0,0	3,0	54,0	22,4	23,3	31,7
■ Use A/A+	48,4	27,7	27,8	25,8	54,1	31,7
■ Supply exter. heat	-8,3	-8,3	-10,2	-10,2	-9,2	-16,8
■ Supply H2	0,0	-0,4	0,0	0,0	0,0	-1,7
■ Supply HP	-32,4	-30,8	-20,7	-19,6	-40,2	-39,7
■ Supply Gas	-21,6	-46,9	-49,9	-63,8	0,0	-0,2
■ Supply solar ther.	-1,1	-1,1	-0,9	-0,9	-28,0	-39,8

Figure 4.13: Heat balance for residential sector (top) and service sector (bottom) for the what-if case considering limited energy quality of buildings compared to the TRANSFORM base case.

Primary energy supply

In primary energy, the restriction of insulation levels in buildings only affects the use of renewable heat, namely solar thermal and ambient heat, together their use increases by 34 PJ in 2050, see **Figure 4.14**.

	TRANSFORM 2030	What-if 2030	TRANSFORM 2040	What-if 2040	TRANSFORM 2050	What-if 2050
■ Other	48	48	52	52	51	51
■ Nuclear	37	37	364	364	766	766
■ Synthetics	8	8	6	6	5	5
■ Rewew. heat	92	94	152	161	411	445
■ Renew. electricity	468	469	1184	1192	1876	1877
■ Biomass/biofuels	235	235	556	553	862	862
■ Fossil fuels	2117	2165	1263	1298	213	213
■ Hydrogen import	0	0	46	60	201	201
■ Electricity import	201	196	35	32	55	55

Figure 4.14: Primary energy supply, including feedstock and international bunker fuels for the what-if analysis considering limited energy quality of buildings compared to the TRANSFORM base case.

Electricity balance

The electricity balance hardly changes for the built environment. The electricity demand in the built environment (i.e. residential and service sector) is 2 PJ higher in the what-if case in 2050 compared to the base case, see **Figure 4.15**.

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use transport	35	44	116	118	158	155
■ Use built envir.	134	133	81	80	100	102
■ Use industry	231	230	196	189	193	195
■ Use Fuel conv.	15	14	25	25	19	18
■ Use H2 prod,	42	42	482	461	756	756
■ Use export	148	176	192	216	571	571
■ Supply E-sector	-404	-442	-1057	-1058	-1743	-1743
■ Supply import	-201	-196	-35	-32	-55	-55
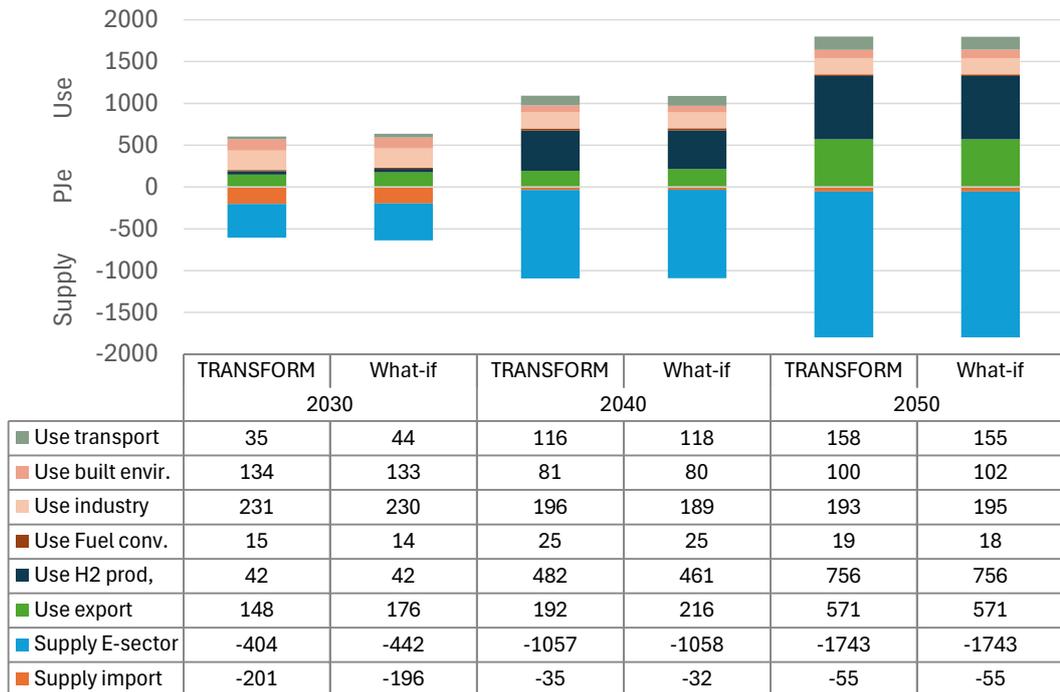
Figure 4.15: Electricity supply and demand balance for the what-if analysis considering limited energy quality of buildings compared to the TRANSFORM base case.

Hydrogen balance

The model searches for a new cost optimum in the what-if case resulting in minor changes in the hydrogen balance compared to the base case: **Figure 4.16** shows in 2050 more hydrogen production by steam-methane reforming (SMR) and by electrolysers, respectively 4 and 6 PJ. This is used for methanol production (+3 PJ) and for power-lo-liquids (+6 PJ). The total volume of hydrogen changes marginally: 10 PJ or about 1,4%.

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use other	86	84	101	104	63	66
■ Use NH3 energy	0	0	88	80	293	293
■ Use NH3 fertiliser	0	0	13	4	14	14
■ Use feedstock	9	9	13	13	9	9
■ Use P2L	9	9	58	61	142	148
■ Use energy	0	9	4	1	1	2
■ Use export	46	46	50	66	196	196
■ Supply import	0	0	-46	-60	-201	-201
■ Supply process	0	0	0	0	0	0
■ Supply electrolyser	-29	-29	-273	-262	-501	-507
■ Supply SMR	-122	-129	-8	-8	-16	-20

Figure 4.16 Hydrogen supply and demand balances for the what-if analysis considering limited energy quality of buildings compared to the TRANSFORM base case.

CO₂ balance

As carbon capture hardly plays a role in the built environment or for the energy they consume, marginal changes are to be noticed in the CO_2-capture, use and storage balance. As **Figure 4.17** shows, in 2050 there are about 0.3 Mton more captured in the what-if case, mainly from direct air capture and 0.1 Mton less from biogenic sources. This switch of 0.2 Mton is also noticeable in the amounts stored. These small shifts are due to cost optimisation.

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ CCS DAC	0,00	0,00	0,00	0,10	2,40	2,63
■ CCS bio	3,38	4,31	11,43	11,44	11,11	10,89
■ CCS fossil	6,15	4,79	3,57	4,15	1,49	1,48
■ CCU DAC	0,00	0,00	0,00	0,02	1,29	1,48
■ CCU bio	0,92	0,89	3,22	2,96	6,39	6,47
■ CCU fossil	2,04	4,02	3,42	3,66	1,40	1,45
■ CC DAC	0,00	0,00	0,00	-0,12	-3,69	-4,12
■ CC bio	-4,30	-5,21	-14,65	-14,39	-17,49	-17,36
■ CC fossil	-8,19	-8,81	-6,99	-7,81	-2,90	-2,93

Figure 4.17 CO_2 balances for the what-if analysis considering limited energy quality of buildings compared to the TRANSFORM base case.
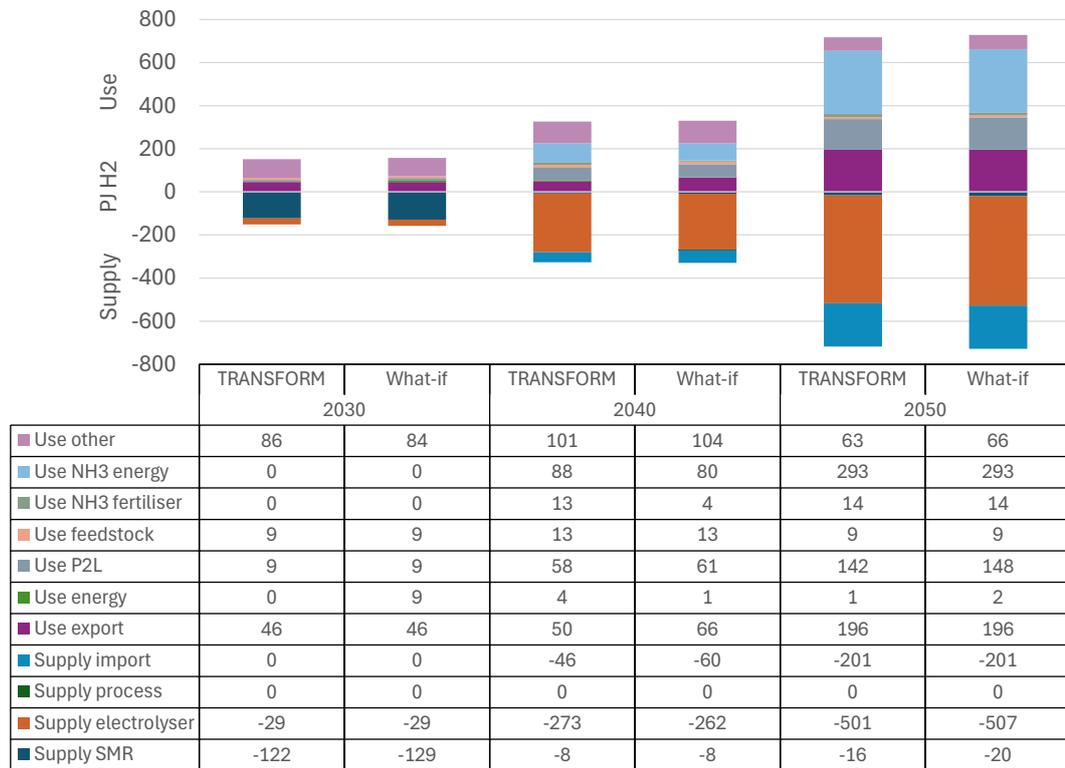
Summary

Limiting improvement of the building envelope in the residential and service sector leads to a different composition of the building stock regarding building quality with evidently more stock with lower energy labels (B, C/D or E/F/G). For households dwellings mostly label B and C/D are affected, for the service sector, mostly buildings with label A/A+ and to a lesser extent level B. Although energy levels in GJ heat per unit (dwelling or million km^2 GFA) are higher for lower insulation levels, the system seeks to satisfy this demand and efficient as possible, hence the small differences in absolute heat supply and a bit more difference in the heat supply mix. Overall, system effects for the different indicators are small.

4.5 Financing cost uncertainty

To assess the impact of the perceived risks of investors in energy projects on energy system development, a what-if analysis was conducted by increasing the weighted average cost of capital (WACC) from the societal discount rate of 2.25% to 6.5%

Primary energy supply

The higher WACC modelled under this what-if case results in different trends in the total primary energy supply between the ADAPT and TRANSFORM scenarios, see **Figure 4.18**. Similar to previous what-if cases, the most noticeable effects happen in 2050, where ADAPT's primary energy supply decreases by 79 PJ in 2050 compared to the reference, meanwhile TRANSFORM increases by 58 PJ.

These differences between the scenarios in primary energy can be pinpointed to one main component, uranium imports. In ADAPT, the decrease in primary energy is due to 177 PJ less of nuclear primary energy in the system. This drop does not occur in TRANSFORM, resulting in the disparity observed in the total primary energy. A notable commonality is the

increase of primary renewable heat production compared to baseline for ADAPT (+27 PJ) and TRANSFORM (+61 PJ) in 2050, mainly through solar thermal development for centralized heating purposes.

In the following paragraphs, these effects are explored on sub-system level in the electricity, hydrogen and carbon balances.
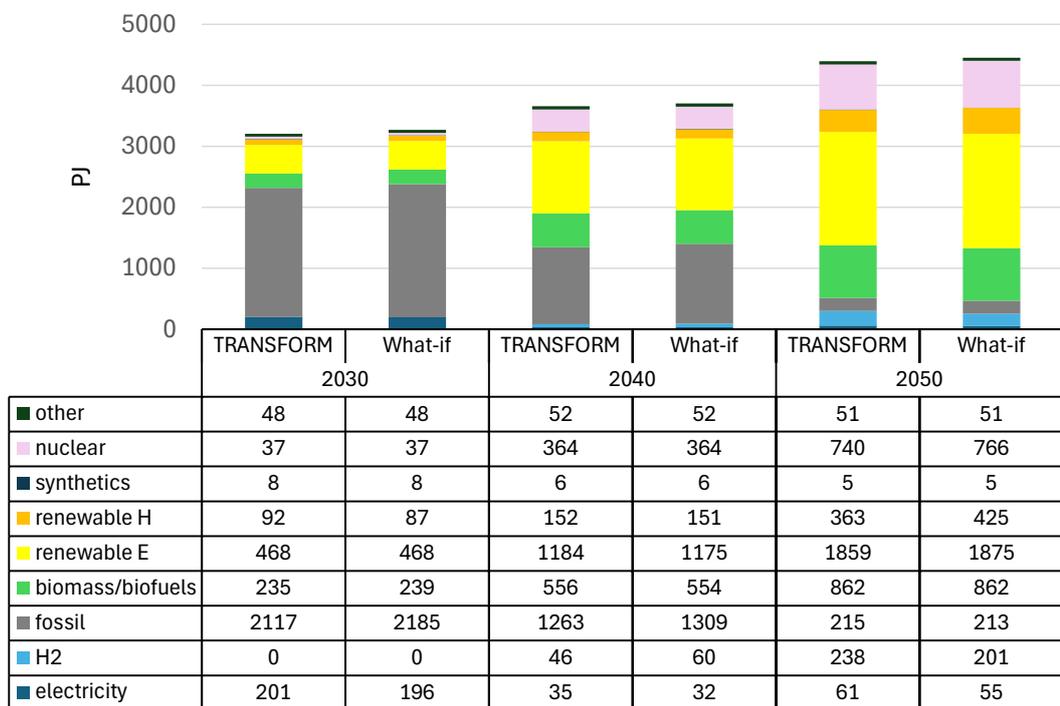
Electricity balance

Figure 4.19 shows the electricity balances for ADAPT and TRANSFORM across the analysed years for the baseline and the what-if case.

In ADAPT, an increase in the WACC affects the optimal deployment of nuclear capacity. By 2050, the installed capacity of large nuclear power plants decreases from 6 GW in the reference case to 5.2 GW in the what-if scenario. Similarly, the capacity of small modular reactors (SMRs) drops from 1.95 GW to 0.85 GW. These reductions result in a 56 PJ_e (–25%) decline in nuclear electricity generation. Some of this generation is replaced by solar, which increases output generation by 30 PJ_e in that year compared to the reference. An increase in WACC has virtually no impact on wind electricity generation.

The domestic electricity demand decreases in the ADAPT what-if case by almost 40 PJ_e in 2050 compared to the reference, mainly driven by a decrease in demand of 33 PJ_e for hydrogen production, followed by 6 and 5 PJ_e less electricity demand for fuel conversion and transport, respectively. Meanwhile, the electricity demands of the built environment and industry increase marginally by 15 and 8 PJ_e, respectively. In the built environment, district heating is affected by the increase in WACC, resulting in the substitution of centralized electric heating for decentralized hybrid heat pumps. For industry, an increase of electrification occurs by the electrification of steam cracker processes in the chemical sector. This electrification allows partial compensation of the additional usage of fossil fuels in other harder to abate sectors, as explored in more detail in the hydrogen and carbon balances. Overall, the net decrease in domestic electricity demand reduces the import volumes needed and increases slightly the exports available.

In the TRANSFORM scenario, nuclear capacity remains unaffected by the increase in WACC. By 2050, the full potential for both large-scale plants and small modular reactors (SMRs) is deployed in both the reference and what-if cases. Slight increases in electricity generation from nuclear and wind energy leads to a total rise in domestic supply of 43 PJ_e (+3%) in 2050.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Other	48	48	54	54	61	61
■ Nuclear	37	37	354	354	728	551
■ Synthetics	9	9	9	9	10	10
■ Rewew. heat	96	122	212	232	289	316
■ Renew. electricity	417	417	795	778	1094	1114
■ Biomass/biofuels	246	250	560	568	884	893
■ Fossil fuels	2384	2399	1825	1827	1165	1194
■ Hydrogen import	0	0	95	103	178	196
■ Electricity import	189	174	34	34	90	85

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ other	48	48	52	52	51	51
■ nuclear	37	37	364	364	740	766
■ synthetics	8	8	6	6	5	5
■ renewable H	92	87	152	151	363	425
■ renewable E	468	468	1184	1175	1859	1875
■ biomass/biofuels	235	239	556	554	862	862
■ fossil	2117	2185	1263	1309	215	213
■ H2	0	0	46	60	238	201
■ electricity	201	196	35	32	61	55

Figure 4.18 Primary energy supply, including feedstock and international bunker fuels for the what-if analysis with a higher WACC compared to ADAPT (top) and TRANSFORM (bottom).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use transport	54	54	133	133	171	166
■ Use built environment	135	103	112	122	110	125
■ Use industry	252	253	198	199	294	302
■ Use fuel conversion	15	14	31	27	24	18
■ Use H2 production	61	39	58	48	397	364
■ Use export	143	169	215	222	102	105
■ Supply domestic	-472	-458	-714	-718	-1007	-993
■ Supply import	-189	-174	-34	-34	-90	-85

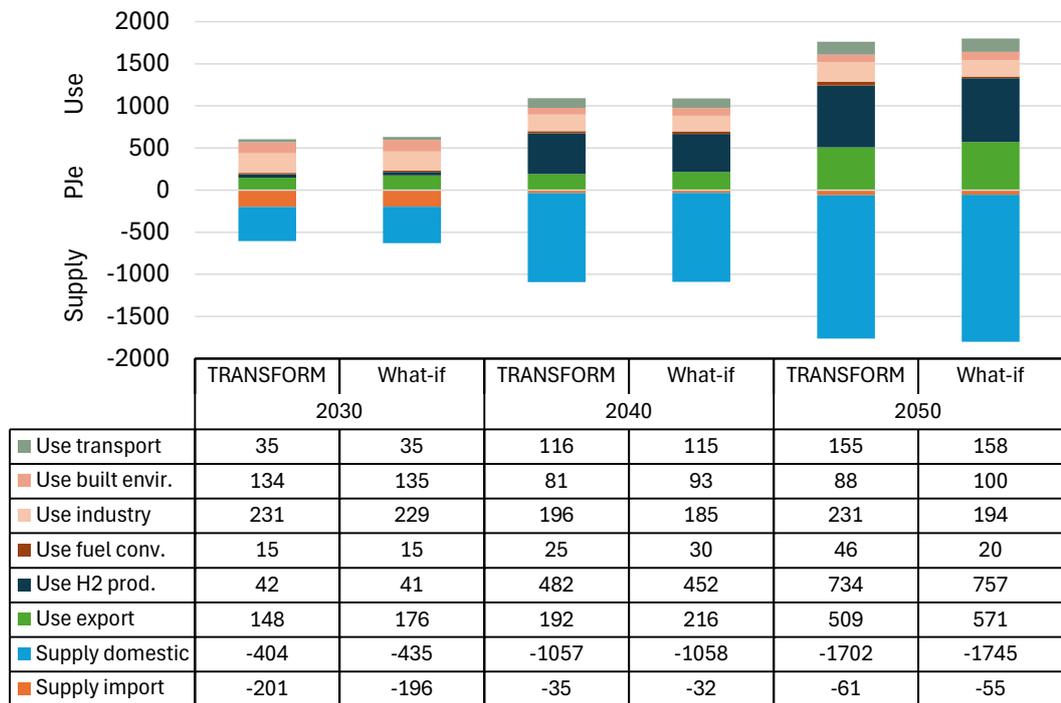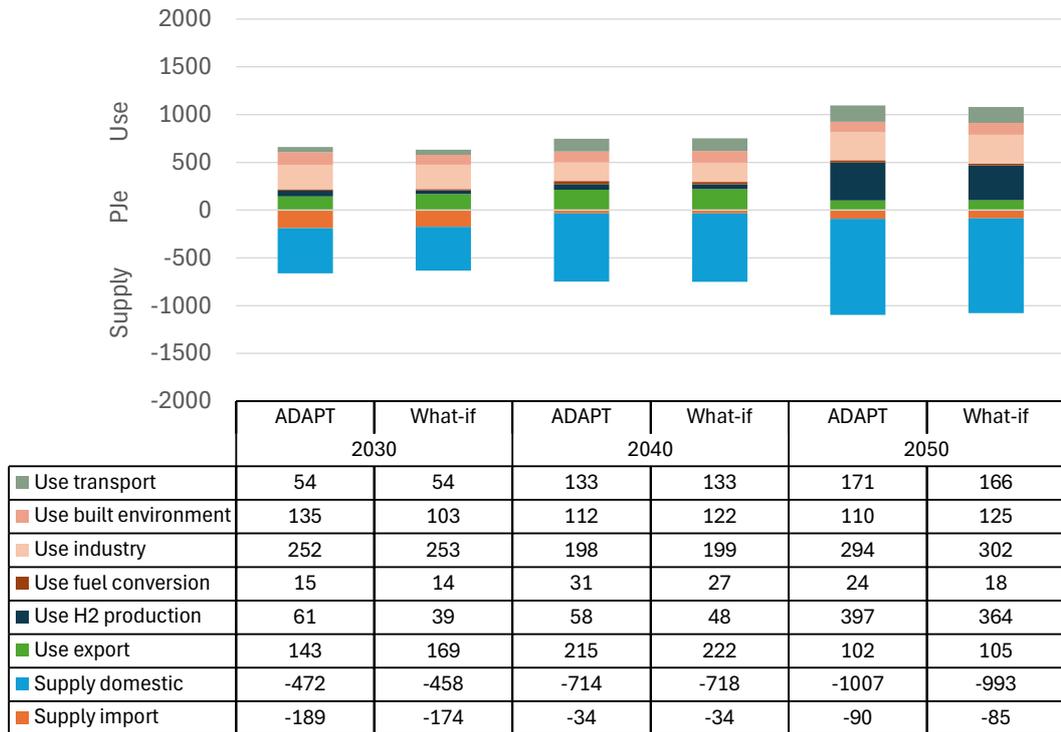|	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use transport	35	35	116	115	155	158
■ Use built envir.	134	135	81	93	88	100
■ Use industry	231	229	196	185	231	194
■ Use fuel conv.	15	15	25	30	46	20
■ Use H2 prod.	42	41	482	452	734	757
■ Use export	148	176	192	216	509	571
■ Supply domestic	-404	-435	-1057	-1058	-1702	-1745
■ Supply import	-201	-196	-35	-32	-61	-55

Figure 4.19: Electricity supply and demand balances for the what-if analysis with a higher WACC compared to ADAPT (top) and TRANSFORM (bottom).

In the TRANSFORM what-if case, the domestic electricity demand has a net increase in 2050 of 37 PJ_e compared to the reference scenario. Electricity demand increases for hydrogen production (+23 PJ_e), the built environment (+12 PJ_e) and transport (+3 PJ_e). The slightly higher demand for hydrogen production is explained in more detail under the hydrogen balance section. In the built environment, there is a similar effect as in ADAPT, where there are lower investments in the heat grid, with more focus on decentralized hybrid and ground-source heat pumps for households, which drive up electricity demand.

In the what-if case, the electricity demand for industrial applications and fuel conversion is lower compared to the reference. In industry this is mainly caused by less electrification of steam crackers, substituted by the conventional process with natural gas. Also, there is an increase in solar and geothermal energy, substituting electricity as a source for heat production. Lower electricity demand for fuel conversion can be attributed to shifts in the fuel mix for aviation and maritime bunker fuels. The combined effect of increased domestic electricity production and shifts in electricity demand results in a rise in net electricity exports of 68 PJ_e (+15%).

Hydrogen balance

Figure 4.20 showcases the hydrogen balance for both scenarios. The observed changes in the hydrogen system are correlated to decreasing hydrogen use in industry and bunker fuel production. Both ADAPT and TRANSFORM show an increase in hydrogen exports, since domestic demand for this energy carrier slightly declines. From the supply side, electrolysis is the main component affected leading to the reduction of hydrogen output of the system in both scenarios.

In the ADAPT what-if case, the domestic hydrogen demand (including exports) decreases by 6 PJ compared to the reference in 2050. This reduction is due to the substitution of ammonia in the navigation bunkers by a methanol-based fuel produced from fossil and biomass sources. This change in the end-use of the fuels has repercussions in the supply chain for industry, causing a decrease in hydrogen use for methanol production (- 8 PJ).

In the TRANSFORM what-if case a net decrease in hydrogen supply compared to the reference affects the P2L processes (-79 PJ), followed by lower use of hydrogen in industry for production of hydrogen-base methanol (-8 PJ) and for direct energy use (-4 PJ). This reduction is compensated by an increase of ammonia use (+49 PJ) and exports (+40 PJ). The synthetic fuels pathway (i.e. P2L) that uses hydrogen is partially substituted for bio-based processes, hence the lower hydrogen demand in this case. This has ultimate repercussions on the international bunkers, where the system moves from synthetic fuels to other alternative sources. In the navigation sector, ammonia use increases by 43 PJ in 2050, reducing the need for biofuels by 33 PJ and synthetic fuels by 10 PJ. On the other hand, the aviation sector fully replaces 33 PJ of synthetic fuel with biofuels. The increase of ammonia production to supply the navigation sector helps to liberate bio-sources which ultimately replace synthetic kerosine in the aviation sector.

Carbon balance

Figure 4.21 shows the carbon balance for both scenarios across the analysed years. In ADAPT, the impact remains relatively limited, with total CCU increasing by 0.6 Mt (+45%) and fossil carbon use rising by 0.9 Mt (+10%) in 2050. That same year, DAC grows by 0.4 Mt (+25%), while BECCS declines by 0.8 Mt (–3%), leading to a reduction in negative emissions. Despite these shifts, total CO_2 storage remains at the maximum level of 40 Mt.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use other	87	85	93	75	91	77
■ Use NH3 energy	0	0	0	10	65	51
■ Use NH3 fertiliser	0	0	0	0	52	57
■ Use feedstock	11	11	17	17	13	13
■ Use P2L	5	5	0	0	0	0
■ Use energy	0	0	0	1	1	1
■ Use export	41	46	113	106	215	233
■ Supply import	0	0	-95	-103	-178	-196
■ Supply process	-9	-16	-7	-12	0	0
■ Supply electrolyser	-41	-29	-38	-31	-250	-226
■ Supply SMR	-94	-101	-84	-65	-10	-10

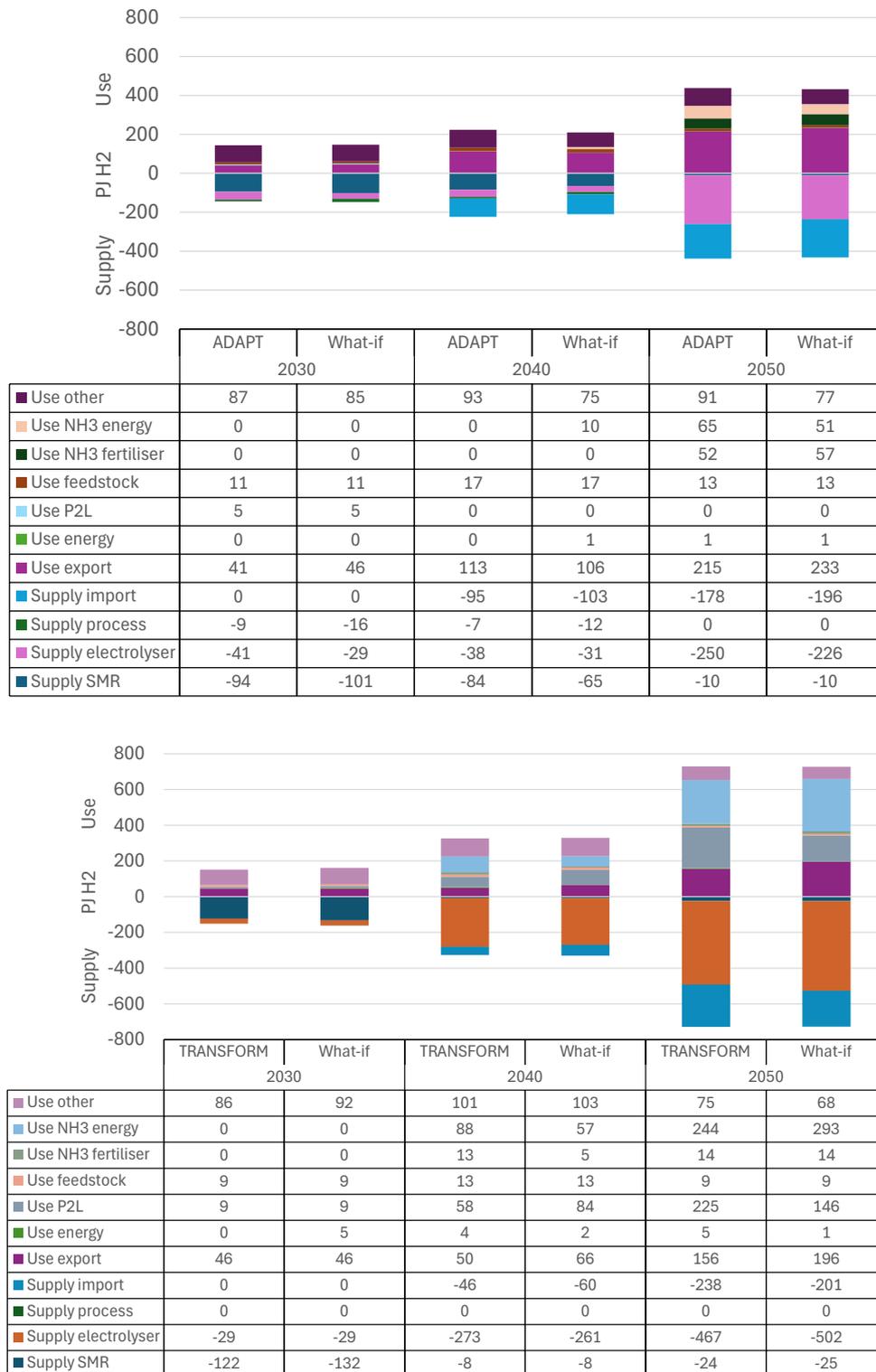|	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use other	86	92	101	103	75	68
■ Use NH3 energy	0	0	88	57	244	293
■ Use NH3 fertiliser	0	0	13	5	14	14
■ Use feedstock	9	9	13	13	9	9
■ Use P2L	9	9	58	84	225	146
■ Use energy	0	5	4	2	5	1
■ Use export	46	46	50	66	156	196
■ Supply import	0	0	-46	-60	-238	-201
■ Supply process	0	0	0	0	0	0
■ Supply electrolyser	-29	-29	-273	-261	-467	-502
■ Supply SMR	-122	-132	-8	-8	-24	-25

Figure 4.20: Hydrogen demand and supply balance for the what-if analysis with a higher WACC compared to ADAPT (top) and TRANSFORM (bottom).

In the TRANSFORM what-if scenario, total CCU is 4.9 Mt (–35%) lower than in the reference case, driven by reduced demand for synthetic fuels, which affects all CO_2 sources. Meanwhile, non-fossil CCS, responsible for generating negative emissions, increases slightly by 0.7 Mt (+6%), with total CCS remaining at the maximum of 15 Mt.
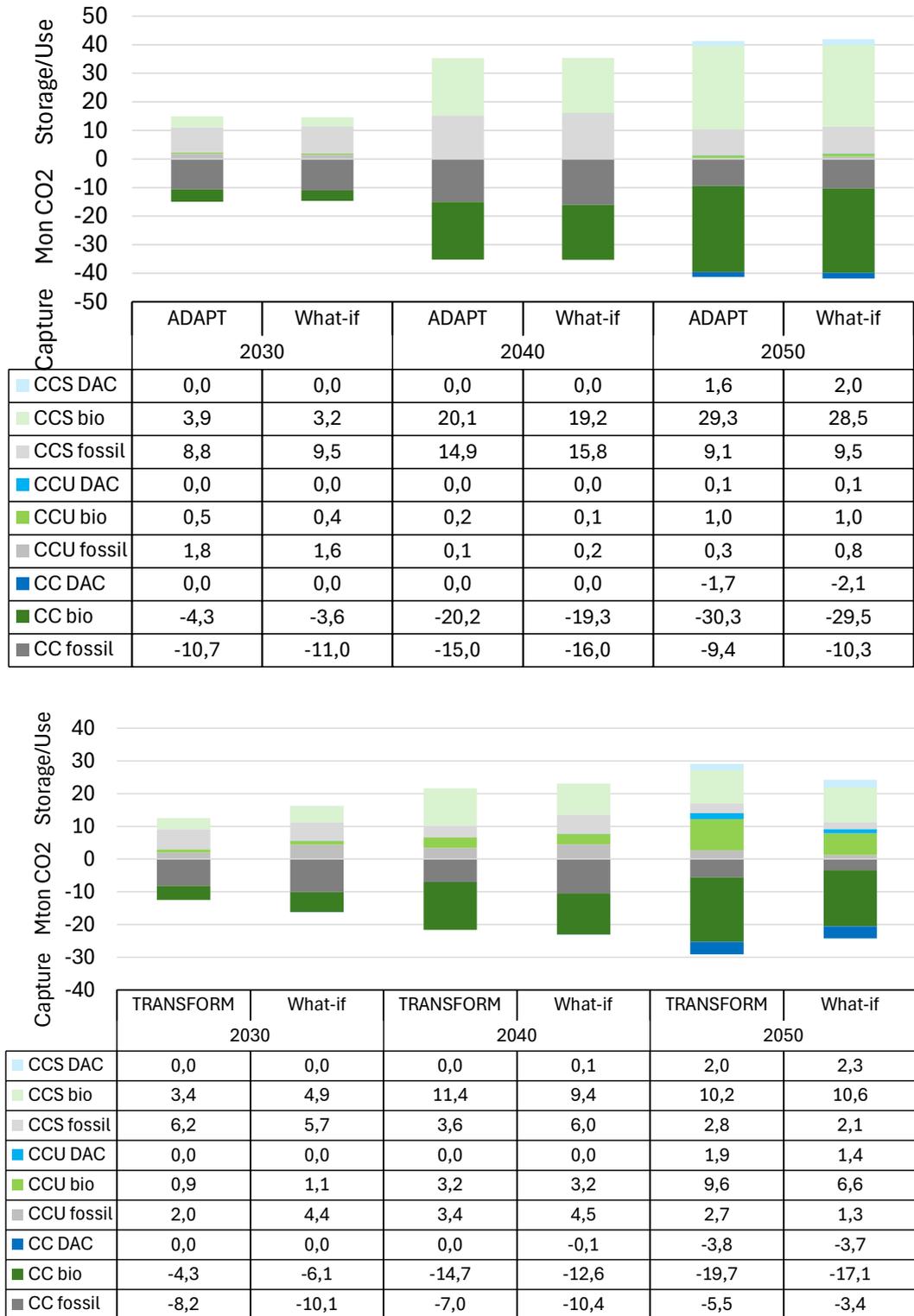
In summary

In this what-if case, the WACC was set to 6.5% to reflect perceived investment risks. When the cost of financing energy projects rises, it can have far-reaching effects on the entire energy system. This increase on the WACC penalizes capital-intensive assets, favouring technologies with lower upfront capital costs instead.

This effect is clearly observed under ADAPT. Because nuclear power plants require high upfront investments, higher WACC assumptions makes them less attractive from a cost minimization perspective. As a result, the capacity of large nuclear plants is lower than in the reference, and investments increase in small modular reactors (SMRs). This impacts the uranium import needs in 2050.

This reduced investment means less electricity production from nuclear, but wind electricity generation is hardly affected. Instead of nuclear, the system installs more solar PV capacity, but overall, the electricity supply becomes tighter, leading to lower electrification in some sectors. One of the main areas affected is the production of fuels for international transport. To ease pressure on electricity demand, the system reduces its use of electrolysis to produce ammonia, which is used for maritime bunkers in the reference. Instead, it supplies maritime bunkers with methanol, made from natural gas and biomass. This switch lowers electricity demand and domestic hydrogen demand in 2050. To balance the system, carbon capture, both from fossil sources and direct air capture (DAC), is slightly expanded.

In TRANSFORM, the rise in WACC has an even stronger impact on the energy system due to its more ambitious GHG reduction targets, relying heavily on synthetic fuel production to achieve them. In this scenario, the synthetic fuel production route is significantly affected with the increase in WACC. In the reference scenario, synthetic kerosene supplies aviation bunkers, but under a 6.5% WACC, this route becomes too expensive due to the capital intensive technologies along its supply-chain. There is an increase in the use of ammonia in the maritime sector, which replaces mainly biofuels use in the reference. This frees up bio-based fuels to replace synthetic fuels used in the aviation sector, which must fully decarbonize by 2050 in this scenario. Because synthetic fuel production declines, less carbon capture and utilization (CCU) is needed, as reflected in the carbon balance.

Altogether, in ADAPT, the higher WACC mainly affects the electricity supply side, reducing nuclear power (but not wind and solar PV) and leading to lower use of hydrogen. The system compensates by relying more on biomass and fossil fuels. The dynamics differ in TRANSFORM, where electricity production is not affected by a higher WACC. The impact is mostly in the production of sustainable fuels, where the model explores pathways with lower capital costs. Because TRANSFORM envisions fully carbon-neutral fuels for international aviation and shipping by 2050, fossil fuels are no longer an option like in ADAPT, forcing the system to reallocate limited bio-resources and adopt the lower-cost, carbon-free pathway of ammonia-based fuel.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ CCS DAC	0,0	0,0	0,0	0,0	1,6	2,0
■ CCS bio	3,9	3,2	20,1	19,2	29,3	28,5
■ CCS fossil	8,8	9,5	14,9	15,8	9,1	9,5
■ CCU DAC	0,0	0,0	0,0	0,0	0,1	0,1
■ CCU bio	0,5	0,4	0,2	0,1	1,0	1,0
■ CCU fossil	1,8	1,6	0,1	0,2	0,3	0,8
■ CC DAC	0,0	0,0	0,0	0,0	-1,7	-2,1
■ CC bio	-4,3	-3,6	-20,2	-19,3	-30,3	-29,5
■ CC fossil	-10,7	-11,0	-15,0	-16,0	-9,4	-10,3

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ CCS DAC	0,0	0,0	0,0	0,1	2,0	2,3
■ CCS bio	3,4	4,9	11,4	9,4	10,2	10,6
■ CCS fossil	6,2	5,7	3,6	6,0	2,8	2,1
■ CCU DAC	0,0	0,0	0,0	0,0	1,9	1,4
■ CCU bio	0,9	1,1	3,2	3,2	9,6	6,6
■ CCU fossil	2,0	4,4	3,4	4,5	2,7	1,3
■ CC DAC	0,0	0,0	0,0	-0,1	-3,8	-3,7
■ CC bio	-4,3	-6,1	-14,7	-12,6	-19,7	-17,1
■ CC fossil	-8,2	-10,1	-7,0	-10,4	-5,5	-3,4

Figure 4.21: CO_2 balance for the what-if analysis with a higher WACC compared to ADAPT (above) and TRANSFORM (below).

4.6   Limited flexibility options

This what-if analysis explores how increased flexibility costs and limited industrial flexibility could influence the Dutch energy system. Flexibility technologies, such as battery storage, electrolysers, and demand response are crucial for integrating variable renewable generation and ensuring reliable operation of the system. However, their long-term cost trajectories remain uncertain. To assess the system-wide implications of such uncertainty, flexibility-related costs are uniformly increased over time: by 10% in 2030, 30% in 2040, and 50% in 2050. Additionally, the flexibility of industrial plants is limited, see Section 3.6.
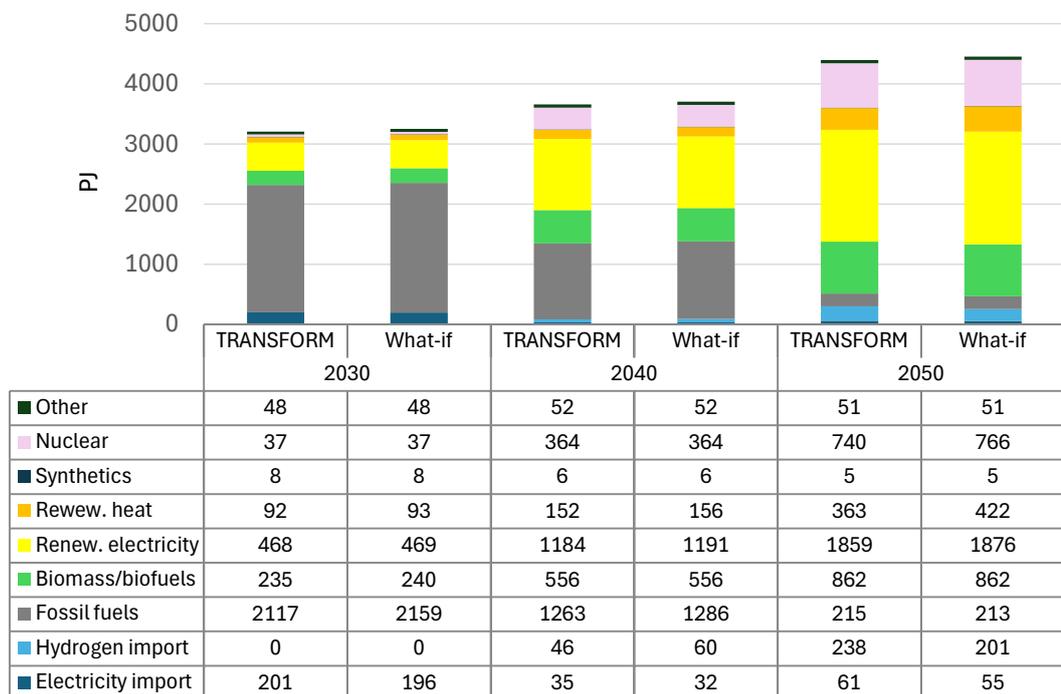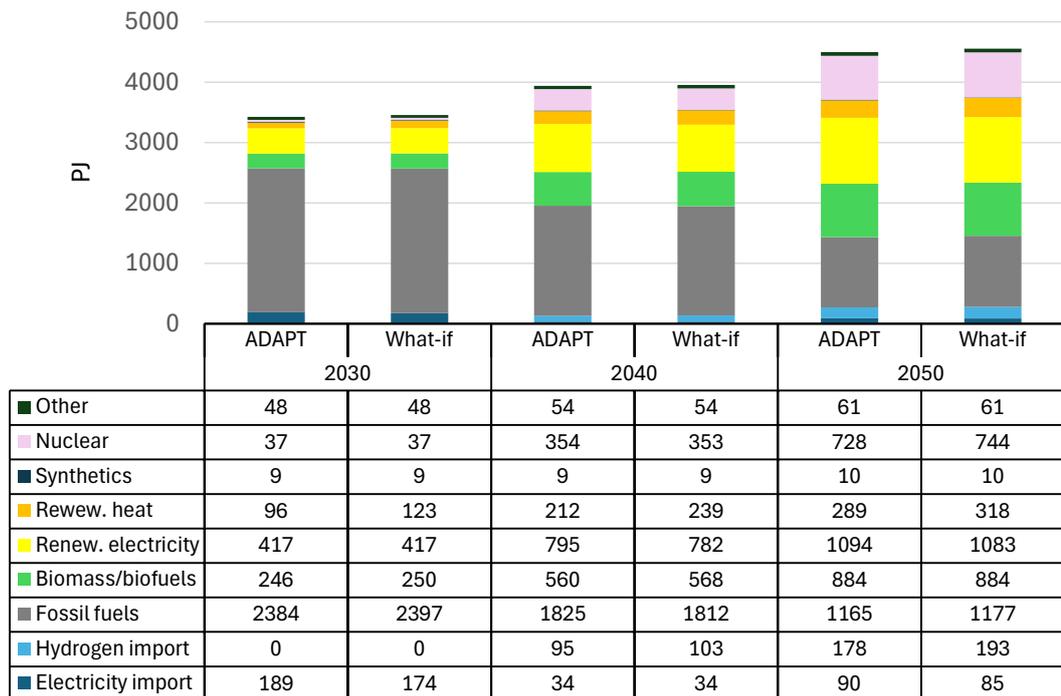
Primary energy supply

Under these higher-cost assumptions, total primary energy consumption remains relatively stable in both scenarios, showing that the system adapts mainly through internal reallocation rather than overall demand reduction. In ADAPT, total primary energy increases only marginally by 14 PJ (0.4%) in 2040 and 56 PJ (1.2%) in 2050, while in TRANSFORM, the increase is 46 PJ (1.3%) in 2040 and 57 PJ (1.3%) in 2050 (see **Figure 4.22**). The composition of primary energy supply, however, shifts significantly. The higher flexibility costs make renewable electricity less attractive for meeting heat demand, leading to a notable substitution by renewable heat sources such as geothermal and solar thermal. In ADAPT, renewable heat rises by 27 PJ (12%) in 2040 and 28 PJ (10%) in 2050, while in TRANSFORM the increase reaches 59 PJ (16%) in 2050. This transition occurs because electric heating depends on the ability to shift or store electricity across time, particularly important in residential applications where heat demand fluctuates daily and seasonally. As storage and flexibility become more expensive, using renewable heat becomes a more cost-effective and reliable solution. Heat pumps that use ambient heat can provide flexibility to the electricity system through demand management.
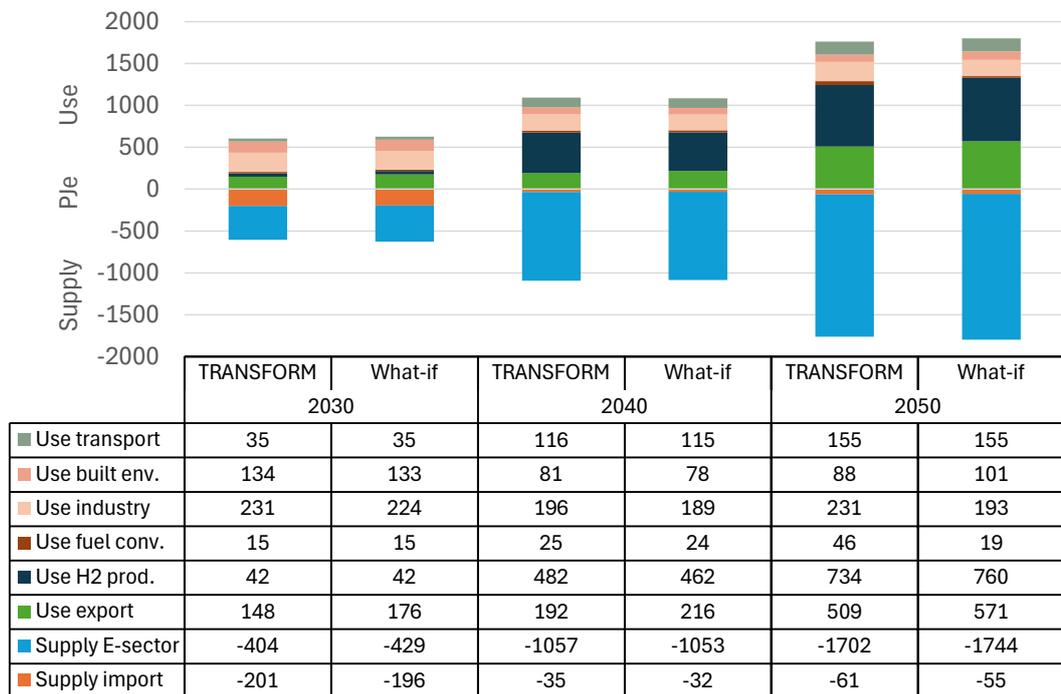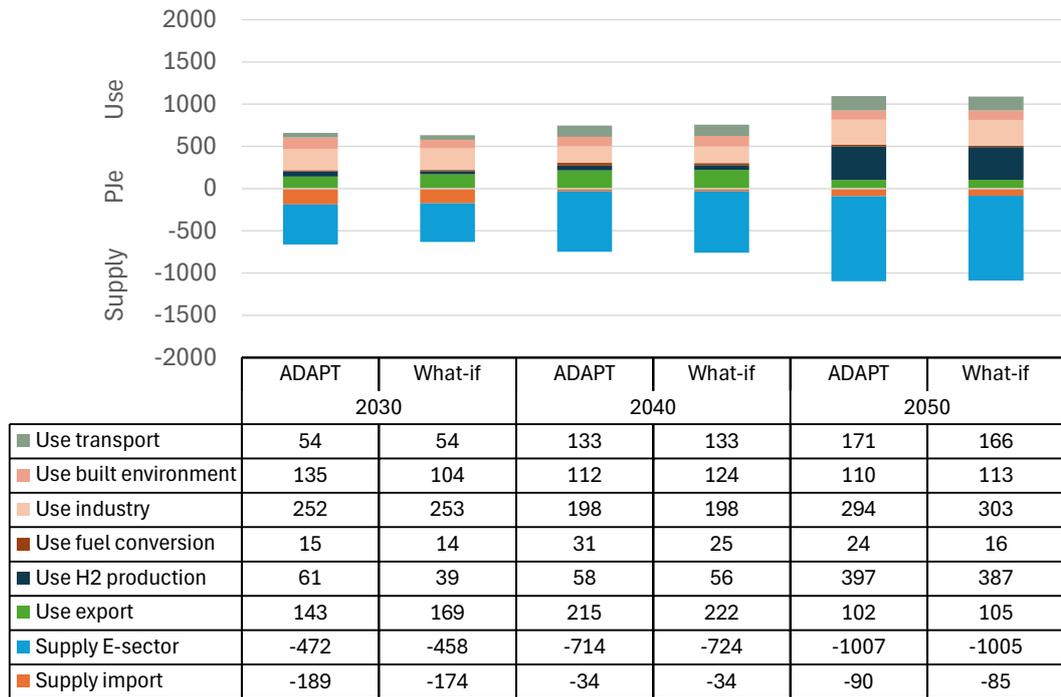
Electricity balance

The electricity balance reflects the shifts identified in the primary energy supply analysis. In ADAPT, domestic electricity production slightly decreases by 2 PJ (-0.2%) in 2050, while imports fall more notably by 4 PJ (-5%), as **Figure 4.23** shows. Electricity use for secondary conversions and hydrogen production declines: electricity to fuel conversions decrease by 8 PJ (-32%), and electricity to hydrogen by 10 PJ (-3%) in 2050. Electricity consumption also falls in district heating (-14%) and transport (-5 PJ or -3%). These reductions indicate that higher flexibility costs make electricity a scarcer and more expensive energy carrier, limiting its use in conversion and heating processes.

In TRANSFORM, overall electricity production and consumption remain broadly balanced, with a modest 36 PJ (2%) increase in total volumes in 2050. However, the internal structure again shifts: electricity for industry decreases by 38 PJ (-17%), electricity for central heating decreases by 23 PJ (-85%), and these are replaced by 17 PJ of solar thermal, 10 PJ of natural gas, and 5 PJ from heat pumps. Electricity exports increase by 62 PJ (12%), and electricity use for hydrogen production rises 26 PJ (3%), partly due to the use of cheaper but less efficient electrolysers.

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Other	48	48	54	54	61	61
■ Nuclear	37	37	354	353	728	744
■ Synthetics	9	9	9	9	10	10
■ Rewew. heat	96	123	212	239	289	318
■ Renew. electricity	417	417	795	782	1094	1083
■ Biomass/biofuels	246	250	560	568	884	884
■ Fossil fuels	2384	2397	1825	1812	1165	1177
■ Hydrogen import	0	0	95	103	178	193
■ Electricity import	189	174	34	34	90	85

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Other	48	48	52	52	51	51
■ Nuclear	37	37	364	364	740	766
■ Synthetics	8	8	6	6	5	5
■ Rewew. heat	92	93	152	156	363	422
■ Renew. electricity	468	469	1184	1191	1859	1876
■ Biomass/biofuels	235	240	556	556	862	862
■ Fossil fuels	2117	2159	1263	1286	215	213
■ Hydrogen import	0	0	46	60	238	201
■ Electricity import	201	196	35	32	61	55

Figure 4.22: Primary energy balances, including feedstock and international bunker fuels for the what-if case with limited flexibility options compared to ADAPT (top) and TRANSFORM (bottom).

	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use transport	54	54	133	133	171	166
■ Use built environment	135	104	112	124	110	113
■ Use industry	252	253	198	198	294	303
■ Use fuel conversion	15	14	31	25	24	16
■ Use H2 production	61	39	58	56	397	387
■ Use export	143	169	215	222	102	105
■ Supply E-sector	-472	-458	-714	-724	-1007	-1005
■ Supply import	-189	-174	-34	-34	-90	-85

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use transport	35	35	116	115	155	155
■ Use built env.	134	133	81	78	88	101
■ Use industry	231	224	196	189	231	193
■ Use fuel conv.	15	15	25	24	46	19
■ Use H2 prod.	42	42	482	462	734	760
■ Use export	148	176	192	216	509	571
■ Supply E-sector	-404	-429	-1057	-1053	-1702	-1744
■ Supply import	-201	-196	-35	-32	-61	-55

Figure 4.23: Electricity supply and demand balances for the what-if case with limited flexibility options compared to ADAPT (top) and TRANSFORM (bottom).

Hydrogen balance

Hydrogen dynamics vary between the scenarios, see **Figure 4.24**. Higher flexibility costs (storage and electrolysers) cause only minor changes in the hydrogen balance for both ADAPT and TRANSFORM. In ADAPT, electrolytic production decreases by 10 PJ (-4%) in 2050, while SMR output rises by 3 P (31%) to partially replace lost e-hydrogen. On the demand side, ammonia use for energy (mainly bunkers) falls by 7 PJ (-15%). Total hydrogen consumption increases slightly by 8 PJ (2%), driven by higher exports.

In TRANSFORM, the response differs. Despite higher electrolyser CAPEX, electrolytic hydrogen production increases by 39 PJ (8%). This additional output is absorbed by a 20% rise in ammonia production and higher exports. Whereas ADAPT offsets higher electrolyser costs by shifting toward SMR, TRANSFORM, constrained by fewer fossil options, continues to depend strongly on green hydrogen.

Carbon balance

In the ADAPT what-if case, the volumes for CO_2 capture, utilisation, and storage remain virtually unchanged compared to the baseline scenario. The total amount of CCS also remains unchanged at a maximum of 40 Mt in 2050. **Figure 4.25** shows a marginal shift between DAC and fossil CO_2 capture: DAC decreases by 0.6 Mt (-38%), while fossil CO_2 capture increases by the same amount. This is also reflected in the composition of CCS: a decrease of 0.6 Mt from DAC is offset by an increase of 0.3 Mt from biogenic CO_2 and 0.3 Mt from fossil fuels.

The changes in TRANSFORM are somewhat larger. Compared to the baseline scenario, CO_2 capture is 5 Mt (-33%) lower in the what-if case, but CCS remains at its maximum of 15 Mt. The decrease in CO_2 capture occurs at roughly the same rate for fossil and biogenic CO_2. This is also reflected in the lower CO_2 use for the production of synthetic fuels and feedstocks.

Other observations

Flexibility capacity responds differently across the two scenarios. In ADAPT, overall flexibility declines: battery capacity drops by 12 GWh (-26%), electrolyser capacity by 1 GW (-7%), and compressed-air storage remains limited. The reduced flexibility leads to an increase in required transmission capacity, high-voltage lines expand by 14%, and medium- and low-voltage lines by 4 and 6%, respectively.

In contrast, TRANSFORM maintains system flexibility by altering its composition rather than reducing it. Battery storage increases sharply from 41 GWh to 66 GWh (+61%), compensating for the disappearance of compresses-air storage (-18 GWh) and a 2 GW reduction in electrolyser capacity (-16%). This indicates a substitution among flexibility technologies: the system relies more heavily on batteries despite their higher costs, while scaling back other options to sustain operability.
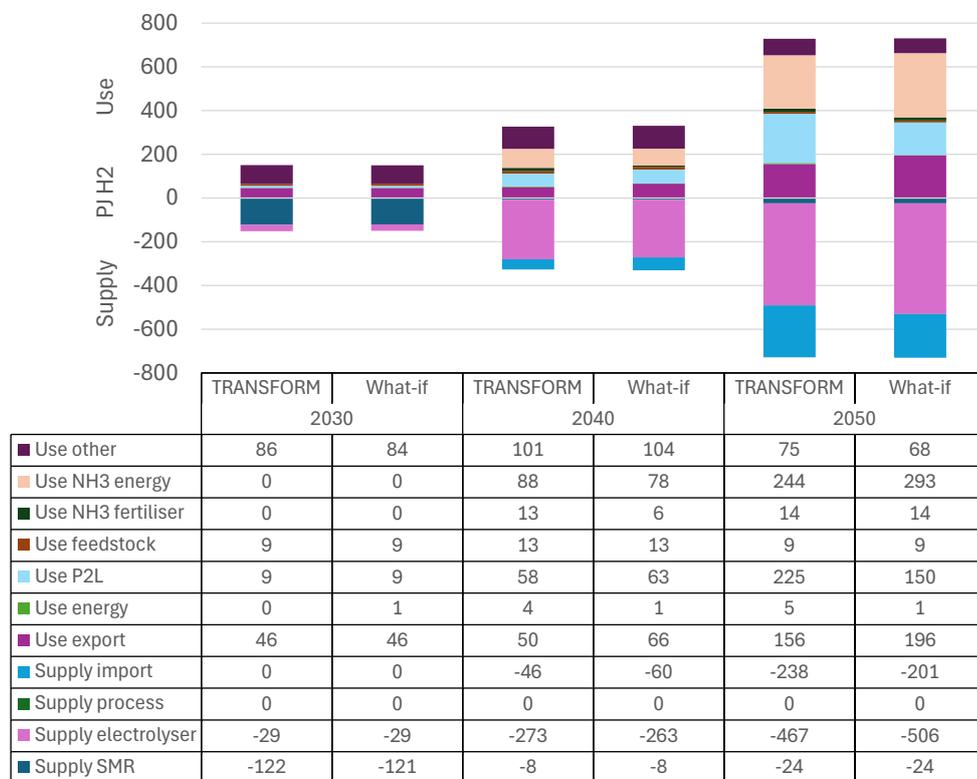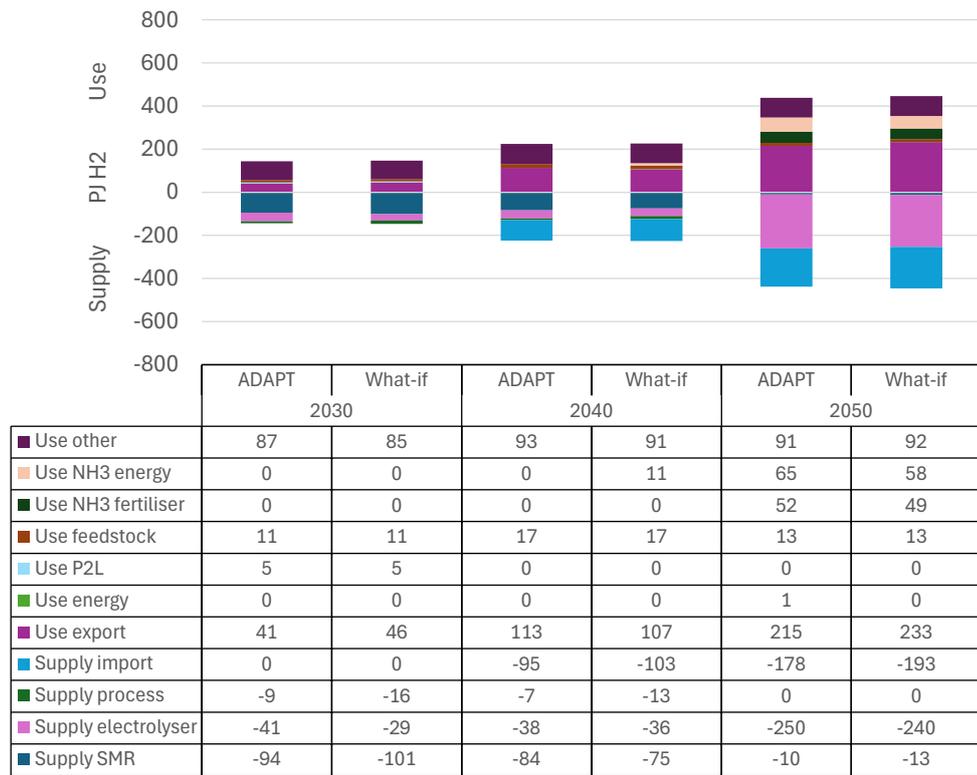
	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
■ Use other	87	85	93	91	91	92
■ Use NH3 energy	0	0	0	11	65	58
■ Use NH3 fertiliser	0	0	0	0	52	49
■ Use feedstock	11	11	17	17	13	13
■ Use P2L	5	5	0	0	0	0
■ Use energy	0	0	0	0	1	0
■ Use export	41	46	113	107	215	233
■ Supply import	0	0	-95	-103	-178	-193
■ Supply process	-9	-16	-7	-13	0	0
■ Supply electrolyser	-41	-29	-38	-36	-250	-240
■ Supply SMR	-94	-101	-84	-75	-10	-13

	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
■ Use other	86	84	101	104	75	68
■ Use NH3 energy	0	0	88	78	244	293
■ Use NH3 fertiliser	0	0	13	6	14	14
■ Use feedstock	9	9	13	13	9	9
■ Use P2L	9	9	58	63	225	150
■ Use energy	0	1	4	1	5	1
■ Use export	46	46	50	66	156	196
■ Supply import	0	0	-46	-60	-238	-201
■ Supply process	0	0	0	0	0	0
■ Supply electrolyser	-29	-29	-273	-263	-467	-506
■ Supply SMR	-122	-121	-8	-8	-24	-24

Figure 4.24: Hydrogen balance for the what-if case with limited flexibility options compared to ADAPT (top) and TRANSFORM (bottom).

Capture Mton CO2 Storage/Use	ADAPT	What-if	ADAPT	What-if	ADAPT	What-if
	2030		2040		2050	
☐ CCS DAC	0,00	0,00	0,00	0,00	1,60	0,99
☐ CCS bio	3,85	3,32	20,06	21,58	29,32	29,61
☐ CCS fossil	8,85	9,38	14,94	13,42	9,09	9,40
☐ CCU DAC	0,00	0,00	0,00	0,00	0,05	0,03
☐ CCU bio	0,45	0,37	0,16	0,05	0,95	0,75
☐ CCU fossil	1,80	1,51	0,09	0,26	0,29	0,66
☐ CC DAC	0,00	0,00	0,00	0,00	-1,65	-1,02
☐ CC bio	-4,31	-3,69	-20,23	-21,63	-30,27	-30,36
☐ CC fossil	-10,65	-10,89	-15,03	-13,67	-9,38	-10,07

Capture Mton CO2 Storage/Use	TRANSFORM	What-if	TRANSFORM	What-if	TRANSFORM	What-if
	2030		2040		2050	
☐ CCS DAC	0,00	0,00	0,00	0,00	1,97	2,39
☐ CCS bio	3,38	3,96	11,43	10,82	10,18	10,66
☐ CCS fossil	6,15	5,68	3,57	4,19	2,84	1,95
☐ CCU DAC	0,00	0,00	0,00	0,00	1,85	1,44
☐ CCU bio	0,92	0,87	3,22	2,86	9,56	6,67
☐ CCU fossil	2,04	2,83	3,42	3,67	2,68	1,32
☐ CC DAC	0,00	0,00	0,00	0,00	-3,83	-3,84
☐ CC bio	-4,30	-4,83	-14,65	-13,68	-19,75	-17,33
☐ CC fossil	-8,19	-8,51	-6,99	-7,86	-5,53	-3,27

Figure 4.25: CO$_2$ balance for the what-if case with limited flexibility options compared to ADAPT (top) and TRANSFORM (bottom).

Summary

This what-if analysis demonstrates that increasing flexibility costs do not drastically change total energy demand but fundamentally reshape how energy is produced, converted, and balanced. Electricity becomes a more constrained resource, reducing its role in heating and industrial processes, while renewable heat and hydrogen, especially imported hydrogen, take

on greater importance. ADAPT responds primarily through contraction and substitution, relying more on gas and solar thermal, whereas TRANSFORM emphasizes structural flexibility shifts and technology substitution. In both cases, the energy system adapts to higher costs by diversifying supply sources and reducing dependence on highly flexible, electricity-intensive pathways.

5 Discussion and conclusions

5.1 Discussion

Scope of the analysis

Scenarios such as ADAPT and TRANSFORM are used to examine pathways for making the Dutch energy system more sustainable and climate-neutral. These scenarios serve as exploratory analyses, meaning that only a limited number of constraints are applied to the modeling, primarily to prevent unrealistic outcomes.

In reality, the energy transition faces several bottlenecks, which may prevent the transition pathways outlined by exploratory scenarios like ADAPT and TRANSFORM from being realized. This study therefore examined how these pathways change when several constraints and limitations are considered.

These alternative pathways were determined using what-if analyses performed in the same way as the original ADAPT and TRANSFORM scenarios, i.e., modeled with the same cost optimization model OPERA. The model assumes that investment decisions are made to achieve system-wide cost optimality. In reality, individual actors, such as businesses and citizens, make choices that are optimal for themselves, which may not always align with overall economic efficiency. However, government policies can influence these decisions through targeted interventions.

A second remark relates to the scenario assumptions. The ADAPT and TRANSFORM scenarios explore how the energy system could evolve, meeting both energy and non-energy demand primarily through domestic renewable energy potential, supplemented by imports of raw biomass and a gradually declining share of fossil fuels. Other imports such as sustainable fuels and semi-finished products are restricted. Additionally, it is assumed that Dutch energy intensive industry continues producing the same types of goods as today and that fuels for international aviation and shipping (bunker fuels) are supplied from the Dutch energy system. If more supply options become possible, such as allowing the import of sustainable fuels or semi-finished products, this will change the scenario outcomes. The same applies to a reduction in energy demand. Both effects were analysed in industry variants of the TRANSFORM scenario in (Scheepers, et al., 2024).

In energy modeling based on cost optimization, limiting the possible solutions results in higher total system costs compared to the base scenarios. On the other hand, expanding supply options could lead to lower system costs. This study, however, did not analyze the impact on system costs because the focus is on energy system changes.

Overall observations

The what-if analyses reveal several valuable insights:
⟩ Achieving a sustainable Dutch energy system by 2050 requires the availability of innovative technologies and the ability to produce sufficient sustainable energy. For instance, the analysis "Limited availability of innovative technologies" shows that the Dutch sustainable energy system relies heavily on TRL 6, TRL 7 and several essential TRL 5 technologies, which still require further development and scaling-up. There are also inherent limits to reducing renewable electricity production capacity. The what-if analysis

"Spatial limitations" indicates that, given a limited renewable electricity potential, a sustainable Dutch energy system is, under the given demand assumptions, only feasible if another sustainable supply option increases, such as the import of biofuels.

⟩ Future technology costs remain uncertain, and altering cost assumptions in a cost-optimized energy system results in different transition pathways. Three what-if analyses ("Critical minerals", "Financing costs uncertainty", and "Limited flexibility options") illustrate this, sometimes producing similar outcomes, but also notable differences. In "Financing costs uncertainty", higher capital costs across all technologies particularly impact capital-intensive options such as nuclear energy, favouring less capital-intensive alternatives and reshaping the final energy mix. The "Critical minerals" analysis examines the effect of increased investment costs for renewable electricity, green hydrogen, and batteries, primarily influencing electricity and hydrogen production and, ultimately, end-user energy mixes. Finally, "Limited flexibility options" shows that higher flexibility costs raise electricity costs, prompting diversification toward lower-cost supply options. In all these what-if analyses changes in electricity and hydrogen costs also affect import and export flows.

⟩ The what-if analyses highlight the strong interdependence between subsystems for electricity, hydrogen, sustainable fuels, and carbon, resulting in cascading effects. For example, in "Limited availability of innovative technologies," restricting biofuel production increases synthetic fuel output in one scenario, which in turn raises demand for hydrogen and electricity. At the same time, reduced CO_2 capture from biofuel production makes the system more reliant on DAC. Similarly, in "Spatial limitations," limiting renewable electricity production reduces domestic hydrogen production, which in one scenario lowers synthetic fuel production and shifts the mix toward fossil fuels, biofuels, and ammonia as marine fuel.

⟩ Several what-if analyses indicate that constraints on available technologies or renewable electricity supply drive greater reliance on renewable heat and more efficient energy use. In "Limited availability of innovative technologies," the shift of electricity toward hydrogen production results in increased renewable heat use in buildings, supported by energy-efficient heat pumps. Similarly, "Spatial limitations" shows a move toward renewable heat due to restrictions on renewable electricity production.

⟩ Different boundary conditions for the scenarios lead to varying, and sometimes contradictory, responses to imposed constraints. The ADAPT scenario, with its less ambitious sustainability goals, allows more flexibility for alternative transition pathways compared to the more ambitious TRANSFORM scenario. This is evident in the "Critical Minerals" analysis: the systemic sensitivity to critical mineral constraints is higher in a more CCS and fossils reliant scenario (ADAPT) and lower in higher renewable strongly electrified systems (TRANSFORM), indicating that deep electrification can mitigate, but not eliminate, costs increases due to mineral supply scarcity. Conversely, TRANSFORM's higher sustainability ambitions can amplify responses seen in ADAPT, as demonstrated in "Spatial limitations" and "Financing Costs Uncertainty".

⟩ Constraints in end-user sectors, as explored in the what-if analysis "Limiting energy quality of buildings", primarily affect the composition of the final energy mix. Since higher energy demand can also be met through more efficient energy use (e.g. increased deployment of heat pumps), the impact on overall energy supply remains limited.

5.2 Conclusions

The following key conclusions can be drawn from this study:
⟩ To enhance the policy relevance of scenario studies, it is essential to account for real obstacles to the energy transition. Transition pathways toward a climate-neutral energy system, derived from exploratory scenarios with a limited number of preconditions and based on cost-optimisation modelling, may overlook real-world bottlenecks. Introducing

additional constraints uncovers alternative pathways to a climate-neutral energy system in 2050, while also identifying technologies and supply options that are critical for achieving climate neutrality. In some cases, policy measures can address the bottleneck (e.g. spatial limitations), but in other cases (e.g. scarcity of critical minerals), insight into possible alternative transition pathways may be relevant for energy and climate policy.

⟩ Scenarios outline possible futures that combine societal and political preferences with external factors such as the international context. A scenario where the transition to a sustainable energy system progresses more slowly (e.g., ADAPT) tends to be more resilient to emerging obstacles (e.g. critical minerals scarcity or spatial limitations) than one where the transition occurs more rapidly (e.g., TRANSFORM).

⟩ If obstacles emerge during the energy transition and the objective remains to achieve a cost-optimized sustainable energy system, it must be acknowledged that such limitations will require adjustments across multiple subsystems.

⟩ Energy supply constraints may necessitate adjustments in demand sectors, such as implementing energy efficiency measures. The reverse effect, i.e. constraints on end-user technologies, has a less pronounced impact on energy supply, as end-user sectors often have alternative solutions of their own to mitigate constraints.

References

4C Offshore News. (2025). *Germany's latest offshore wind tender falls flat with zero bids.* Opgehaald van https://www.4coffshore.com/news/germany27s-latest-offshore-wind-tender-falls-flat-with-zero-bids-nid31615.html

4C Offshore News. (2025). *Germany's latest offshore wind tender falls flat with zero bids.*

European Commission. (2021). *COM (2021) 562 Directive on renewable and low-carbon fuels in maritime transport.*

European Commission. (2022). Recommended parameters for reporting on GHG projections in 2023, unpublished document shared with Member States. European Commission.

European Commission. (2023). Directieve (EU) 2023/959.

European Commission. (2023). *ReFuelEU Aviation regulation.*

Fuelcellsworks.com. (2024). *Over a Fifth of European Hydrogen Projects Stalled or Cancelled.* Opgehaald van https://fuelcellsworks.com/2024/12/12/h2/westwood-insight-over-a-fifth-of-all-european-hydrogen-projects-stalled-or-cancelled#google_vignette

Hajonides van der Meuelen, T., Scaric, M., Tyraskis, I. L., & Verstraten, P. (2022). D7B.3 – Cost analysis and comparison of different hydrogen carrier import chains and expected costs development. HyDelta .

IEA. (2020). *Energy Technology Perspectives.*

IEA. (2024). *Energy Technology Perspectives.*

IEA. (2025). *Global Critical Minerals Outlook 2025.*

IEA. (2025). *Global Hydrogen Review 2025.*

IRENA. (2024). *Renewable power generation costs in 2024.*

IRENA. (2025). *Constructing a ranking of crtical materials for the global energy transition.*

(2022). *Klimaat en Energieverkenning.* PBL.

Klimaatakkoord. (2019).

Koirala, B., Hers, S., Morales-Espana, G., Ozdemir, O., Sijm, J., & Weeda, M. (2021). Integrated electriciity, hydrogen and methane system modelling frameworks: Application to the Durch Infrastructure Outlook 2050. *Applied Energy, 289*. doi:https://doi.org/10.1016/j.apenergy.2021.116713

Koivisto, M. (2022). *Pan-European wind and solar generation time series (PECD 2021 update).* DTU. Opgehaald van https://data.dtu.dk/collections/Pan-European_wind_and_solar_generation_time_series_PECD_2021_update_/5939581

Matthijsen, J., Dammers, E., & Elzinga, H. (2018). *De toekomst van de Noordzee - De Noorzee in 2030 en 2050: een scenariostudie.* PBL.

Ministerie van Infrastructuur en Waterstaat. (2023). *Nationaal Programma Circulaire Economie 2023-2030.*

Ministery of KGG. (2023). *Nationaal Plan Energiesysteem.*

Ministry of EZK. (2019a). Klimaatwet.

Ministry of EZK. (2019b). Wet verbod op kolen bij elektriciteitsproductie.

OECD. (2021). *Assessment of a Social Discount Rate and Fiancial Hurdle Rates for Energy System modelling in Viet Nam.*

Offshorewind.biz. (2024). *Zero Bids in Danish Offshore Wind Tender.* Opgehaald van https://www.offshorewind.biz/2024/12/06/zero-bids-in-danish-offshore-wind-tender/

Offshorewind.biz. (2025). Zero Bids in 1 GW Dutch Offshore Wind Tender. Opgehaald van https://www.offshorewind.biz/2025/10/31/zero-bids-in-1-gw-dutch-offshore-wind-tender/

PBL. (2022). *Klimaat en Energieverkenning (KEV).*

PBL. (2023). *Ruimtelijke verkenning 2023 - Vier scenario's voor de inrichting van Nederland in 2050.*

PBL. (2025). *Klimaat en Energieverkenning.*

Platform Geothermie. (2018). *Masterplan Aardwarmte in Nederland - Een brede basis voor een duurzame warmtevoorziening.*

Profundo. (2024). *Financing new nuclear - Governements paying the price?*

Scheepers, M., Gamboa Palacios, S., Janssen, G., Moncaddo Botero, J., van, S. J., Oliveira Machado dos Santos, J., & Uslu, A. W. (2022). *Towards a sustainable energy system for the Netherlands in 2050 - Scenario update and analysis of heat supply and chemical and fuel production form sustainable feedstocks.* TNO 2022 P 10162.

Scheepers, M., Stralen, J. v., Giraldo Chavarriaga, J., Elberry, A., Uslu, A., & Oliveira, C. (2024). *Towards a sustainable energy system for the Netherlands in 2050 - Scenario update an scenario variants for industry.* TNO 2024 P10607.

Sijm, J., Morales-Espana, G., & Hernández-Serna, R. (2022). *The role of demand response in the power system of the Netherlands, 2030-2050.* TNO P10131.

Stralen, J., Dalla Longa, F., Daniëls, B., Smekens, K., & Zwaan, B. v. (2021). OPERA: a New High-Resolution Energy System Model for Sector Integration Research. *Environmental Modelling & Assessment*, 873-889.

Stralen, J., Janssen, G., Koornneef, J., Scheepers, M., & Zwaan, B. (2025). Prospects for offshore hydrogen production in the Netherlands. *Environmental Research Energy*. doi:https://doi.org/10.1088/2753-3751/adb6a2

Taminiau, F., & van der Zwaan, B. (2022). *The Physical Potential for Dutch Offshore Wind Energy.* Journal of Energy and Power Technology.

The Brattle Group. (2018). *Risk and the Weighted Average Cost of Capital.*

The New York Times. (2023). *No Bidders in British Offshore Wind Auction.* Opgehaald van https://www.nytimes.com/2023/09/08/business/no-bidders-in-british-offshore-wind-auction.html

Weeda, M., & Eblé, L. (2024). *Evaluation of the levelised costs of hydrogen based on proposed electrolyser projects in the Netherlands.* TNO R10766.

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