Transformative change for 1.5°C

Identifying Paris-compatible landing zones for the energy system of the EU27 and selected member states

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Abstract

In this report, we develop and apply a new framework for assessing and classifying low-carbon energy and emissions pathways, based on the level and characteristics of energy system transformation required to align with the Paris Agreement. We apply this framework to assess the latest energy and emissions pathways included in the IPCC's Sixth Assessment Report, exploring what transformation may be necessary for the EU27 and selected seven member states to achieve the 1.5°C temperature goal.

We quantify and classify pathways based on the level of transformation observed in the four cross-cutting core challenges at the heart of the long-term transformation effort, the 4i's. These are: fostering innovation, mobilising investment and finance, rolling out infrastructure, and enabling greater integration across sectors. In addition, we use two illustrative mitigation pathways to perform an in-depth assessment of 1.5°C compatible energy and emissions pathways for the EU27 and seven selected member states: Germany, Finland, France, Belgium, Poland, the Netherlands and Spain. These pathways are then compared to current national plans and policies, and other national scenarios and modelling studies.

The report finds that the EU27 and member states could reduce emissions in the 2020s much faster than planned. The report finds technically feasible routes for the EU27 to reduce emissions in 2030 by 64-67% below 1990 levels by 2030, more than the currently submitted NDC of 54% (excluding LULUCF). While the recently released REPowerEU plan further accelerates the bloc's energy transition, it remains incompatible with the 1.5°C target as assessed by this report, leading to emissions reductions of 57-58% in 2030 relative to 1990. Climate action is also lacking at the member state level. None of the seven member states assessed has a 2030 target for domestic emissions reductions which aligns with globally cost-effective 1.5°C compatible pathways.

The report further explores how this transition could be achieved at the sectoral level for the EU27 and selected seven member states. Rapid power-sector decarbonisation driven by wind and solar deployment is a central component of 1.5°C compatible pathways. In all member states, coal is effectively phased out of the power sector by 2030, and in the most ambitious pathways, fossil gas exits in the 2030s. Clean electricity then forms the backbone of the future energy system, with widespread buildings, transport and industry electrification. Electrification, efficiency improvements and some reduction in consumer demand for the most carbon intensive goods leads to strong reductions in final energy demand in most pathways and countries. By transitioning to a more efficient energy system powered by renewable electricity, the EU27 and individual member states can rapidly displace fossil fuels from the energy mix and align with the 1.5°C goal.

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Abbreviations

Abbreviation	Description
BECCS	Biomass with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CDR	Carbon dioxide removal
EVs	Electric Vehicles
ESR	Effort Sharing Regulation
EU	European Union
ETS	Emission Trading System
IPCC AR6	IPCC 6th Assessment Report
PA	Paris Agreement
PA LTTG	Paris Agreement Long-term temperature goal
SDGs	Sustainable Development Goals
GHG	Greenhouse gas emissions
MS	Member states
VRE	Variable Renewable Energy
SIAMESE	Simplified Integrated Assessment Model with Energy System Emulator
LULUCF	Land use Change Land use change and forestry

Executive summary

Limiting warming to 1.5°C will require a rapid energy system transformation towards a zero-carbon future. This report explores how the EU27 and its member states can transform their energy systems to align with the 1.5°C goal and provide global leadership on climate action. It quantifies and classifies energy and emissions pathways, based on the level of transformation observed in the four cross-cutting core challenges at the heart of the long-term transformation effort, **the 4i's.** These are: fostering **innovation**, mobilising **investment** and finance, rolling out **infrastructure**, and enabling greater **integration** across sectors. It does so for a set of eight 1.5°C compatible pathways, produced by a range of models and representing a diverse set of possible low-carbon futures.

The report then conducts an in-depth exploration of the transformation required to align with 1.5°C across the sectors of power, transport, industry and buildings. Action at the member state level is crucial to the EU27's overall climate agenda. This report explores transformation pathways for the EU and seven selected member states: Germany, Finland, France, Belgium, Poland, the Netherlands and Spain using two illustrative pathways, the HighRE and SusDev[1]. These pathways demonstrate how the EU could maximise its domestic contribution to emissions reductions. Given the bloc's historical responsibility and economic/regulatory capacity to reduce emissions rapidly, identifying high ambition pathways for the EU27 and underlying member states provides valuable information on what a Paris-aligned NDC for the bloc could entail.

The report finds that the EU27 and member states can reduce emissions in the 2020s much faster than currently planned. **The EU27 can feasibly reduce emissions to 64-67% below 1990 levels in 2030** (excluding LULUCF). Table ES1 summarises the current 2030 targets as reported in government documents and compares them to 1.5°C compatible benchmarks derived from this report. **None of the seven member states assessed has a legislated 2030 emissions target that aligns with globally cost-effective 1.5°C pathways.**

The EU27 and individual member states continue to reduce greenhouse gas (GHG) emissions rapidly after 2030 on the path to net zero GHG emissions by 2050. **In 2040, EU27 emissions reach 85-86% below 1990 levels** (excluding LULUCF). As the EU27 begins to consider a post-2030 emissions reduction goal, this highlights the minimum level of ambition that the bloc should be considering, if it is to align with the 1.5°C temperature limit.

[1] The HighRE pathway focuses on rapid deployment of solar and wind (supported by storage/demand response) and high electrification of end-use sectors. Green hydrogen plays a key role in providing long-term energy storage and driving sector coupling between industry/transport and the power sector. There are relatively limited changes in the energy service demands.

The SusDev pathway focuses on achieving the Sustainable Development Goals alongside the Paris Agreement's temperature target. It exhibits strong and sustained reductions in CH_4 and N_2O emissions from the agricultural sector, as well as a transition away from energy-intensive lifestyles in Global North which results in strong reductions in EU final energy demand.

This 2040 target is also contingent on the EU27 strengthening its 2030 emissions target further, towards a 65% emissions reduction in 2030.

The analysis conducted in this report further indicates that a clean electricity sector is at the heart of transformation pathways for the EU27, with most selected member states achieving 100% clean electricity in the 2030s. Post-2030, end-use electrification then emerges as a key element of transformative change, with a huge growth of final electricity demand between 2030 and 2050. This has substantial implications for the level and timing of infrastructure needs. The analysis presented here suggests that infrastructure to facilitate renewables deployment in the power sector is needed urgently for the 2020s, while infrastructure required to substantially expand end-use electrification is more important for the post-2030 period.

Table ES1: 1.5°C compatible 2030 targets for the EU27 and selected member states

Country	Current 2030 Target (reduction below 1990 levels, excluding LULUCF)	1.5°C compatible 2030 target (reduction below 1990 levels, excluding LULUCF)
EU27	54%	64-67%
Germany	65%	73-77%
Finland	60%	64-70%
France	40%	42-57%
Belgium	23%	44-50%
Poland	29%	68-70%
The Netherlands*	49%	52-55%
Spain	23%	46-52%

*The coalition government in the Netherlands has proposed increasing their 2030 emissions reduction target to be 55% below 1990 levels, rather than the 49% inscribed in the existing Climate Act of 2019. This would broadly align the Netherlands with the cost-effective pathways assessed in this report. However, this still remains below the Netherlands' fair share contribution to global mitigation (Climate Analytics 2022a, Fekete *et al* 2022).

The report then explores how this transition can be achieved at the sectoral level. It finds some emerging areas of consensus in the IPCC's latest assessment report, while identifying other areas where uncertainty around the energy transition still remains.

Rapid power sector decarbonisation is crucial to achieving the 1.5°C goal. In the majority of low-carbon pathways, this is driven by wind and solar deployment. In pathways which represent the highest plausible ambition for Europe, **renewables provide over 80% of electricity generation in 2030 in the EU27, growing to 97-100% by 2050.** There is variation in individual member states, but in all countries the share of renewables approaches at least 70% in 2030 and 90% in 2050. In all member states, **coal is effectively phased out of the power sector by 2030.** The pathways also demonstrate that **it is feasible to phase out electricity generation from fossil gas in the 2030s,** to achieve a fossil-free power sector by the early 2040s in all selected member states.

Alongside power sector decarbonisation, electrification of buildings, transport, and industry emerges as a robust decarbonisation option. In the illustrative pathways, **electricity provides 57-66% of final energy in 2050 at the EU27 level**. The transition to a more efficient and electrified system can substantially reduce total energy demand, cutting out the energy wasted as heat in burning fossil fuels. **Electrification is energy efficiency.** Efficiency improvements, coupled with some reductions in consumer demand for final products, lead to a strong reduction in final energy demand in most pathways and countries.

Hydrogen also plays a key, but limited, role in the energy system. Models tend to deploy hydrogen in energy intensive industries and long-distance transport (where direct electrification is less competitive), as well as providing long-duration energy storage in a power sector dominated by wind and solar generation. Hydrogen is not deployed in the buildings sector, where electrification emerges as the cost-effective mitigation strategy.

This report helps to identify an emerging consensus within the literature on the form of transformation needed to align the energy system transition with 1.5°C. Renewable-based electrification, efficiency improvements, and some reductions in demand for final products can rapidly displace fossil fuels from the energy mix. However, in other transformation areas, uncertainty remains.

The level of hydrogen demand, CCS reliance and energy storage deployment varies strongly across the pathways. This highlights that choices must still be made about the shape of the EU27's energy transition. However, this flexibility should not be used as a reason to delay or deter action. Rather, it highlights the urgent need for leadership from the EU and member state governments to determine the energy transition's shape, set expectations, and guide investments.

The time has come to deliver, rather than plan, the energy transition. Transformative change is necessary to align the EU27 and member states with the 1.5°C goal. It remains to be seen whether such change will emerge in this critical decade for climate action.

Key messages for member states

Germany

Germany's energy transition is rapidly accelerating, driven in part by the Russian invasion of Ukraine and associated energy security concerns. The proposal to phase out coal by 2030 is the minimum ambition that could be seen as 1.5°C compatible and should be increased where possible. Recently increasing the renewable electricity target to 80% by 2030 is also to be welcomed, but there are pathways that show Germany could feasibly achieve over 90% of electricity generation from renewables by 2030. Germany can also reduce final energy demand by 19% in 2030, relative to 2019 levels. Progress on energy efficiency and demand reduction can reduce German energy import dependence and help address the costs to society of fossil-fuel import and supply disruptions, exemplified by the inflation and exploding consumer prices resulting from the current energy crisis.

Finland

Finland has already made strong progress towards decarbonisation, with over 50% of its energy coming from renewable sources in 2019. However, to align with 1.5°C, Finland would need to target a 64-70% reduction in GHG emissions (excluding LULUCF) in 2030 rather than the proposed 60%. A future 1.5°C compatible energy mix for Finland sees strong continued use of district heating in the buildings and industry sectors, in addition to increased direct electrification.

France

In 1.5°C compatible pathways, there is a strong transition towards renewables in France's power sector. Renewables provide 68-75% of electricity generation by 2030, up from 20% in 2019. This represents an unprecedented transformation in the French power sector, which has historically been dominated by nuclear power. France also has the greatest potential for direct electrification, with 67-73% of final energy demand electrified by 2050 in the illustrative pathways. Renewable based electrification leads to France's GHG emissions reaching 42-57% below 1990 levels in 2030 (excluding LULUCF).

Belgium

Among the EU member states analysed in this report, Belgium needs some of the greatest improvements in its climate targets, along with Poland and Spain. It has not updated its 2030 target since 2018 when it committed to a 23% reduction in GHG emissions relative to 1990 levels. In contrast, 1.5°C compatible pathways that demonstrate the highest plausible ambition for Europe reduce Belgium's GHG emissions by 44-50% relative to 1990 (excluding LULUCF). This is achieved by widespread electrification, energy efficiency and using other renewable fuels. Belgium also does not have a clear, economy-wide emissions target for 2050, which is a key omission that should be addressed.

Poland

Poland has one of the largest cost-effective mitigation potentials of all selected EU member states but is lagging behind. In the illustrative pathways (which are produced on principles of cost-effectiveness), Poland's GHG emissions (excluding LULUCF) reach 68-70% below 1990 levels by 2030 – far beyond its proposed target of 29%. This is partly due to Poland's heavy reliance on coal, which provides more than 30% of total final energy demand in 2019. To align with 1.5°C, Poland would need to considerably accelerate the pace of its energy transition. For this purpose it can already benefit from access to significant EU funds as well as redistributed EU ETS revenues.

The Netherlands

The Netherlands' current 2030 target is to reduce GHG emissions to 49% below 1990 levels by 2030. The latest coalition government has recently proposed to increase this, targeting a 55% reduction below 1990 levels, which unlike the 49% target is however not inscribed in law yet. Strengthening the 2019 Climate Act to include the 55% target is strongly welcomed and would align the Netherlands with the cost-effective illustrative pathways in this report. However, it may still be plausible for the Netherlands to outperform this target, particularly given recent cost reductions in offshore wind. Rapidly reducing fossil gas consumption in the power sector is a key step for the Netherlands to align with globally cost-effective 1.5°C compatible pathways and address the country's vulnerability to disruption of international supply, as apparent from the current energy crisis. Gas generation in the power sector falls at least 50% by 2030 in 1.5°C compatible pathways and is phased out by as early as 2041.

Spain

Spain has recently set a target to achieve net zero GHG emissions by 2050, which is to be welcomed. However, its 2030 target has not been increased, remaining at a 23% reduction relative to 1990 levels. Like for Belgium and Poland, this is far removed from what is needed for 1.5°C and will make achieving the 2050 target much more challenging. In 1.5°C compatible pathways which demonstrate the highest plausible ambition for the European continent, Spanish GHG emissions fall to 46-52% below 1990 levels in 2030 (excluding LULUCF). As in other member states, electrification, energy efficiency and the use of renewable hydrogen/biomass can help Spain reduce emissions rapidly and align with the 1.5°C target.

1. Introduction

In December 2015, the global community adopted the Paris Agreement to combat climate change, enhance action, and intensify investments toward a sustainable, low-carbon future. The Paris Agreement commits signatories to strengthen the global response to the threat of climate change by holding the increase in the global average temperature well below 2°C above pre-industrial levels and to pursue efforts to limit warming to 1.5°C

Limiting global warming to 1.5°C will require rapidly reducing global greenhouse gas (GHG) emissions and achieving net zero CO_2 emissions around mid-century. A substantial transformation of all economic sectors is needed. Such a transformative change could be achieved in a range of ways, and there is scope to further assess the implications for different world regions and individual countries to guide policy interventions and investments. Long-term energy and emissions pathways can explore how different policy levers and low-carbon technologies can reduce emissions while considering a range of future uncertainties. In this report, we use the latest evidence assessed by the Intergovernmental Panel on Climate Change's (IPCC) to explore what transformation may be necessary for the EU27 and the selected seven member states to fulfil the Paris Agreement goal.

There is a wide range of literature defining what transformative change consists of (Moore *et al* 2021, Fazey *et al* 2018, Feola 2014, Williams *et al* 2020, IPCC 2018). Fazey *et al* (2018) define transformative change in terms of the depth, breadth and speed of change. Transformative change occurs at greater depth, disrupting existing practices; greater breadth, with changes happening in parallel across multiple systems and sectors; and greater speed. The IPCC defines transformative change as "a system-wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale" (IPCC 2018, p 559), which aligns well with the definition from Fazey *et al*.

Exploring the need for transformative change in the context of the 4i-TRACTION project, our analysis focuses on four cross-cutting core challenges at the heart of the long-term transformation effort, **the 4i's:** fostering **innovation**, mobilising **investment** and finance, rolling out the **infrastructure**, and enabling greater **integration** across sectors. We apply the taxonomy developed by the 4i-TRACTION consortium (Görlach *et al* 2022) to identify the level of transformation across each of the 4i's for a selected subset of eight 1.5°C compatible pathways from the IPCC's Sixth Assessment Report (AR6) (IPCC 2022). Having done this, we can classify pathways based on the level of transformation observed.

We also filter the set of eight pathways further to select two illustrative mitigation pathways. We use these pathways to provide an in-depth assessment of 1.5°C compatible transformation pathways for the EU27 and seven selected member states: Germany, Finland, France, Belgium, Poland, the Netherlands and Spain. This is then compared to the current domestic targets and other national modelling studies to provide an in-depth assessment of

1.5°C compatible action at the national level, and assess the opportunities for EU27 member states to initiate or accelerate transformative change.

This report is structured as follows: Section 2 describes the methodology applied throughout this report for evaluating transformation pathways at EU27 and member state level. It presents the pathway selection procedure, the methodology used to downscale global pathways to the national level, and elaborates on the selection of key indicators for assessing the 4i's. Section 3 presents the results of analysis. Section 3.1 presents the results for the EU27 as a whole, while Sections 3.2 to 3.8 focus on the seven selected member states. Finally, Section 4 summarises the report and draws conclusions.

2. Methodology

2.1 Summary

The aim of this report is two-fold. First, the report aims to quantify and classify a selection of 1.5°C compatible pathways, based on the level of transformation observed across the transition's four key dimensions: infrastructure, integration, innovation and investment. Quantifying and classifying pathways with respect to the 4i's enables us to:

- Improve our understanding of transformative change in the EU, including the relationship between the 4i's.

- Identify Paris compatible "landing zones" of the transformation for the EU and selected member states. These are particular areas in the space of possible pathways which demonstrate particular combinations of transformation across the different dimensions, e.g., high levels of transformation across all dimensions or high levels of transformation across infrastructure and integration, but medium levels of transformation in innovation and low investment requirements. The more pathways represented in a particular landing zone, the greater the evidence that this particular approach is a central component or least-regrets option for achieving transformative change.

Second, the report aims to provide an in-depth, sectoral level perspective on energy and emissions pathways for the EU27 and selected seven member States: Germany, Finland, France, Belgium, Poland, the Netherlands and Spain. These member states have been selected as they represent seven relatively large economies in the EU, span the EU's range of energy-system characteristics (incl. fuel mix) and demonstrate a strong variation in the current level of mitigative ambition. They also correspond to many of the countries that 4i-TRACTION project partners belong to, which enables detailed country-specific expertise to be leveraged.

We use the latest literature on 1.5°C compatible energy and emissions pathways as assessed by the IPCC in the Sixth Assessment Report (AR6) (IPCC 2022). This report and the accompanying database provides a diversity of pathways that limit warming to 1.5°C at the global level. The key steps in the methodology are as follows:

1. From the AR6 database, a subset of eight low-carbon pathways are selected for investigation, based on an in-depth filtering process.
2. These pathways provide data at the European level. They are downscaled to provide data at the EU27 and member state level.
3. The level of transformation across each of the 4i's is quantified, using a set of underlying indicators to assess transformation.

4. The pathways are then classified based on the level of transformation in each of the 4i's. Pathways with similar levels of transformation across the 4i's can be grouped together, while those with distinct performance can also be identified.
5. Of the eight initial pathways, two illustrative pathways are selected for further investigation. Energy and emissions pathways are then explored at the sectoral level, covering the power sector and the end-use sectors of industry, transport and buildings.

Figure 1 summarises the methodology in a flow chart, highlighting the analysis's key outputs. The following sections provide further detail on each step involved in the methodology.

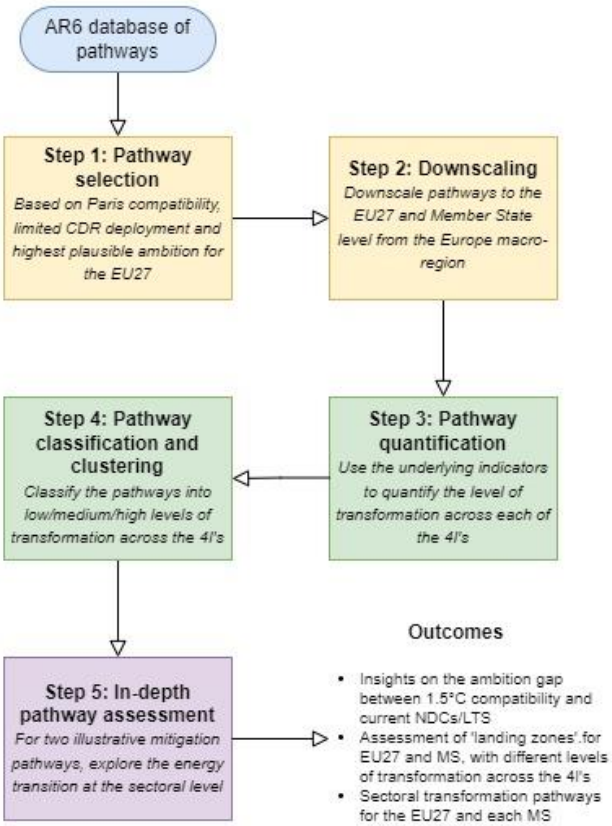


Figure 1| Summary of methodology

Summarises the methodology used in this report to classify pathways based on the level of transformation across the 4i's, and to perform an in-depth assessment of energy system transformations.

2.2 Pathway selection

The starting point for this analysis is the AR6 database (Byers *et al* 2022), which provides the latest evidence on global pathways limiting warming towards 1.5°C.

2.2.1 Definition of pathways, scenarios and models

In this report, a scenario is defined as an integrated description of the human-environment system's possible future (Clarke *et al* 2014). Global mitigation scenarios are produced by integrated assessment models (IAMs). These models link together representations of the energy, economy, land and climate systems in an attempt to present a self-consistent description of how these coupled systems could develop in the future (Weyant 2017). There are a wide range of different integrated assessment models, each of which has a particular structure, underlying assumptions and typical behaviour (Harmsen *et al* 2021). However, each of them produces scenarios in which a range of technologies are deployed to meet total energy service demands in each region over the time horizon, with associated emissions and investment requirements. An IAM scenario therefore consists of a range of quantitative pathways for future energy demand, technology deployment, associated emissions, and economic indicators such as investment requirements. The IPCC's recent AR6 report provides further detail on IAM scenarios (Riahi *et al* 2022).

Multiple IAMs are often used to produce pathways that reflect the same overall scenario narrative. To achieve this, a range of key assumptions, such as on the size of the global carbon budget or the availability of key low-carbon technologies, are used to define the scenario narrative and applied across all models, while a range of other minor variables are left to vary between models. The unique combination of a scenario (a particular narrative about future developments in the human-environment system), and the model that produces the scenario, is called a *pathway*. This is shown in Figure 2.

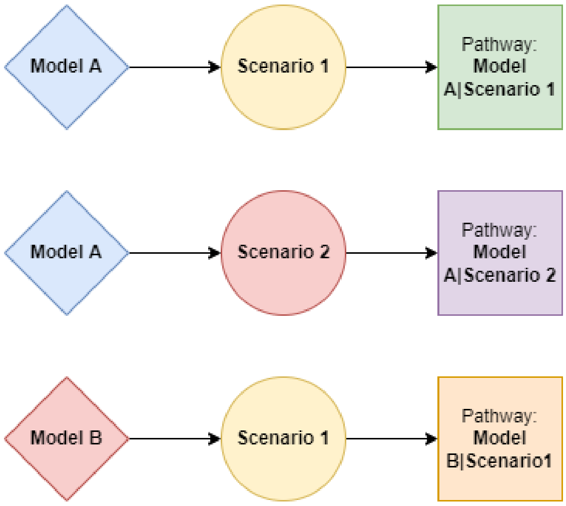


Figure 2 | Models, scenarios and pathways

Figure demonstrates the difference between models, scenarios and pathways. A pathway (as defined in this report), is the combination of a particular model producing a particular scenario narrative. Multiple models can produce their own variants of this scenario (Models A and B both produce Scenario 1), but while these are the same *scenario*, they remain distinct *pathways*.

The AR6 database contains over 3,000 pathways produced by a wide range of models. There are many cases where the same scenario has been produced by a range of models, during a model intercomparison project. In these instances, the distinction between scenarios and pathways is a valuable perspective.

2.2.2 Filtering global pathways

Not all pathways included in the AR6 database are fully compatible with the Paris Agreement, and many pathways use levels of carbon dioxide removal (CDR) which may transgress feasibility/sustainability limits (e.g. (Fuss *et al* 2018). In addition, not all pathways provide data at the correct regional resolution to enable downscaling as well. It is, therefore, necessary to filter this database to select a subset of pathways which are compatible with the Paris Agreement, have limited CDR deployment, and provide the necessary data. This report applies the following filters to select a subset of eight pathways for further analysis.

Compatibility with the Paris Agreement's objectives

Article 2.1 of the Paris Agreement commits signatories to hold global temperature increases to "well below 2°C" and "pursue efforts to limit warming to 1.5°C". To identify pathways compatible with this goal, we filter the AR6 database to only include those which are compatible with limiting warming to 1.5°C with no or low overshoot. These are pathways which provide at least a 33% chance of limiting warming to 1.5°C across the century, and at least a 50% chance of returning warming to below 1.5°C in 2100. The majority of these pathways are simultaneously very likely (>90% chance) to hold warming below 2°C across the century. This provides a set of 97 pathways.

Article 4.1 of the Paris Agreement sets out the objective of achieving a balance between anthropogenic sources and sinks in the second half of the century. This represents a commitment to achieving net zero greenhouse gas emissions before 2100, at a global level. We therefore apply this as an additional filter. This provides a set of 49 pathways for analysis which are compatible with the Paris Agreement's objectives as outlined in Article 2.1 and Article 4.1.

Compatibility with the sustainability criteria

Of these 'Paris compatible' pathways, we further filter to select pathways which limit the use of carbon dioxide removal (CDR) to sustainable levels, as assessed by the literature (Fuss *et al* 2018). This means that globally, they deploy less than 5GtCO_2/y of bioenergy with carbon capture and storage (BECCS) in 2050, and under 3.6GtCO_2/y of afforestation/reforestation in the second half of the century. Applying this filter reduces the number of pathways to 18.

Data availability

Finally, we filter this database to select pathways which provide the necessary data for analysis. This means they must provide data at the European macro-region level, which can then be downscaled to the EU27 and selected member states. This results in a set of seven pathways for analysis[2].

We complement these seven pathways with a final pathway, the DeepElec_SSP2_HighRE_Budg900 scenario produced by the REMIND-MAgPIE integrated assessment model. While this pathway does not reach net-zero GHGs globally, and is thus not fully Paris compatible, it remains a valuable line of evidence for the following reasons:

- It still limits warming to 1.5°C with low overshoot and holds warming to well below 2°C across the century and is thus compatible with Article 2.1 of the Paris Agreement.
- This pathway displays faster emissions reductions at the European level than any of the other seven pathways out to 2040. It therefore provides information on higher

[2] In reality, the filtering process produces a set of twelve pathways, but five of them are identified as duplicates/highly similar to other pathways in the ensemble produced by the same model, and are therefore dropped to avoid biasing the results unduly.

levels of transformative change within the EU27 and selected Member States and will guarantee the final pathway selection adequately reflects the literature.

This additional, high-renewables pathway demonstrates the feasibility of rapidly reducing emissions by deploying renewables. While it does not reach net-zero GHG emissions by 2100, the rapid decarbonisation of the energy system by 2050 means this pathway would be well-placed to achieve net-zero GHGs, if so desired. For example, it could achieve this while still deploying less CDR than some of the other selected pathways. It remains a valuable point of evidence, particularly when the timescale of analysis is focused on the pre-2050 period.

The selected eight pathways are summarised in Table 1, highlighting the model used to produce the scenario, the scenario name, and the pathway abbreviation used in this report. In the interests of clarity, these pathways are henceforth referred to by their abbreviations.

Of these eight pathways, six are produced from the REMIND modelling framework (Luderer *et al* 2020). Three are also produced as part of the ENGAGE multi-model intercomparison project (Riahi *et al* 2021). In the pathway abbreviation, these are all highlighted as ENGAGE pathways. However, it is important to highlight that each pathway is produced using a different model, and also with a different scenario narrative (the difference between each is the size of the global carbon budget, which varies from 200GtCO_2 to 400GtCO_2 across the three scenarios). For more details on all eight pathways, see Appendix B.

Table 1 | Filtered scenario subset

Model	Scenario	Pathway abbreviation
AIM/CGE 2.2	EN_NPi2020_300f	AIM | ENGAGE
REMIND 2.1	LeastTotalCost_LTC_brkLR15_SSP1_P50	REMIND | LTC
REMIND 2.1	R2p1_SSP1-PkBudg900	REMIND | SSP1
REMIND-MAgPIE 2.1-4.2	CEMICS_SSP1-1p5C-fullCDR	REMIND | CEMICS
REMIND-MAgPIE 2.1-4.2	EN_Npi2020_200f	REMIND | ENGAGE
REMIND-MAgPIE 2.1-4.2	SusDev_SDP-PkBudg1000	REMIND | SusDev
REMIND-MAgPIE 2.1-4.3	DeepElec_SSP2_ HighRE_Budg900	REMIND | HighRE
WITCH 5.0	EN_Npi2020_400f	WITCH | ENGAGE

2.3 Pathway downscaling

The selected pathways as reported by the IPCC AR6 database, do not provide energy and emissions data for the EU27 or individual Member States, but for a wider European "macro region". This is a wider region that includes the EU27 and a range of non-EU countries such as Switzerland, Norway and the UK. It is therefore necessary to downscale the results to obtain pathways for the EU27 and selected Member States.

We performed energy system downscaling using the SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator) tool (Sferra *et al* 2019). SIAMESE works by two main steps:

1. First, SIAMESE allocates energy consumption (primary, secondary or final energy) to the individual countries within the European macro-region, by equating marginal fuel prices across all countries. By finding a fuel price equilibrium for all countries, SIAMESE maximises welfare in the macro-region as a whole, providing a cost-effective allocation of energy demand.

2. Having obtained energy consumption for each individual country, SIAMESE computes energy sector CO_2 emissions by applying emissions factors for each fuel.

From the regional pathways, SIAMESE is used to downscale final energy demand in the industry, buildings and transport sectors, as well as electricity generation in the power sector. SIAMESE then reports total energy demand, and total energy-related CO_2 emissions for the EU27 / each member state. Additional downscaling was needed to provide process-based CO_2 emissions, and non-CO_2 emissions at the EU27 and member state level. This is performed using a range of algorithmic approaches. For more detail on both SIAMESE and the algorithmic downscaling, see Appendix C.

2.4 Pathway quantification and classification on the basis of the 4i's

After downscaling the selected pathways to obtain energy and emissions use for the EU27 and selected member states, the level of transformation across the 4i's can now be quantified and pathways classified accordingly.

Transformation in line with the 4i's is assessed using key indicators which are used to signify the level of transformation across each 4i dimension.

2.4.1 Indicators used to quantify the 4i's

Infrastructure

The following indicators are used to quantify the level of transformation in infrastructure in the pathways.

- VRE share: % share of electricity generation from variable renewable energy (VRE) in a given year
- CCS volume: total sequestered carbon in $MtCO_2$ via fossil CCS and BECCS in a given year
- Final energy – hydrogen: Hydrogen consumption (EJ) in final energy in a given year
- Final energy – electricity: Electricity consumption (EJ) in final energy in a given year

The transition to energy systems powered mostly by variable renewable energy (VRE) such as wind and solar will require an energy infrastructure transformation, particularly through the expansion of transmission infrastructure. This is essential to increase grid flexibility and take advantage of different availability especially of wind and solar PV in different regions.

CCS is also an infrastructure intensive mitigation option, requiring the creation of new transport and storage infrastructure in addition to extensive infrastructure at the capture site. The production of hydrogen from renewable electricity to replace fossil fuels in transport and industry imposes further infrastructure needs to the system, especially in form of hydrogen production, transportation, and storage infrastructure. Finally, the level of total electricity demand is taken as an indicator of infrastructure transport. This represents the level of total power system (generation, transmission and distribution) infrastructure that will be required in the pathways.

Innovation

The following indicators are used to quantify the level of transformative innovation in the pathways:

- VRE share: % share of electricity generation from VRE in a given year
- Storage capacity: Total capacity of electricity storage technologies (GW) deployed in a given year
- Final energy – hydrogen: Hydrogen consumption (EJ) in final energy in a given year
- Electrification rate: % share of electricity in final energy demand in a given year
- Final energy demand: Reduction in final energy demand in a given year relative to 2019

- CCS volume: total sequestered carbon in $MtCO_2$ via fossil CCS and BECCS in a given year

These indicators aim to capture the level of innovation in both the supply of and demand for energy. First of all, a transition to an electricity system based predominantly on VRE generation will require a wide range of innovation. This will include novel forms of generation, such as new solar PV and floating offshore wind turbines, innovative technologies to enable grid integration, such as electricity storage and grid interconnection, and system-wide innovations such as smart grids and demand response to help match supply and demand. This innovation is covered by the first two indicators of VRE share and storage capacity.

The use of hydrogen in the end-use sectors will require innovation, not only in end-use sectors such as shipping and aviation, but in the production of (green) hydrogen, where rapid advances are now being made. The electrification of final energy demand, via electric vehicles (EVs), heat pumps and more, further scales up innovation needs in future scenarios. This report also applies the reduction in final energy demand in 2050 as a measure of innovation. Strong reductions in energy demand represent societal innovation towards new consumption patterns, as well as continued innovation in energy efficiency measures to reduce energy demand.

Finally, successful CCS deployment will require further innovation in capture methodologies to achieve commercial scale deployment. Therefore, CCS deployment is taken as an indicator of the level of innovation observed in the pathways.

Integration

The following indicators are used to quantify the level of transformative integration in the pathways.

- Electrification rate: % share of electricity in final energy demand in a given year
- Final energy – hydrogen: Hydrogen consumption (EJ) in final energy in a given year
- RE share: % share of electricity generation by total renewables (solar, wind, hydro, biomass, geothermal) in a given year

Cross-sectoral integration allows for a cost-efficient decarbonisation of the entire energy system by capitalising on the potentials and synergies between different energy sectors. Electrification of final energy is one key strategy applied across all pathways to decarbonise the energy system. We, therefore, use the electrification rate as a key indicator for the overall level of sectoral integration in the pathways.

Hydrogen, particularly when produced by electrolysis via renewable electricity and used in transport/industry, is another way to couple together supply and demand sectors, via indirect electrification. IAMs model the use of hydrogen in a wide range of end-use sectors, including in the transport sector, the industrial sector and the buildings sector (Quarton *et al* 2019). The demand for hydrogen in the end-use sectors is taken as an indicator of sectoral integration.

Finally, the total share of renewable energy, mostly coming from variable energy sources, in the power sector is taken as a measure of the level of integration in the system. This is explained by the fact that most of the electricity will be coming from variable sources of energy, such as wind and solar. Next to grid development and storage, sector coupling will play an important role in ensuring a balance between electricity supply and demand.

Investment

A core challenge to energy system transition is mobilising sufficient investment to drive transformative change. To assess and classify the pathways with respect to investment needs, we calculate the cumulative investment requirements by pathway out to 2050. In the scenarios used here, there is insufficient data to calculate investment requirements for the whole energy system. We therefore instead focus on the level of cumulative investments in the power sector, as a key energy transition sector. This is calculated by taking the downscaled electricity system for each member state and inferring capacity installation requirements for this system on the basis of capacity factors and technology lifetimes. We then apply cost data for renewable technologies to obtain investment needs. We then take cumulative investments in the power sector from 2025-2050 as a proxy to reflect the investment needs across pathways.

2.4.2 Quantification and classification against the 4i's

The quantification and classification process involves three steps:

First, we plot how each pathway performs on the different underlying indicators over the time period 2020-2050.

Second, we take the value of the underlying indicators in 2050 as a measure of the overall transformative change by mid-century. We rank the pathways between 0 and 1 for all the selected indicators. We use a linear ranking, in which for each underlying indicator, the maximum value in 2050 receives a score of 1 and the minimum value in 2050 receives a score of 0. We then sum over all relevant indicators for each of the 4i's to give an overall 'transformation score' for each pathway and each dimension. This enables us to observe which pathways demonstrate the most transformative change in each of the 4i's, and which demonstrate the lowest levels of transformative change.

Finally, we classify the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These classifications are defined as follows:

- Low transformation: up to 33rd percentile of the distribution (bottom three pathways)
- Medium transformation: 33rd to 67th percentile of the distribution (middle two pathways)
- High transformation: above the 67th percentile of the distribution (top three pathways)

In the main body of the report, we assess the level of transformation in line with the 4i's for the EU27 as a whole. This is because all the necessary underlying indicators can be calculated at the EU level, while CCS deployment and storage capacity cannot be calculated at the Member State level due to data availability (and a different proxy for investment needs is required). A quantification and classification exercise for each individual member state is provided in Appendix A.

2.5 In-depth analysis of illustrative pathways

In addition to quantifying and classifying the pathways with respect to the 4i's, the report conducts an in-depth analysis of energy system transformations at the EU27 and member state level. Two illustrative pathways were selected to conduct this analysis.

The illustrative pathways are the **SusDev_SDP-PkBudg1000** and **DeepElec_SSP2_ HighRE_Budg900** scenarios, both of which are produced by the REMIND-MAgPIE integrated assessment modelling framework. These pathways are abbreviated as 'SusDev' and 'HighRE' in the report. They are chosen because they represent the "highest plausible ambition" for the EU27 as a whole. We define this as 1.5°C compatible pathways that are technically and economically feasible, that demonstrate the steepest GHG emissions reductions out to 2030, and that do not violate sustainability criteria as laid out in Section 2.2.

Arguably, the EU27 should be aiming to reduce emissions in line with the "highest plausible ambition". As a region with significant historical emissions and the economic and regulatory capacity to reduce GHG emissions rapidly, the EU27's equitable share of the global carbon budget is very small (van den Berg *et al* 2019) and requires almost total decarbonisation by 2030 (CAT 2022). While this is unlikely to be achievable domestically, it highlights that to minimise inequality in global climate action, the EU27 should aim to achieve the highest plausible ambition in emissions reductions. Aiming for the highest plausible ambition is also consistent with the precautionary principle, which aims to minimise environmental harm when making decisions under uncertainty.

Given widespread uncertainty around the scale of future carbon budgets and potential climate impacts, the precautionary principle would suggest that governments aim to maximise emissions reductions. This would insure against possible adverse outcomes e.g., if the global carbon budget is more restricted or future climate impacts are greater than anticipated. The precautionary principle is enshrined as a key principle in EU policy making (European Commission 2000). Both the SusDev and HighRE pathways were also selected as illustrative pathways in the IPCC's AR6 report, which further underlines their value.

These illustrative pathways do not explicitly consider the political or social feasibility of the transformations that they envisage, focusing instead of techno-economic feasibility considerations (Brutschin et al 2021). These considerations include renewable potentials, constraints on the pace of technology deployment, and power sector dynamics such as storage requirements. These pathways do not consider the regulatory or societal barriers to achieving transformative change. However, highlighting that technically feasible pathways to higher ambition exist can provide motivation to identify and address these barriers, and thus achieve the necessary transformation to align with 1.5°C. These pathways provide a quantitative basis to determine the European trajectory toward climate neutrality in accordance with the best available scientific evidence, as determined in the draft of the European Climate Law. This will be feed into the other work packages of this project to deeply assess the impact on the existing and new policy measures to achieve this level of ambition.

2.5.1 An introduction to the illustrative mitigation pathways

Summary of pathways

The HighRE pathway focuses on limiting warming to 1.5°C by a combination of rapid deployment of wind and solar, coupled with widespread electrification of end-use sectors (Luderer *et al* 2021b). This pathway explicitly represents demand-side flexibility, alongside battery storage to help integrate high shares of VRE into the power sector. Green hydrogen also plays a crucial key role in providing long-term energy storage and driving sector coupling between industry/transport and the power sector via indirect electrification. The HighRE pathway has the most detailed representation of power sector dynamics of all the pathways selected for analysis in this report.

The HighRE pathway uses the SSP2 underlying socio-economic set-up (Fricko *et al* 2017), in which social, economic and technological developments do not shift markedly from historical trends. As a result, there is relatively limited change in the level of energy service demands, although efficiency improvements still lead to strong reductions in final energy.

The SusDev pathway has an explicit focus on achieving the Sustainable Development Goals alongside the Paris Agreement's long-term temperature target (Soergel *et al* 2021). It does so by combining ambitious climate policy with an additional sustainable development package, which includes international climate finance, a global transition to sufficient and healthy nutrition, and ambitious reductions in energy service demand in developed countries.

The SusDev pathway focuses on achieving the SDGs while reducing emissions. In this pathway, there is a gradual shift to the EAT-Lancet planetary health diet by 2050 (Willett *et al* 2019). In this diet, meat and dairy are still consumed, but in significantly smaller proportions than whole grains, fruits, vegetables, nuts, and legumes. The reduction in meat and dairy intake in the EAT-Lancet diet reduces pressure on land and enables zero malnutrition to be achieved by 2050. It also leads to strong and sustained reductions in CH_4 and N_2O emissions from the agricultural sector. The pathway also envisages a transition away from energy-intensive lifestyles in the Global North, with strong reductions in demand for energy services in Europe. This enables rapid growth in energy demand in lower-income countries, which enables decent living standards to be achieved by all within planetary boundaries. The SusDev pathway is particularly valuable as it allows greater exploration of the feasibility of reducing emissions via demand-side solutions, which are often under investigated in the energy system transition literature (Creutzig *et al* 2018).

Key features of illustrative pathways

Many global pathways produced by IAMs use large amounts of biomass, which is used to deliver negative emissions when coupled with CCS as BECCS, and as a low-carbon fuel in industry and transport (Bauer et al 2020). Both pathways limit global biomass consumption to 100EJ/y, approximately double today's levels. This is at the low end of global 1.5°C compatible pathways, which often envisage very large-scale biomass consumption. However, the compatibility of this biomass consumption with sustainability constraints remains uncertain.

While a review of the literature found "high agreement" that 100EJ/y of biomass could be provided in a sustainable manner (Creutzig *et al* 2015), there is emerging evidence that the sustainable biomass potential could be as little as 50EJ/y (Energy Transitions Committee 2021). Biomass consumption in the two selected pathways should, then, be seen as an upper bound of what could be achieved without undue sustainability concerns. If the sustainable biomass potential transpires to be lower than 100EJ/y, greater deployment of hydrogen, synthetic fuels, electrification and demand reduction could help avoid unsustainable biomass consumption.

Both pathways also limit warming to 1.5°C with low overshoot, with peak warming kept to below 1.6°C with a >50% likelihood. However, the relative contribution of CO_2 and non-CO_2 mitigation varies between the pathways. In the SusDev pathway, the deeper reductions in CH_4 and N_2O emissions (due to greater ambition in the agricultural sector) means that CO_2 emissions can fall at a slower rate while still limiting warming to 1.5°C with low overshoot. As a result, the 1.5°C consistent carbon budget that is applied in the SusDev pathway is 100GtCO_2 larger than in the HighRE pathway (with cumulative emissions limited to 600GtCO_2 from 2020 onwards, rather than 500GtCO_2 as in the HighRE pathway).

Subsequently, the SusDev pathway sometimes exhibits a slightly slower pace of fossil fuel phase-out, which is compensated for by much greater transformation in the land-use sector. This is due to the internal dynamics of IAMs, which allow increased action in one sector to compensate for reduced action in another. It is particularly evident in the power sector, where the date by which fossil gas is entirely phased out of electricity generation is delayed, and in the industrial sector, where the rate at which oil consumption is phased out is also slower. Robust approaches to climate policy should not generally predicate action in one sector on success or failure in another. Given pervasive uncertainty around the feasibility of various decarbonisation options (Grant *et al* 2021a, Warszawski *et al* 2021), robust climate policy should instead involve maximizing ambition in all sectors where feasible.

The SusDev pathway remains a valuable source of information as it demonstrates by a different approach the feasibility of rapid emissions reductions in the EU27 and selected member states. In the energy sector, the SusDev pathway also demonstrates the potential for ambitious lifestyle shifts, complemented by efficiency improvements, to strongly reduce final energy demand and subsequently the energy infrastructure necessary for the transition. However, we caution against using it to suggest that the pace of decarbonisation in the energy sector can be relaxed substantially. In the SusDev pathway, there are still strong reductions in fossil fuel use in all sectors and all fuels.

2.5.2 Calculating effective phase-out dates

The report presents energy and emissions pathways at both the whole-economy and sectoral levels. It provides a range of 1.5°C compatible benchmarks for the EU27 and each member state. One key benchmark is the date by which fossil fuels are phased out of the energy system, on a fuel- and sector-specific basis.

IAMs often have a bias against complete decarbonisation, due to model structure, applied constraints, or incomplete representation of decarbonisation options (Kaya *et al* 2017). As a result, fossil fuel consumption does not often reach absolute zero but instead falls to low 'residual' levels (Climate Analytics, 2019). In comparison, detailed energy system models which have greater spatial and temporal resolution can often model a complete phase-out of fossil fuels from the energy system. As a result, there is a need to correct for the tendency of IAMs to avoid 'complete' decarbonisation and calculate when fossil fuels will effectively exit the system in these pathways.

This report calculates 'effective' phase-out dates as the date by which fossil fuels provide under 2.5% of total final energy demand in the sector, or 2.5% of total electricity generation in the power sector. At this level, fossil fuels represent a marginal source of energy, and could be fully phased out by limited reductions in demand or slight increases in the deployment of alternative zero-carbon technologies. As such, they can be considered to have been 'effectively' phased out (Climate Analytics 2022b).

In most areas, we use both the SusDev and the HighRE pathway to infer effective phaseout dates for fossil fuels. However, in the power sector, our benchmark for fossil gas phaseout dates is based on the HighRE pathway alone. This is for two reasons. First, as mentioned above, the SusDev pathway rather than entirely phasing out fossil gas in the power sector, has continued (but minor) levels of generation in the EU27 post-2035. This is compensated for by greater ambition in the agricultural sector. Consequently, using the SusDev scenario to set a benchmark for fossil gas phaseout risks pinning this benchmark on specific transitions being made in other sectors, which could result in a less robust benchmark. Second, the HighRE pathway has a more complete representation of power sector dynamics (including demand-side flexibility) than the SusDev pathway. As a result, it is better able to assess when fossil gas could feasibly exit the power sector, without compromising energy security. In most countries, we use only the HighRE pathway to construct benchmarks for fossil gas phaseout in the power sector.

Additionally, we do not use the SusDev pathway to set a benchmark for when oil should be effectively phased out in the industry sector. This is because, in the SusDev pathway, long-term oil consumption in the industrial sector is larger, due to the expanded carbon budget. Oil provides around 5% of EU27 industrial demand in 2050 in the SusDev pathway, compared to <1% in the HighRE pathway. This is still a significant reduction from today's levels, where oil provides around 30% of EU27 industrial demand (including non-energy consumption in the form of chemical feedstocks), but does not represent a phaseout of oil demand. However, any long-term continued oil demand in the SusDev pathway is contingent on additional action in the agricultural sector. We again base our phaseout benchmarks for oil in the industrial sector on the HighRE scenario alone.

3. Pathway analysis for EU27 and selected Member States

IAM pathways assess the feasibility of achieving the proposed climate targets under given boundary conditions. The IPCC's Sixth Assessment Report (IPCC 2022) assesses a broad range of mitigation pathways consistent with limiting warming to 1.5°C above pre-industrial levels while having diverse assumptions about economic growth, technology development, and lifestyles. The pathway analysis we conduct in this report is mainly designed to quantify, compare, and classify those pathways concerning the four cross-cutting core challenges of the transformation, the 4i's: 1) fostering breakthrough innovation, 2) shifting investment and finance, 3) rolling out the infrastructure for a climate neutral economy, and 4) integration of solutions across sectors.

3.1 EU27 Results

3.1.1 Pathway classification with respect to the 4i's

In this section, we explore how the pathways perform across the four cross-cutting dimensions of the energy transition, the 4i's. We classify the pathways into different landing zones, based on the level of transformation that they see in each dimension. Each of those landing zones describes a different mode of achieving the goals of the Paris Agreement, with pathways displaying particular levels of transformation across the 4i dimensions. We focus on the EU27 to provide a European-wide overview of the transformation. For further details on pathway classification for each Member State, see Appendix A.

To start, we show how the underlying indicators, which are used to track transformation, vary across the eight 1.5°C compatible pathways selected for the report.

The eight selected pathways represent a diversity of possible 1.5°C compatible futures for the EU27. Pathways vary strongly in the level of final energy demand, electricity, and hydrogen consumption in the end-use sectors. There is also strong variation in the level of CCS deployment with scenarios capturing between 125 and 855MtCO_2/y by 2050. The share of final energy that is electric varies between 44% and 69% in 2050.

The area where there is greater agreement across pathways is in the power sector. Here, all but one pathway envisage a rapid transition towards 100% renewable electricity. Renewables provide 76-88% of electricity in 2030, rising to 93-100% by 2050. Non-biomass renewables such as wind and solar are key technologies, providing around 70-83% of electricity in 2030 and 88-98% in 2050. The one exception is the scenario produced by AIM/CGE 2.2. The AIM/CGE 2.2 pathway represents an outlier in energy demand with much higher energy demand by 2050 compared to other pathways. It also envisages a higher deployment of nuclear and fossil fuels equipped with CCS as sources of low-carbon electricity, accounting for around 37% of electricity generation in 2050. This further highlights that energy efficiency and demand reduction measures act as an "enabler" for 1.5°C pathways, reducing supply-side challenges to the transformation and allowing deep decarbonisation to be achieved with predominantly renewables deployment, and much less need for nuclear and CCS. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for the EU27 involves a transition towards 100% renewable electricity by 2050, with particularly strong growth by 2030.

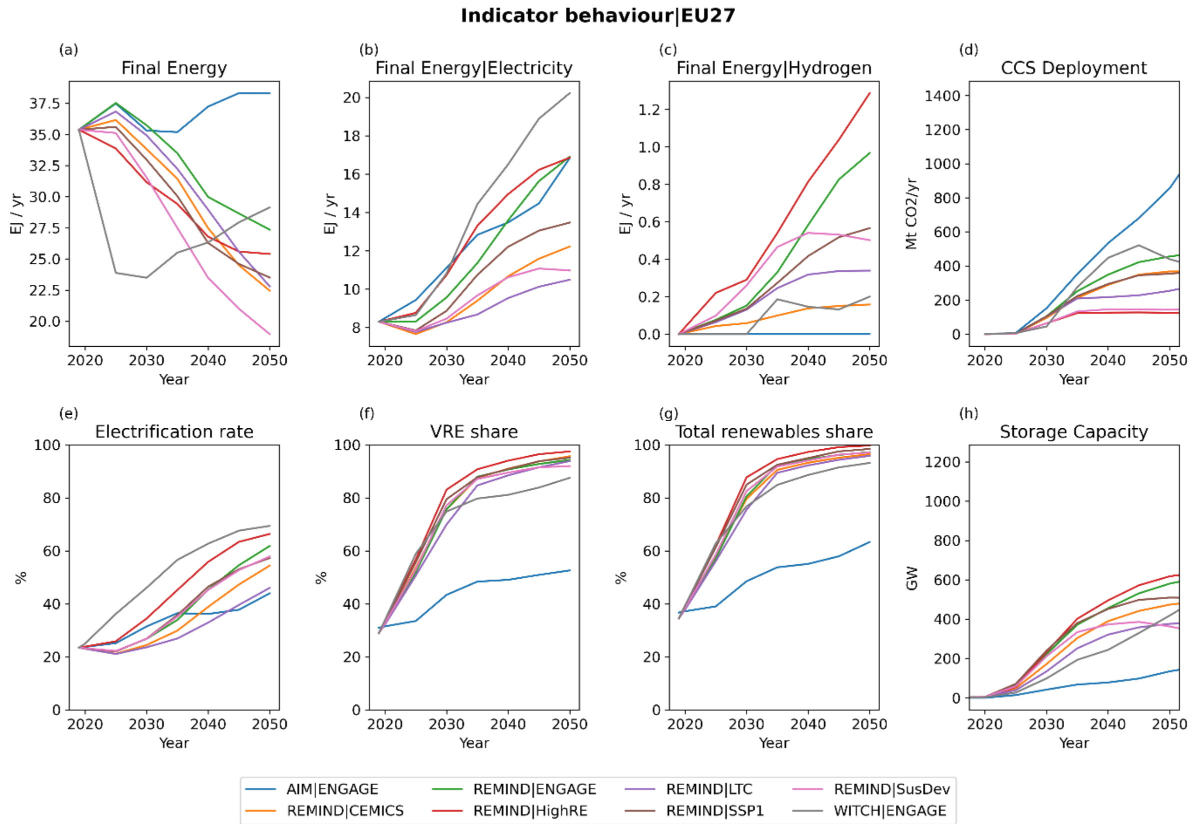


Figure 3 | Behaviour of underlying indicators (EU27).

The chart shows how the underlying indicators used to assess the 4i's vary across the pathways. Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) CCS Deployment (e) Electrification rate (f) VRE share in the power sector, (g) Total renewables share and (h) Storage capacity

As a next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum a score of 0. Figure 3 shows the results in the case of the EU27.

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in infrastructure, integration, innovation, and investment. Meanwhile, the scenario produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of integration and innovation, although its high overall levels of energy demand mean that there are still large investment requirements in this pathway.

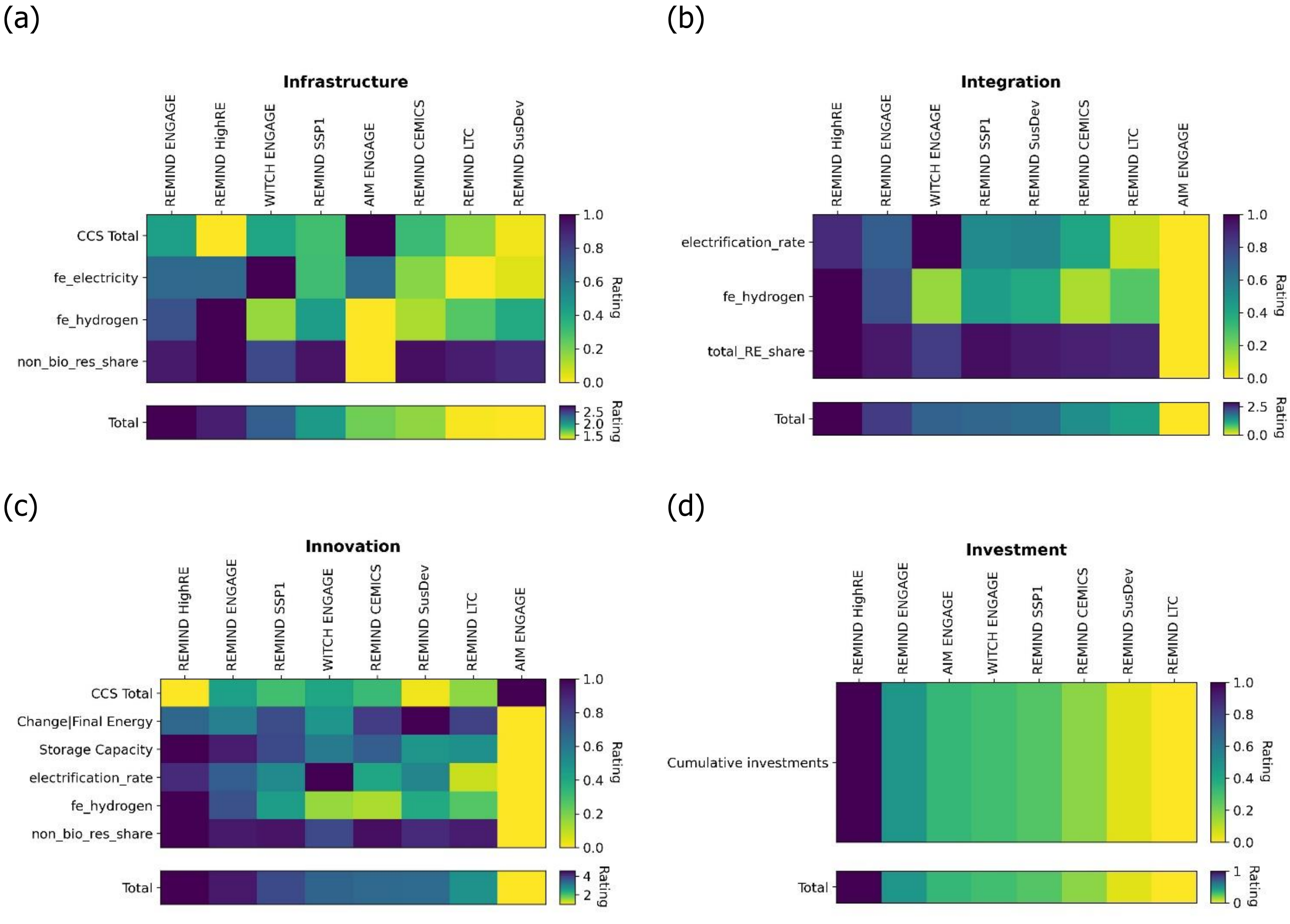


Figure 4|Pathway rating for each 4i dimension (EU27).

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

We then classify the pathways into distinct levels of transformation, using the thresholds defined in the methodology. Table 2 shows which pathways are assessed as low/medium/high regarding the needed level of transformation in infrastructure, innovation, integration and investment.

Table 2 | Pathway classification into low/medium/high categories (EU27).
This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment.

model	scenario	Infrastructure	Integration	Innovation	Investment
AIM	**ENGAGE**	medium	low	low	high
REMIND	**CEMICS**	low	low	medium	low
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	medium	high	medium
	SusDev	low	medium	medium	low
WITCH	**ENGAGE**	high	high	low	medium

Table 2 highlights that some pathways demonstrate similar levels of transformation in multiple i's considered here. For example, two scenarios produced by REMIND, HighRE, and ENGAGE demonstrate high levels of transformation across all 4i's, while the LTC scenario (also produced by REMIND) demonstrates the lowest levels of transformation across all 4i's. However, other pathways demonstrate varying degrees of transformative change across different areas. This further highlights the diversity of possible 1.5°C compatible futures for the EU27. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon.

We can now cluster the pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone represents a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone mean there is more evidence that this combination of indicators is 'optimal' or necessary for achieving 1.5°C. This clustering approach can identify key configurations of transformative change that particularly merit further investigation, and the relationship between each of the 4i's. For example, when plotting the landing zones for innovation/investment, if all pathways are clustered on the diagonal, this means there is a strong positive correlation between the level of innovation in the pathways and the level of investment required. If pathways are distributed homogenously across the space, with limited evidence of clustering, this suggests there is some degree of independence between the level of innovation and level of investment in the pathways.

Figure 5 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	1	1	0
Low	0	0	3

(b)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	1	0
Medium	0	0	2
Low	1	1	1

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	2	0	1
Medium	1	0	1
Low	0	2	1

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	0	1
Medium	1	1	0
Low	0	1	2

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

Figure 5 | Pathway classification into landing zones with respect to the 4i's (EU27). Showing (a) Investment vs. Infrastructure, (b) Investment vs. Integration, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

Some relationships can be observed across the 4i's. First of all, there is a strong correlation between total infrastructure needs and total investment needs, with the majority of pathways demonstrating the same level of transformation in each dimension. Pathways that have high/low investment needs often also have high/low levels of transformation in integration as well. This highlights that developing a large-scale and well-integrated energy system requires strong levels of investment. There is also some correlation between the level of transformation required in infrastructure and integration, with 75% of pathways sitting on the diagonal. This is partly due to the use of shared underlying indicators but highlights that the presence of interlinkages between the transformative challenges facing the EU27. Transformation in one dimension can entail transformation in another dimension. As a result, the 4i's should be viewed as a joint challenge, rather than as separate and isolated issues.

3.1.2 Relationship between the underlying indicators

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for EU27, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. Table 3 highlights the correlation (r-value) between each pair of underlying indicators.

Table 3 | Correlation between underlying indicators (EU27).

The darker the color, the stronger the relationship between the two variables.

	CCS Total	Change | Final Energy	Cumulative Investments	Storage Capacity	Electrification Rate	Final Energy | Electricity	Final Energy | Hydrogen	VRE Share	Total Renewable Share
CCS Total	1.00	0.90	-0.09	-0.65	-0.44	0.43	-0.57	-0.88	-0.89
Change | Final Energy	0.90	1.00	0.27	-0.53	-0.22	0.68	-0.30	-0.86	-0.86
Cumulative Investments	-0.09	0.27	1.00	0.51	0.53	0.60	0.73	0.07	0.07
Storage Capacity	-0.65	-0.53	0.51	1.00	0.70	0.08	0.80	0.86	0.85
Electrification Rate	-0.44	-0.22	0.53	0.70	1.00	0.55	0.55	0.53	0.58
Final Energy | Electricity	0.43	0.68	0.60	0.08	0.55	1.00	0.14	-0.31	-0.28
Final Energy | Hydrogen	-0.57	-0.30	0.73	0.80	0.55	0.14	1.00	0.56	0.57
VRE Share	-0.88	-0.86	0.07	0.86	0.53	-0.31	0.56	1.00	1.00
Total Renewables Share	-0.89	-0.86	0.07	0.85	0.58	-0.28	0.57	1.00	1.00

Two results can be observed. First, the average level of correlation between the underlying indicators is low, with an average R^2 of 0.36[3]. This highlights the continued degree of flexibility in the form of the EU27's energy transition along certain dimensions. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states down a particular transformation pathway. While a transition towards 100% renewable electricity is an emerging consensus in the pathways, decisions must still be made around the level of hydrogen consumption, CCS deployment, reduction in final energy demand, storage capacity, and more. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the ensuing level of electricity generation), but others merit further investigation. Some of these relationships are highlighted here.

[3] This is excluding the self-correlations shown on the diagonal of Table 3

Demand reduction and renewables deployment can reduce CCS

Figure 6 shows the relationship between CCS deployment in the pathways and the level of final energy demand in 2050. The positive correlation between these indicators suggests that reducing final energy demand can help minimize CCS reliance. Accordingly, greater transformation in the innovation dimension can reduce the scale of transformation required in the infrastructure dimension, specifically if this innovation is focused on the demand-side.

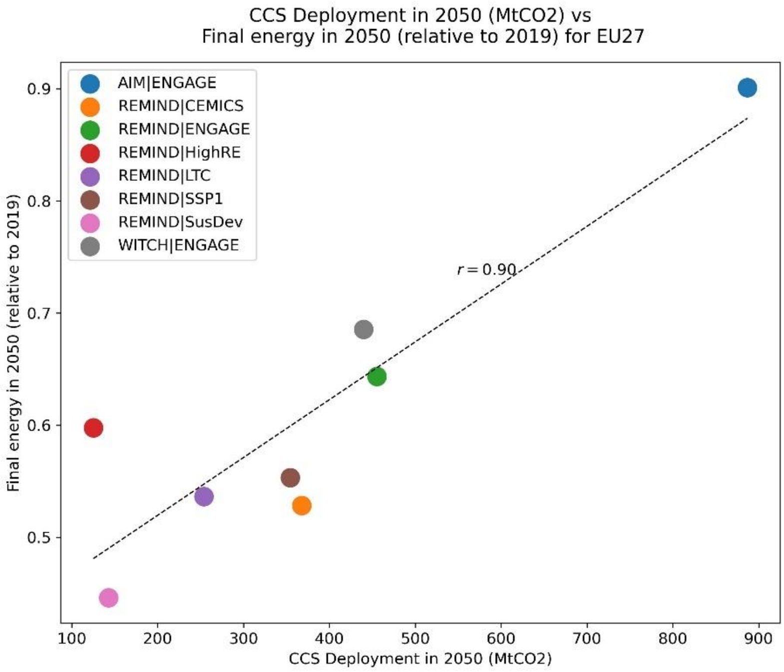
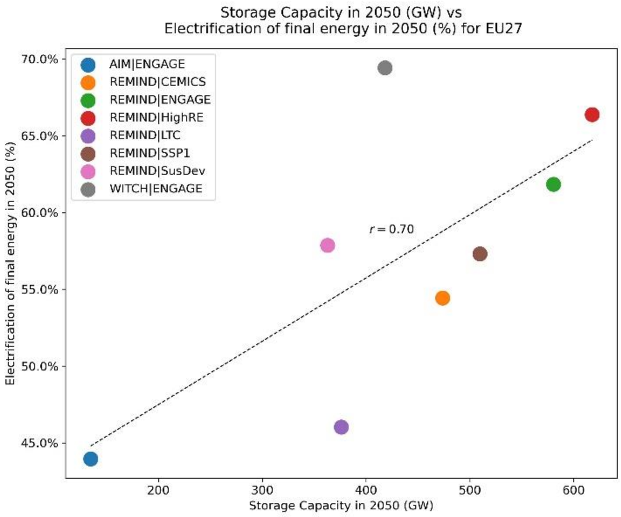


Figure 6 | Relationship between CCS deployment and final energy demand in 2050 (EU27)

Shows CCS deployment in 2050 vs. final energy demand in 2050

Storage capacity drives electrification and hydrogen deployment

Figure 7a shows the relationship between the level of storage capacity in 2050 and the level of electrification in 2050. The positive correlation here suggests that in the underlying pathways, storage capacity deployment can enable greater electrification levels. In turn, this increases the level of transformation across both integration and innovation dimensions. Figure 7b shows the correlation between storage capacity in 2050 and the level of hydrogen demand in final energy in 2050. Models which deploy greater amounts of storage capacity also generally see greater levels of hydrogen consumption in the end-use sectors.



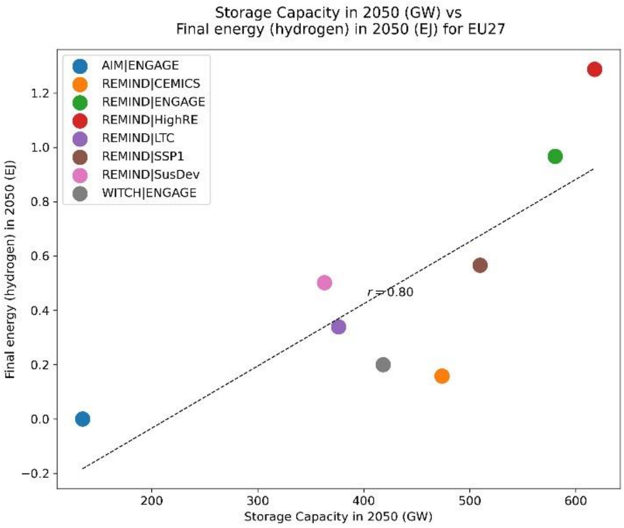


Figure 7 | Relationship between storage capacity, electrification and hydrogen demand (EU27).

Shows (a) Storage capacity in 2050 vs. electrification final energy demand in 2050, (b) Storage capacity in 2050 vs. final energy demand (hydrogen) in 2050.

3.1.3 1.5°C compatible emissions pathways: EU27

The EU27 aims to reduce its GHG emissions by at least 55% below 1990 levels (including LULUCF) by 2030 and reach net zero GHG emissions by 2050.

This translates to a reduction of GHG emissions of at least 53.9% by 2030 below 1990 levels, excluding LULUCF (CAT 2022). This is an improvement over the previous target of a 40% cut by 2030, which had been deemed insufficient following Paris Agreement adoption. However, the illustrative 1.5°C compatible pathways considered in this report are considerably more ambitious still. **In these pathways, emissions decline by 64-67% below 1990 levels by 2030 (excluding LULUCF).** Such pathways outline technically feasible routes to higher near-term decarbonisation (Figure 8). **There is an ambition gap in 2030 of 500-700MtCO_2e between the EU's current NDC and 1.5°C compatible action as assessed by this report.**

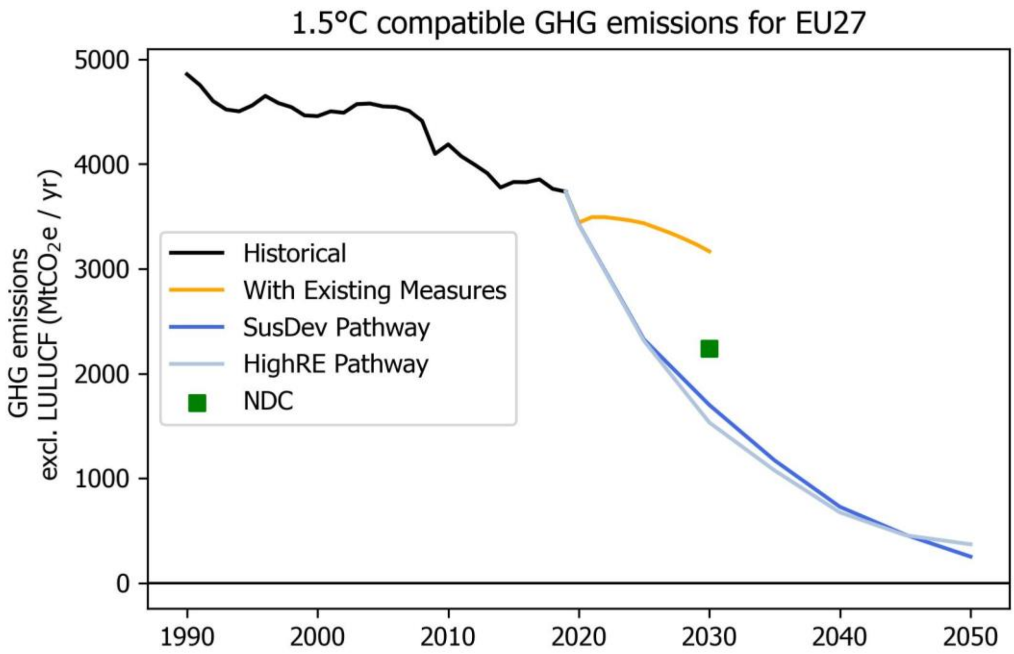


Figure 8 | 1.5°C compatible emissions pathways for the EU27

3.1.4 1.5°C compatible sectoral transformation pathways: EU27

In July 2021, the European Commission put forward a legislative package to revise existing measures, in addition to adopting new initiatives, to deliver on the 55% GHG reduction target, referred to as the Fit for 55 package (European Commission 2021a). The Fit for 55 package includes increasing the share of renewables in final energy to 40% by 2030 and reducing final energy demand by 36% in 2030, relative to final energy demand in 2030 from the 2007 reference scenario (European Commission 2021c). This equates to a reduction in final energy demand of 9% below final energy demand in 2019[4]. The 'Fit for 55' package is still under review by the European Parliament and Council before being formally adopted as EU legislation.

In May 2022, the EU Commission launched the **REPowerEU** plan, aimed at rapidly reducing the EU's dependence on Russian fossil fuels and accelerating the energy transition. This plan proposes to further raise the target of share of renewables in the energy consumption to 45% by 2030 (European Commission 2022a). Furthermore, the new plan also aimed to improve energy efficiency targets to a 13% reduction in final energy consumption by 2030, relative to final energy consumption in 2019.

[4] The EU commission quantifies energy efficiency targets with reference to a baseline projection for 2030. Historically this has been the 2007 reference scenario, but in 2021 the Commission moved to using the 2020 baseline. In this report, we convert these numbers into comparison with a historical reference year (2019), to better communicate the ambition on energy efficiency.

Figure 9 displays 1.5°C compatible pathways for total final energy demand in EU27. In both pathways, final energy demand declines across the time horizon, falling 17-18% by 2030 and 33-50% by 2050 relative to 2019 levels. This is due to a combination of progress on energy efficiency and some reduction in the level of consumer demand for final products.

There are two key drivers of energy efficiency in the selected pathways. The first is reducing energy losses via insulation in buildings, greater efficiency in industrial processes and other steps. This results in incremental, but substantial, reductions in final energy demand. The second critical driver of energy efficiency is electrification. Electric technologies such as EVs and heat-pumps are much more efficient at converting final energy into energy service demands (such as transportation and heating) than their fossil counterparts. **An electrified energy system is a more efficient system** and can be smaller in terms of final energy needs while providing the same overall energy service demands. The HighRE pathway cuts final energy demand by electrification and energy efficiency improvements, without substantial reduction in energy service demands. In the SusDev pathway, there is still some increase in the efficiency of the energy system due to incremental improvements and electrification of demand. However, the SusDev pathway also envisages ambitious lifestyle shifts in the EU27 which further reduce final energy demand (Section 2.5.1).

Whether by incremental efficiency improvements, electrification, or demand reduction, these pathways see final energy demand fall faster than the EU27's current discussed target. As a result, they demonstrate that greater EU ambition on reducing final energy demand would be feasible.

In these pathways, renewables provide 41-48% of final energy demand by 2030 and 89-92% by 2050. The REPowerEU target for the share of final energy provided by renewables in 2030 (of 45%) is broadly aligned with the pathways, although it falls behind the most ambitious 1.5°C compatible pathways for the EU27.

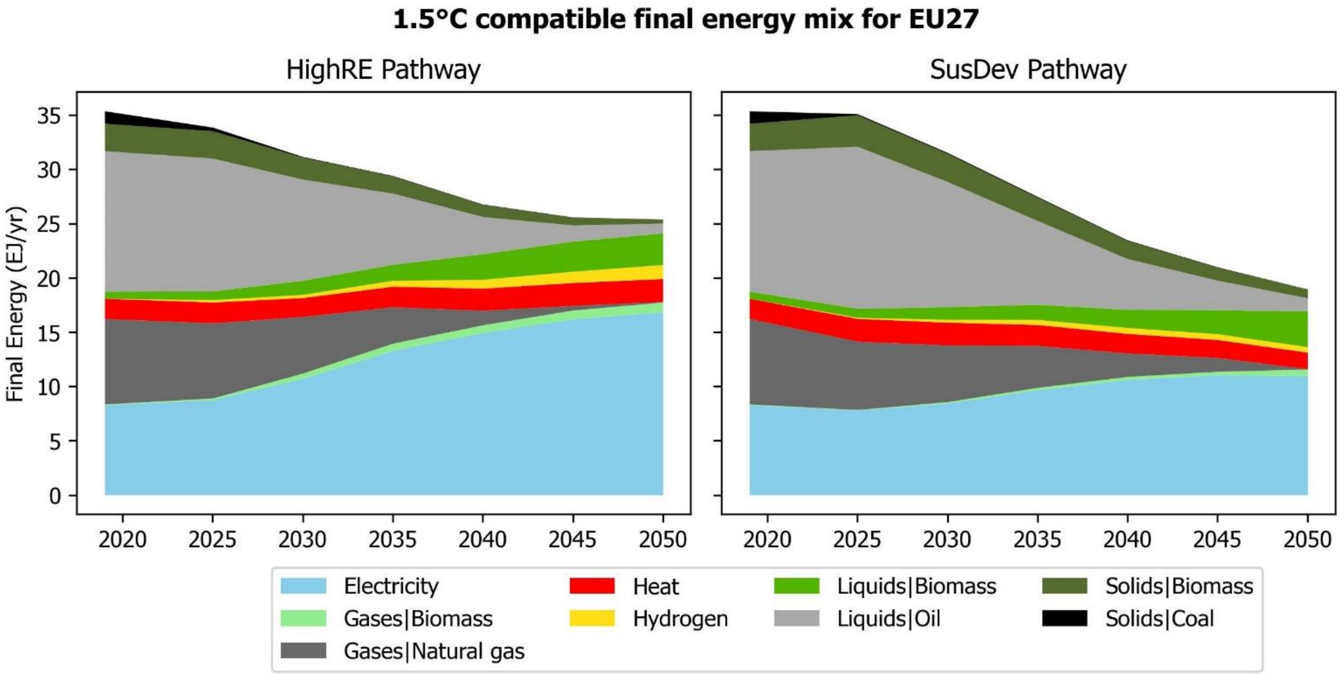


Figure 9 | 1.5°C compatible final energy pathways for the EU27

Electricity sector decarbonisation pathways

A climate-neutral power system for the EU would require a rapid uptake in renewable energy generation within each member state. In the RepowerEU plan, the European Commission proposed increasing the installed capacity of solar PV to almost 600 GW by 2030 – more than four times today's capacity (European Commission 2022a). Alongside this, the Strategy on Offshore Renewable Energy aims to increase the EU's offshore wind capacity by at least five-fold to reach 60 GW by 2030 (European Commission 2020b).

In the illustrative pathways considered here, non-biomass renewables (mainly wind and solar) provide the majority of future electricity demand in Europe. The share of non-biomass renewables increases from nearly 30% today to 75-81% by 2030 and 88-92% by 2050. Both pathways demonstrate a diminishing role of nuclear in the future EU27 power mix[5]. With limited contribution from biomass, nuclear, and hydrogen, the EU would be able to achieve close to 100% clean power by 2035 (97-99%). Further innovation and investment would be required to accommodate this high share of variable renewables in the power system, including grid expansion and interconnection, storage technologies, and sector coupling. Hydrogen plays a particularly important role in providing long-term energy storage. Recent

[5] In the illustrative pathways, new nuclear is not competitive with renewables as a source of electricity generation. As a result, no new nuclear is installed and generation declines slowly over the time horizon to reach zero by 2050. Lifetime extensions on existing nuclear power plants could enable a greater contribution of nuclear to the future EU27 power system (IEA 2019). However, the viability of lifetime extensions may be limited by safety concerns and by continued cost reductions in renewables.

analysis has conducted detailed power sector modelling with a high degree of regional and temporal resolution to assess transformation in the EU's power sector towards the 1.5°C goal (Ember 2022). The results of this analysis broadly align with the power sector transitions for the illustrative pathways assessed in this report.

According to the pathways, there is no space for coal in the EU power mix after 2030. The pathways also envisage a rapid reduction in gas consumption in the power sector, with gas effectively phased out by 2033 in the HighRE pathway. In the SusDev pathway, gas still contributes around 3% of electricity generation post-2035. At this low level, gas will be relegated to the role of a 'peaking technology', operating only to meet electricity demand on limited occasions, and could potentially be phased out entirely as alternative low-carbon flexibility options such as hydrogen and demand-side response diffuse into the energy system.

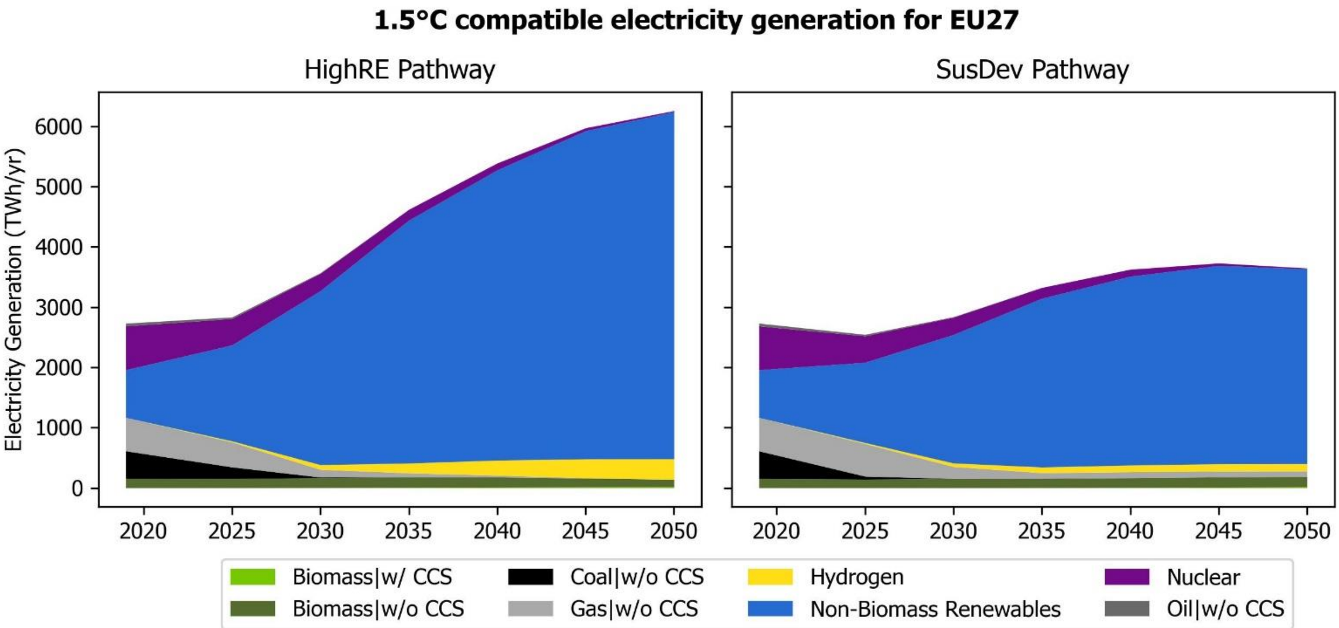


Figure 10 | 1.5°C compatible electricity generation mix for the EU27

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand more than doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand only grows by 33% across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables quadrupling by 2030 in the HighRE pathway and tripling in the SusDev pathway.

Transport sector decarbonisation pathways

As part of the 'Fit For 55' proposals, the European Commission aims for all new cars to be zero-emissions by 2035, and has also proposed to set up a new emissions trading system for the transport sector (European Commission 2021a). In the underlying Commission scenarios, the share of electricity in road transport reaches around 3% in 2030, while the share of biofuels rises from 5% in 2019 to 8.7% in 2030 (European Commission 2021b).

In the 1.5°C compatible pathways analysis the transport sector is electrified much faster. Electricity provides 10-14% of final energy by 2030 and 41-46% by 2050.

Hydrogen also becomes increasingly important in decarbonising the transport sector. **In the illustrative pathways the share of hydrogen in the transport sector reaches 1-3% by 2030 and 1-9% by 2050.** Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option. In 2030, 84% of hydrogen is produced by electrolysis, and this trends towards 100% by 2050.

The share of biofuels in the transport sector reaches 7-9% by 2030, and 31-38% by 2050 in the HighRE and SusDev pathways. This represents a large-scale reliance on biofuels by 2050. However, this share is lower than in previously assessed pathways from the IPCC's Special Report on 1.5°C. Transportation decarbonisation pathways based on higher-resolution and sectorally specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019), instead relying on direct electrification, hydrogen and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing carbon dioxide emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops and negative biodiversity impacts (Energy Transitions Committee 2021).

Due to the expansion of electricity, hydrogen and biofuels, the share of oil falls to 76-81% by 2030 and 14-19% by 2050. Remaining transport oil demand is largely confined to the aviation sector and could be further reduced by introducing renewable-based synthetic fuels, which are not included in the assessed model pathways.

Buildings sector decarbonisation pathways

Buildings account for more than one-third of final energy consumption in the EU (IEA 2021). Rapid decarbonisation of buildings is, then, crucial to achieve the EU's climate objectives.

The EU's current policy framework for buildings decarbonisation includes substantial electrification driven by heat pump and rooftop solar uptake, as well as renewable heat from geothermal and solar – with REPowerEU providing additional impetus (European Commission 2022b). The EU has also placed a greater focus on energy efficiency. In 2020, the European

Commission published a strategy to double the annual energy renovation rate of both residential and non-residential buildings by 2030 and to foster deep energy renovations (European Commission 2020c).

In the illustrative pathways direct electrification provides 40-43% of buildings final energy demand by 2030 and 68-80% by 2050. The share of biomass reaches 12-14% by 2030 and 7-17% by 2050. The total share of renewables, including direct electrification, biomass and renewable based heating reaches 64-66% by 2030 and 98-99% by 2050. Despite the interest in hydrogen's role in buildings sector decarbonisation, neither pathway uses hydrogen for heating in buildings, instead relying on electrification.

Industry sector decarbonisation pathways

The EU aims to reduce industrial emissions by a combination of efficiency measures, electrification, and switching to renewable hydrogen and biofuels. The REPowerEU plan sets a target of 20 million tonnes of renewable hydrogen demand by 2030, while the Biomethane Action Plan aims to increase the production of biomethane to 35 bcm by 2030 in the EU (European Commission 2022b).

The electrification of industrial processes can reduce both energy intensity and industrial emissions. In the illustrative 1.5°C compatible pathways, the share of electricity in the industrial sector reaches up to 46% by 2030 and 56-63% by 2050.

The share of hydrogen in industry reaches up to 3% by 2030 and 15% by 2050. In these pathways, the vast majority of hydrogen production is from electrolysis, which produces 83-84% of hydrogen in 2030, rising towards 100% by 2050. Hydrogen consumption in industry could be higher given recent policy developments in the EU, which envisage rapid deployment of hydrogen to drive decarbonisation. For example, one recent study suggested industrial demand for hydrogen in the EU27 could reach 420TWh by 2050 (Fuel Cells and Hydrogen Joint Undertaking (FCH) 2019), providing high-temperature heat, driving primary steel production and acting as a chemical feedstock. For comparison, hydrogen use in the EU27 industry sector in the HighRE pathway reaches 330 TWh by 2050. There is therefore potential for more ambitious deployment of hydrogen to accelerate industrial decarbonisation.

In the selected 1.5°C compatible pathways, the share of biofuels in industry use grows from 9% in 2019 to 13-18% by 2030. In the HighRE pathway, hydrogen becomes the second largest energy source in industry, displacing biofuels, which fall to provide 10% of industrial final energy. The SusDev pathway has slower scale-up of hydrogen production, consequently displaying greater biofuel reliance, with liquid, solid and gaseous biofuels providing 30% of industrial demand in 2050. In both cases, greater consumption of hydrogen or synthetic fuels, as often shown in detailed energy system modelling, could further reduce biofuel reliance (Dena 2018).

These pathways envisage a **coal-free industrial sector by 2030 for the EU**. This would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling using electric arc furnaces. The illustrative pathways also project a rapid reduction in gas demand. Industrial gas demand falls 40% by 2030 relative to 2019 levels, and **gas use is effectively phased out of industry before 2050**. The share of oil falls to 1-5**%** by 2050. Some of this remaining oil consumption could represent non-energy use, with oil being used as a chemical feedstock in industry. However, without greater sub-sectoral resolution, it is not possible to determine whether this oil represent non-energy or energy consumption. In both cases, further use of synthetic fuels and synthetic feedstocks could reduce remaining oil demand further.

3.1.5 Key characteristics of the EU27's 1.5°C compatible pathways and comparison with other analyses

Table 4 provides a summary of key 1.5°C compatible economy-wide and sectoral benchmarks for the EU27 in 2030 and 2050, compared against recent historical values and country targets, where applicable.

Table 4 | 1.5°C compatible benchmarks for the EU27

*In the SusDev pathway, the share of electricity in the industrial sector falls to 25% in 2030, from 33% today. However, when considering all sectors, there is still an increase in electrification of the energy system in both 2030 and 2050, and by 2050 the electrification rate in industry grows to 56% in the SusDev pathway.

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	3610 $MtCO_2e$	64-67% below 1990	92-94% below 1990	54% below 1990	92-95% below 1990
	Share of renewables in electricity production	34%	92-98%	97-100%	-	-
	Renewable share of final energy demand	23%	42-49%	91-95%	45%	-
	Change in final energy demand (relative to 2019)	0%	-18%	-33% to -50%	-9% to -13%	-
	Electrification rate of final energy demand	23%	27-34%	57-66%	-	-
Sectoral perspective	Transport sector electrification rate	2%	10-14%	41-46%	-	-
	Transport sector renewable share	6%	22-28%	80-86%	-	-
	Buildings sector electrification rate	34%	40-43%	68-80%	-	-
	Buildings sector renewable share	33%	57-61%	96-99%	-	-
	Industry sector electrification rate	33%	25*-46%	56-63%	-	-
	Industry sector renewable share	27%	45-63%	93-99%	-	-

The assessed pathways show a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases, except for oil demand in transport, **fossil fuels are effectively phased out before 2050 in the EU27**. Table 5 highlights effective fossil fuel phase-out dates by sector and fuel type for the selected pathways.

Table 5 | Effective fossil fuel phase-out dates for the EU27.

*In these sectors the phase-out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase-out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	2025-2029	2033*	N/A
Industry	2024	2046-2049	2040*
Buildings	N/A	2045-2049	2044-2047
Transport	N/A	N/A	Post-2050

Comparison with other studies

In developing the 'Fit for 55' package, the PRIMES-GAINS-GLOBIOM model was used to explore pathways towards net zero GHG emissions for the EU27 as a whole (European Commission 2020d). The resulting scenarios arrive at a 55% reduction in emissions by 2030 (relative to 1990 levels), reach net zero GHG emissions by 2050. As these pathways were developed to support the 'Fit for 55' package, it is unsurprising that they display lower levels of climate ambition than the illustrative pathways assessed here, as they are explicitly designed to reduce emissions by 55% in 2030. Nevertheless, it is instructive to explore the energy system differences between these scenarios and the downscaled IAM pathways used in this report.

The scenarios produced by the PRIMES model align with the results presented here, in that they envisage a substantial increase in electrification of final energy. In 2030, electricity provides around 30% of final energy, and 45-50% in 2050. This is slightly less than in the illustrative pathways, in which electricity provides 57-66% of final energy in 2050.

However, the scenarios produced by PRIMES compensate for this by greater deployment of synthetic fuels, including hydrogen, synthetic methane and synthetic liquids. Together, these fuels provide around 15% of final energy in 2050, more than three times the level in the illustrative pathways, which only model hydrogen and do not consider synthetic kerosene/methane. As a result, the scenarios produced for the European Commission can further reduce residual fossil fuel consumption in 2050, while displaying similar or reduced reliance on biomass. This again highlights that the pathways assessed in this report could be strengthened by greater representation of synthetic fuels, which could both accelerate the phase-out of fossil fuels and reduce reliance on biomass.

The scenarios produced to support the 'Fit for 55' package envisage a significant increase in the share of renewables in final energy consumption. In 2030, renewables provide 65-70% of electricity production and 40% of overall final energy demand. The illustrative pathways used in this report produced greater renewables consumption in 2030, with renewables providing over 90% of electricity generation, and 42-49% of total final energy demand. This suggests that there are feasible routes for the EU to accelerate the transition in the 2020s faster than envisaged by the PRIMES modelling that was specifically aimed at a smaller emission reduction by 2030.

Another recent study has focused on transformation in the EU's power sector to achieve the 1.5°C goal (Ember 2022). This is based on detailed power sector modelling with a high degree of regional and temporal resolution. The results of this analysis broadly align with the power sector transitions in the illustrative pathways, with a rapid expansion of wind and solar, driving coal and gas out of the power system, while total electricity demand increases strongly. Coal is effectively phased out of the power sector in 2030 in both studies, and gas in the mid-2030s to achieve a clean electricity system. This report adds to the emerging consensus that a clean European power system by the mid-2030s is achievable, and indeed essential to limiting warming to 1.5°C.

3.2 National Results: Germany

3.2.1 1.5°C compatible emissions pathways: Germany

Germany aims to reduce its GHG emissions to 65% below 1990 levels (excluding LULUCF) by 2030, 88% by 2040 and achieve net zero emissions by 2045 (Federal Ministry of Justice 2021). However, 1.5°C compatible pathways, which demonstrate the highest plausible ambition for the EU27 are more ambitious than Germany's climate targets. **In these 1.5°C compatible pathways, emissions decline to 73-77% below 1990 levels by 2030 (excluding LULUCF).** This leaves an emissions gap of 8-12% in 2030 between the current NDC and 1.5°C compatible action as assessed in this report. These pathways identify technically feasible routes to higher near-term decarbonisation. Under current policies (with existing measures), emissions in 2030 are projected to be only 49% below 1990 levels, 300-340MtCO_2e higher than the 1.5°C compatible pathways (Figure 11).

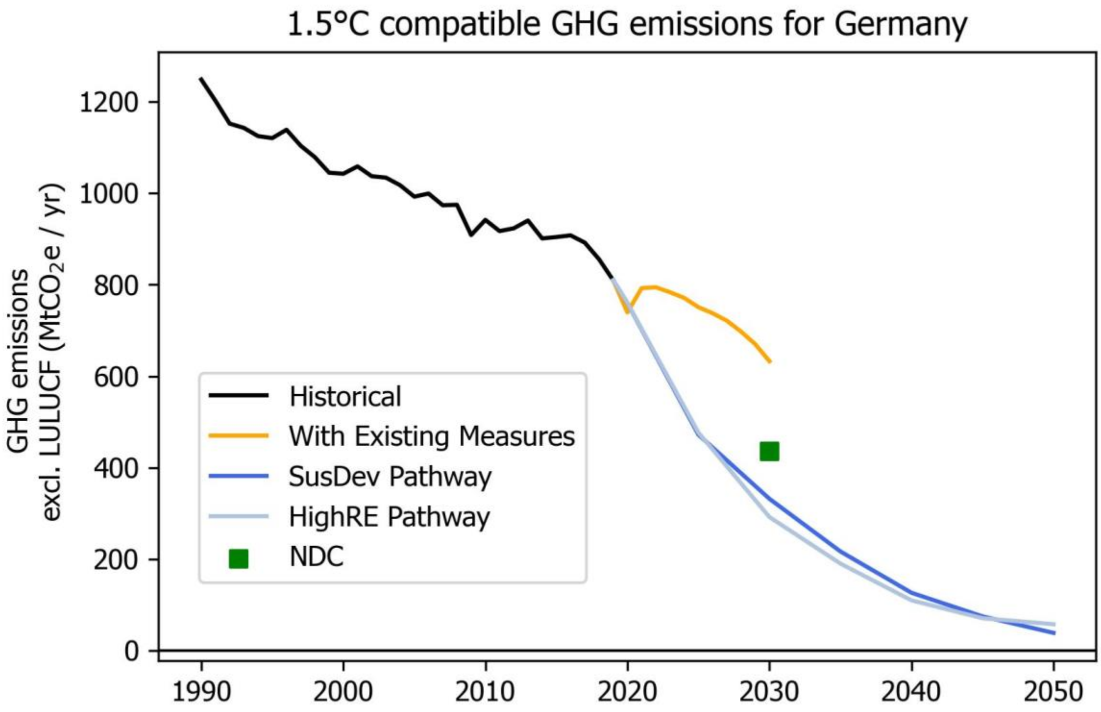


Figure 11 | 1.5°C compatible GHG emissions pathways for Germany

3.2.2 1.5°C compatible sectoral transformation pathways: Germany

Figure 12 displays 1.5°C compatible pathways for total final energy demand in Germany. In both pathways, total energy demand falls due to a combination of improved energy efficiency and reduced demand for final energy consumption. At the same time, renewable energy is rapidly deployed to displace fossil fuels from the energy system.

These pathways show the potential for ambitious reductions in final energy demand in Germany. **Final energy demand falls by 19% by 2030 and 43-58% by 2050 relative to 2019 levels**. However, the pathways cut final energy demand in different ways. In the HighRE pathway, the majority of final energy demand reduction is due to the efficiency gains from direct electrification. As heat pumps and EVs replace gas boilers and petrol/diesel vehicles, final energy demand falls, while overall demand for energy services is relatively unchanged. In the SusDev pathway, some final energy demand reduction is still driven by electrification, with electricity consumption growing 12% across the time horizon. However, this is coupled with ambitious lifestyle shifts that reduce energy demand, and hence the level of final energy in the pathway. While each pathway uses a different approach, **both 1.5°C compatible pathways reduce final energy demand strongly.**

In the illustrative pathways, electricity provides 58-65% of final energy demand in 2050, up from 22% today. At the same time, greater deployment of renewable heat, green hydrogen and bio-energy means that renewables provide 41-47% of final energy demand by 2030 and 93-96% by 2050. Germany's NECP (submitted in June 2020) sets a target that 30% of final energy demand should be renewable by 2030. There is considerable room to improve this target, lending support to the reforms being enacted in Germany as part of the 'Easter' and 'Summer' packages.

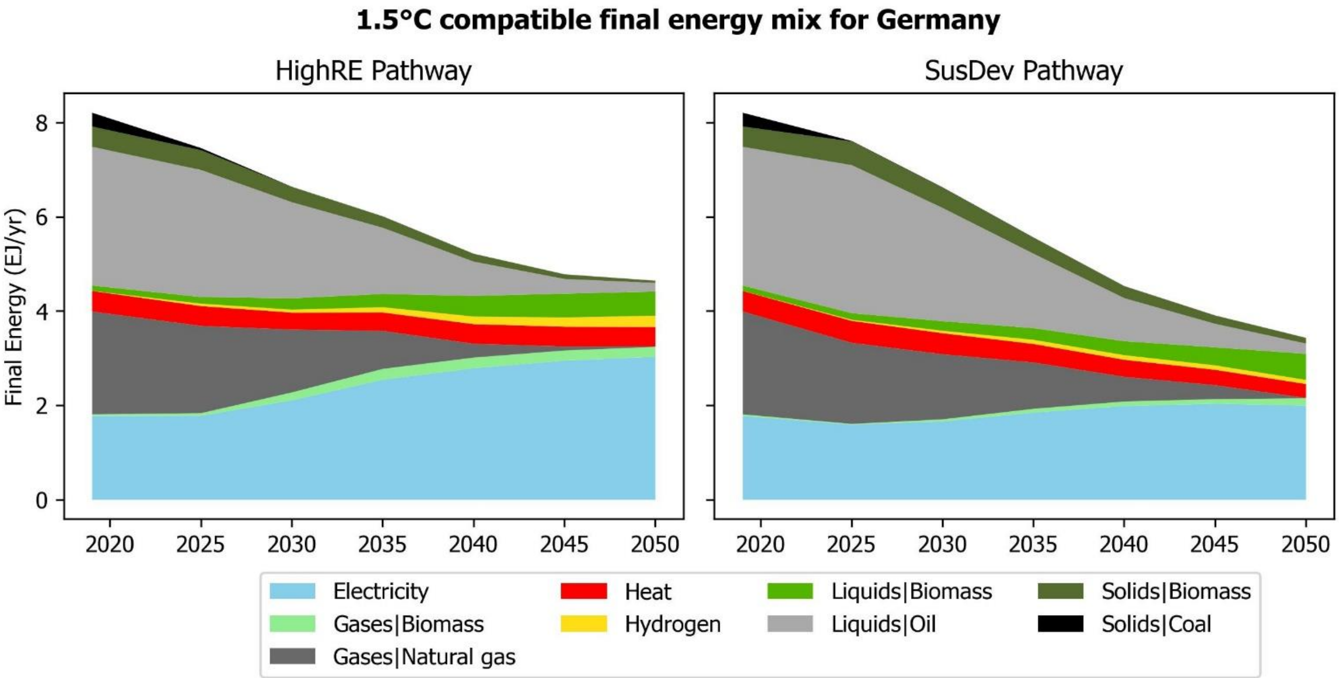


Figure 12 | 1.5°C compatible final energy pathways for Germany

Electricity sector decarbonisation pathways

According to the Renewable Energy Law adopted in July 2022, Germany aims to reach an 80% share of renewables in the power sector by 2030, up from the previous target of 65%. To achieve this, Germany aims to increase onshore wind capacity to 115 GW by 2030 (double the current levels), install 30 GW of offshore wind by 2030 (quadruple the current level) and reach 215GW of solar photovoltaics by 2030 (quadruple the current level). Nuclear will be phased out by end of 2022 with three nuclear reactors operational as of now. Germany's latest coalition agreement sets a coal phase-out date of "ideally" by 2030, although this has not yet been formally legislated for.

In the illustrative 1.5°C compatible pathways, non-biomass renewables provide the vast majority of future electricity demand in Germany. In these pathways, the share of non-biomass renewables (mainly wind and solar) increases from nearly 32% today to 84-89% by 2030 and 93-97% by 2050 (Figure 13). The role of biomass in electricity generation is relatively minor, falling from 8% today to 3-6% by 2050. Large-scale deployment of wind and solar, plus a limited contribution of biomass, sees Germany reach a total renewable share in the power sector of 91-94% by 2030 (greater than the current proposed target) and 98-100% by 2050. Further innovation and investment would be required to accommodate this high share of variable renewables in the power system, including grid expansion and interconnection, storage technologies and sector coupling. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly key role in the HighRE pathway.

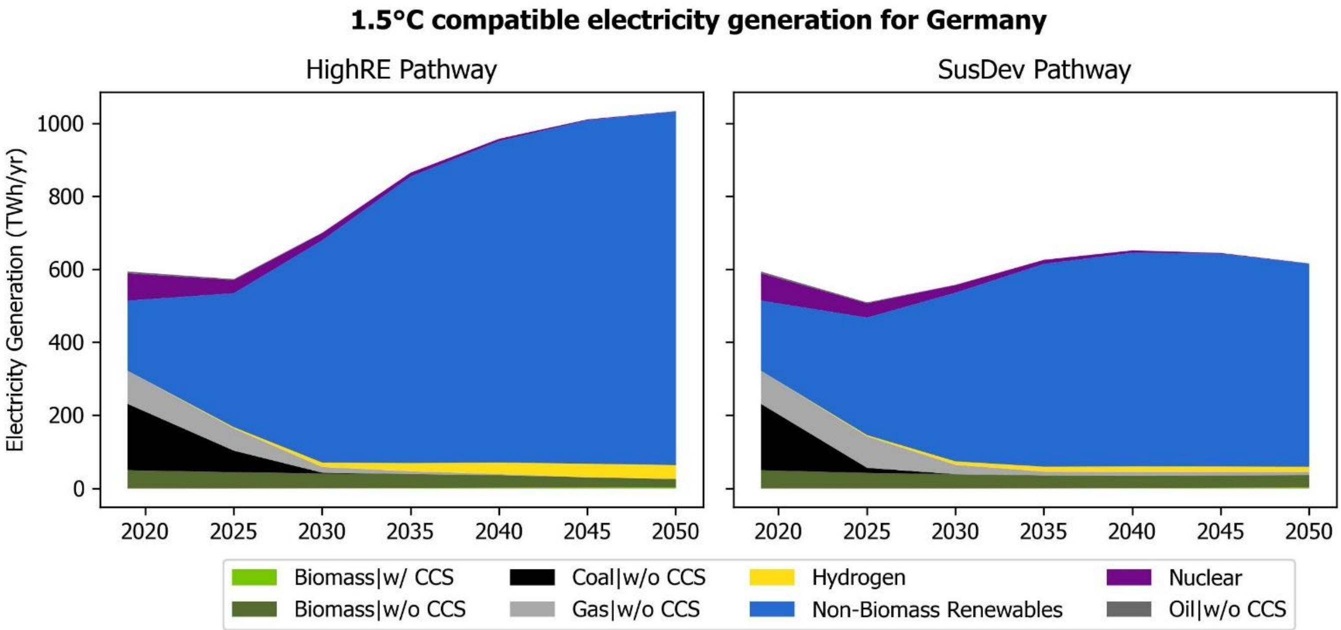


Figure 13 | 1.5°C compatible electricity generation mix for Germany

Both illustrative pathways demonstrate a diminishing role of nuclear in the future German power mix. These pathways are produced by downscaling IAM pathways which do not explicitly account for the policies and targets of individual countries, but instead find cost-effective global and regional energy transitions that achieve the Paris Agreement's LTTG. As a result, the nuclear phase-out by 2022 is not represented in these pathways. However, the extent of nuclear generation remains small and declines over time, with only 3-4% of electricity being produced by nuclear in 2030. If nuclear generation was replaced entirely by coal (the worst possible outcome from an emissions viewpoint), Germany's total emissions would increase only by 4-5% in 2030, demonstrating the limited extent of nuclear generation in its power sector.

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand grows around two-thirds between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand remains broadly constant across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with rapid deployment of non-biomass renewables driving out fossil-based electricity generation.

According to these pathways, there is no space for coal in Germany's power mix after 2030. There is also a rapid reduction in gas in the power sector, which is effectively phased out by 2030-34. As a result, Germany achieves close to 100% clean electricity generation by the mid-2030s at the latest in these illustrative pathways.

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the German transport sector is decarbonised by a mix of electricity, hydrogen and biofuels. **Electricity provides 10-14% of final energy in the transport sector by 2030 and 43-49% by 2050.** Hydrogen could also become increasingly important in the transport sector, providing 1-3% of final energy by 2030 and up to 9% of final energy by 2050. Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

In the illustrative pathways from IPCC AR6, the share of biofuels in the transport sector reaches 6-8% by 2030, and 30-37% by 2050. This represents a large-scale reliance on biofuels to decarbonise transport by 2050. This share, however, is lower than in previously assessed pathways from the IPCC's Special Report on 1.5°C. The IAMs are beginning to reflect the potential for greater hydrogen and electricity consumption in the transport sector. Transportation decarbonisation pathways based on higher-resolution and sectorally specific models often indicate the potential to substantially limit biofuel consumption in the sector (Luderer *et al* 2021a, Breyer *et al* 2019), instead relying on direct electrification, hydrogen and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops and negative biodiversity impacts (Energy Transitions Committee 2021)

Electricity, hydrogen and biofuels all displace oil in the transport sector. Oil provides 78-81% of final energy in the transport sector in 2030 and 12-17% by 2050. Remaining oil demand is largely confined to the aviation sector and could be further reduced by the introduction of renewable-based synthetic fuels.

The share of renewables in the transport sector including renewable electricity, hydrogen and biofuels reaches to 18-21% by 2030 and 82-88% by 2050. Germany aims to reach a 28% renewable share in the transport sector by 2030 including 9% biofuels by 2030. Thus, Germany's renewable target for the transport sector is more ambitious than the selected 1.5°C compatible pathways.

In the assessed pathways, final energy in the transport sector falls by 2030 to 77-80% of 2019 levels, driven in part by the strong efficiency gains of shifting from fossil fuelled to electric vehicles. At present, Germany's legislated target is to reduce 2030 consumption by 10% relative to 2018 levels, although there are current discussions around increasing this further (Escritt *et al* 2022). Further reductions in energy demand will be essential to align the German energy transition with 1.5°C.

Buildings sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the buildings sector is predominantly decarbonised through direct electrification. Electricity provides 31-34% of final energy in Germany's buildings sector by 2030 and 62-76% by 2050. While some analyses have proposed hydrogen as an option to provide low-carbon heating, neither pathway uses hydrogen at all in the buildings sector, instead relying on heat pumps and district heating to provide zero-carbon heat. District heating provides 12-13% of final energy by 2050 in the buildings sector. Direct electrification, renewable district heating and some biomass consumption means that the total share of renewables in the buildings sector reaches 50-54% by 2030 and 96-98% by 2050.

As well as greater electrification of the buildings sector, the pathways envisage a reduction in total energy demand in the buildings sector. Final energy demand falls 14-15% by 2030 and 42-56% by 2050. This is driven by the much greater efficiency of electric technologies such as heat pumps, as well as specific efforts to reduce energy demand in the buildings sector, which are particularly noticeable in the SusDev pathway. Germany's current target is to reduce final energy demand in the buildings sector by 16%, which is aligned with 1.5°C compatible action. However, further strong reductions in final energy demand will be required post-2030 on the road to net zero.

Reductions in energy demand, coupled with a rapid scale-up of renewable energy consumption, lead to a rapid elimination of fossil-based heating from the buildings sector. **Gas demand falls 35-38% by 2030 (relative to 2019) and is phased out entirely from the sector between 2045 and 2049**. A swift reduction in oil demand in the buildings sector results in phase-out before 2050 in the most ambitious pathways.

Industry sector decarbonisation pathways

The electrification of industrial processes can reduce both energy intensity and industrial emissions. In 1.5°C compatible pathways, the share of electricity in the industrial sector reaches 30-48% by 2030 and 63% by 2050.

In these pathways, hydrogen provides up to 3% of industrial final energy demand by 2030 and up to 15% by 2050. The share of biofuels in industry also grows from 5% in 2019 to 8-14% by 2030 and 10-23% by 2050. In the HighRE pathway, hydrogen becomes the second largest energy source in industry by 2050, displacing biofuels, which fall to 10% of industrial final energy. The SusDev pathway has slower hydrogen energy scale-up, and consequently displays greater reliance on bioenergy, with biofuels providing 23% of industrial demand in 2050. In both cases, greater consumption of hydrogen or synthetic fuels, as often shown in detailed energy system modelling, could further reduce biofuel reliance (Luderer *et al* 2021a).

In the illustrative 1.5 °C compatible pathways, unabated coal is effectively phased out before 2030 in German industry. A coal-free industrial sector by 2030 would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling via electric arc furnaces. Any coal-based industry that remains post-2030 would either need to be prematurely retired or lead to increased reliance on CCS deployment in the industrial sector. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls about 37-39% by 2030 relative to 2019 levels, and **gas use is effectively phased out of industry by 2047-2049**.

In the illustrative pathways, the industry sector's final energy demand in 2030 is **74-78%** of 2019 levels. Germany's latest target is to reduce 2030 consumption to 80% below 2018 levels.

3.2.3 Key characteristics of Germany's 1.5°C compatible pathways and comparison with other analyses

Table 6 provides a summary of key 1.5°C compatible economy-wide and sectoral benchmarks for Germany in 2030 and 2050, compared against recent historical values and country targets.

Table 6 | 1.5°C compatible benchmarks for Germany

		Historical	**1.5°C compatible benchmarks**		**Country targets**	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	810 $MtCO_2$	70-74% below 1990	95-97%	65% below 1990	97% below 1990
Whole economy	Share of renewables in electricity production	41%	91-94%	98-100%	80%	-
Whole economy	Renewable share of final energy demand	21%	41-47%	93-96%	30%	-
Whole economy	Change in final energy demand (relative to 2019)	0%	-19%	-43% to -58%	-7%	–
Whole economy	Electrification of final energy demand	22%	25-32%	58-65%	-	
Sectoral perspective	Transport sector electrification rate	2%	10-14%	43-49%	-	-
Sectoral perspective	Transport sector renewable share	5%	18-21%	82-88%	27%	-
Sectoral perspective	Buildings sector electrification rate	27%	31-34%	62-76%	-	-
Sectoral perspective	Buildings sector renewable share	28%	50-54%	96-98%	27% (in heating/cooling)	-
Sectoral perspective	Industry sector electrification rate	34.5%	30-48%	63%	-	-
Sectoral perspective	Industry sector renewable share	27%	49-65%	96-99%	-	

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases except for oil demand in transport, **fossil fuels are effectively phased out prior to 2050** in 1.5°C compatible pathways for Germany. Table 7 highlights effective fossil fuel phase-out dates by sector and fuel type for the selected pathways.

Table 7 | Effective fossil fuel phase-out dates for Germany.

*In these sectors the phase-out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase-out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	2026-2029	2030*	N/A
Industry	2024-2025	2047-2049	2034*
Buildings	N/A	2045-2049	2049*
Transport	N/A	N/A	Post-2050

Comparison with the ARIADNE study

The ARIADNE study uses a multi-model comparison setup to explore how Germany could achieve net zero GHG emissions by 2045 (Luderer *et al* 2021a). A range of models, including detailed sectoral models as well as whole energy system models, are used to explore how Germany could meet its climate targets. The results of the ARIADNE study differ from the results presented here for two primary reasons.

First, the ARIADNE study explicitly constrains pathways to meet Germany's 2030 and 2045 climate goals. This means they aim *a priori* at a 65% reduction of Germany's GHG emissions (excluding LULUCF) by 2030 relative to 1990 levels, achieving net zero emissions by 2045 with a CO_2 sink of 41-74 MtCO2. Our analysis instead focuses on Germany's cost-effective contribution to achieving the 1.5°C goal. To the extent that Germany's cost-effective contribution to the Paris Agreement goals is greater than current near-term climate targets, this analysis demonstrates the potential for increased ambition, explicitly in the context of the global 1.5°C temperature goal. The illustrative pathways we assessed in this analysis achieve 70-74% reduction of GHG emissions relative to 1990 levels (excl. LULUCF) by 2030. This higher ambition is driven in part by greater deployment of renewables in the power sector. In the ARIADNE pathways, renewables account for 79-92% share in electricity generation mix by 2030 and 99-100% by 2050. However, the illustrative pathways assessed in this analysis offer an accelerated perspective, achieving 91-94% share of renewables by 2030, rising to a comparable 98-100% by 2050.

Secondly, the ARIADNE study uses a range of bottom-up sectoral models to produce highly detailed sectoral transition pathways, as well as whole system models. These sectoral models generally have a better representation of mitigation options such as deep electrification, hydrogen and synthetic fuels. The IAM pathways that form the basis of this report have much greater regional and temporal scope (exploring how the whole world could achieve the Paris Agreement goals over the entire 21st century), but this comes at the expense of some detailed sectoral resolution. As a result, the ARIADNE study generally demonstrates the potential for greater consumption of electricity, hydrogen and synthetic fuels in the end-use sectors, and as a result lower reliance on biofuels and a faster phase-out of fossil fuels.

For example, in the ARIADNE pathways electricity provides 7-20% of final energy in transport by 2030 and 26-80% by 2050. Oil consumption is eliminated by 2045-50. In comparison, the illustrative pathways assessed in this report see electricity providing 10-14% of final energy in 2030, rising to 43-49% by 2050. The ARIADNE study also sees greater use of hydrogen, which provides up to 30% of transport demand (compared to a maximum of 9% in the HighRE pathway), and reduced biofuel reliance. Biofuels provide only 4-10% of final energy demand in 2050, compared with 30-37% in the selected 1.5°C compatible pathways. This demonstrates that greater consumption of hydrogen and electricity can reduce biofuel reliance and accelerate the phase-out of fossil fuels in the transport sector.

In the ARIADNE pathways, the share of electricity in buildings energy demand reaches 27-38% by 2030 and 58-74% by 2050. The illustrative pathways assessed in this report envisage a similar level of electrification, with 31-34% of final energy in the buildings sector electrified by 2030 and 62-76% by 2050. They achieve 96-98% share of renewables in buildings final energy demand by 2050, while the ARIADNE pathways reach 100% renewables by 2045.

3.3 National Results: Finland

3.3.1 1.5°C compatible emissions pathways: Finland

According to the new Climate Change Act which entered into force on 1 July 2022, Finland aims to reduce its GHG emissions to 60% below 1990 levels by 2030 (excluding LULUCF), 80% by 2040 and 90-95% by 2050 (Finnish Government 2022). **However, in 1.5°C compatible pathways which demonstrate the highest plausible ambition for Europe, Finnish emissions fall to 64-70% below 1990 levels by 2030 (excluding LULUCF) and 98-100% by 2050.** Such pathways identify technically feasible routes to higher near-term decarbonisation. Under current policies (with existing measures), emissions in 2030 are projected to be only 45% below 1990 levels, and would need to fall an additional 13-18MtCO_2e to be compatible with the Paris Agreement's LTTG (Figure 14).

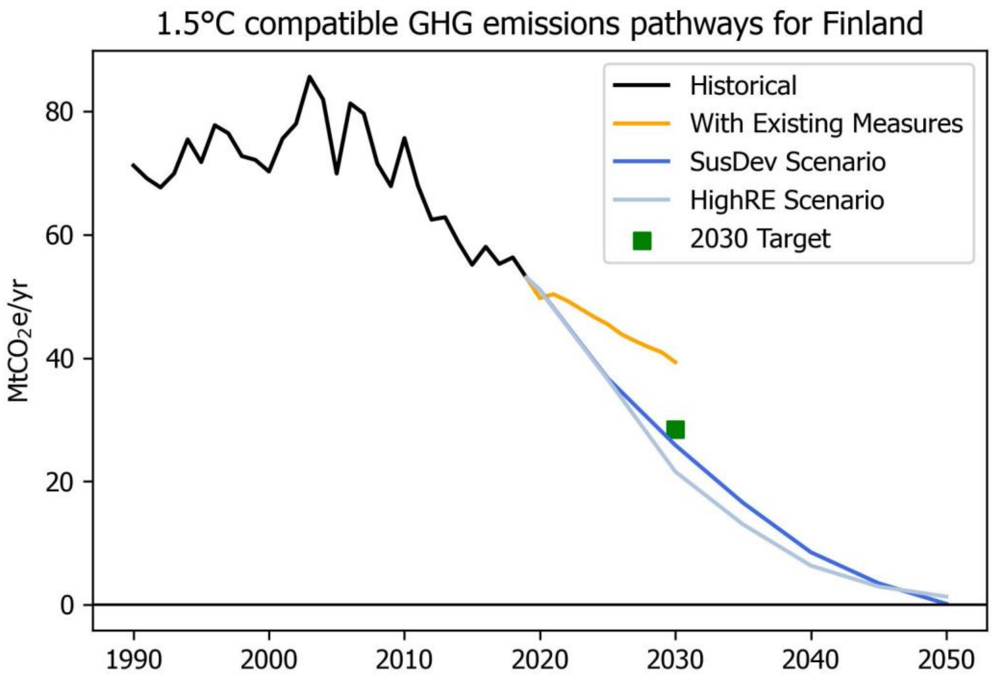


Figure 14 | 1.5°C compatible emissions pathways for Finland

3.3.2 1.5ºC compatible sectoral transformation pathways: Finland

Figure 15 displays 1.5°C compatible pathways for total final energy demand in Finland. In both pathways, total energy demand remains flat or declines slightly.

Both pathways envisage increased electrification as part of 1.5°C compatible action. Electricity demand grows by 50-120% over the time horizon and provides 53-59% of final energy demand in 2050, up from 30% today. There is also a substantial role for district heating in the buildings and industrial sectors. Over 90% of this heat is provided from biomass and geothermal sources by 2030. Currently, 25% of Finland's final energy comes from direct biomass consumption, particularly solid biomass use in industry. In 1.5°C compatible pathways, total biomass demand falls 26-47% by 2050 below 2019 levels, with a transition towards greater use of biofuels in long-distance transport and reduced use of biomass in industry. **Together, renewables provide 70-79% of final energy demand by 2030 and 95-99% by 2050**.

Final energy demand remains relatively flat across the time horizon, rising 10% by 2050 in the HighRE pathway, and falling 15% in the SusDev pathway compared to 2019 levels. This differs from the previous countries assessed (EU27 and Germany), where there were strong reductions in final energy demand in both pathways. The reason for this is that Finland's energy system is already relatively fossil-free, with oil the only remaining fossil fuel. A significant driver of reductions in final energy demand is the efficiency improvement when moving from fossil fuel combustion (with associated heat loss), to more efficient energy vectors such as electricity. The extent of this transition in Finland is less than in the EU27 as a whole, due to the low share of fossil fuels in the energy mix. As a result, the level of demand reduction observed is correspondingly reduced.

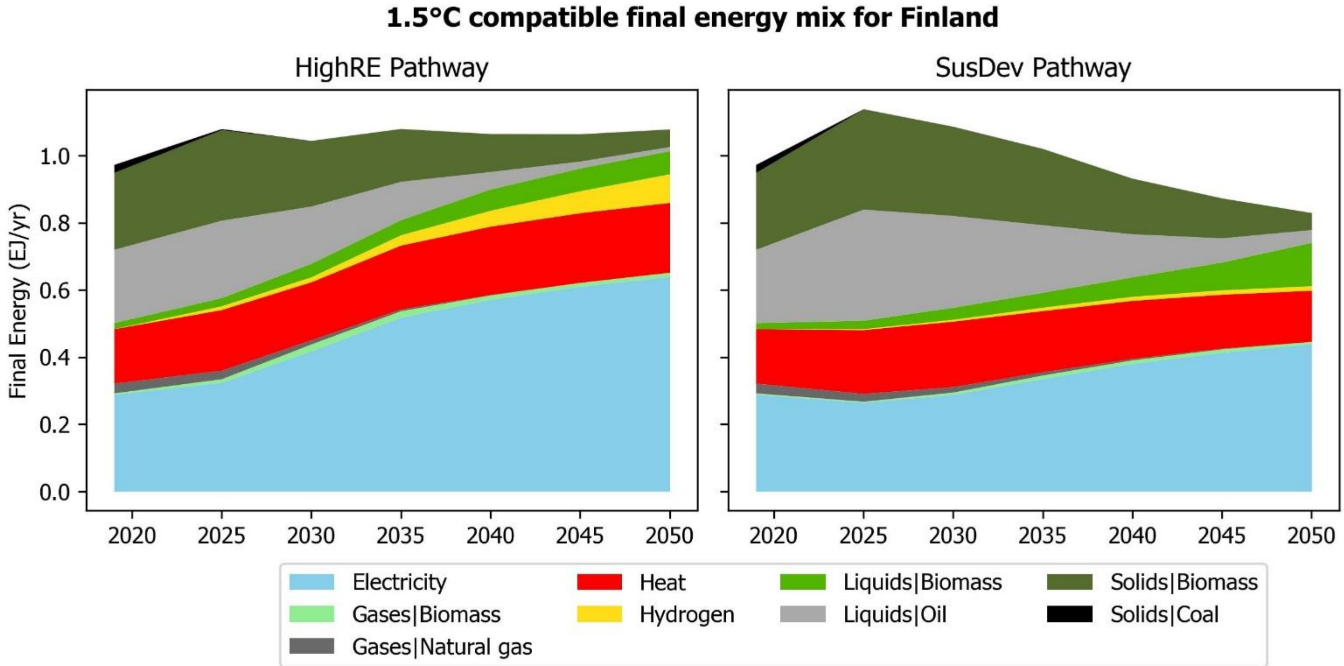


Figure 15 | 1.5°C compatible final energy pathways for Finland

Electricity sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, non-biomass renewables provide the vast majority of future electricity demand in Finland. In these pathways, the share of non-biomass renewables (mainly wind and solar) increases from nearly 27% today to 72-77% by 2030 and 84-93% by 2050 (Figure 16). There is a relatively constant level of electricity generation from biomass of around 11-16TWh/yr across the time horizon. Accounting for this limited contribution from biomass, **the total share of electricity produced by renewables reaches to 88-91% by 2030 and 99-100% by 2050**. Further innovation and investment would be required to accommodate this high share of variable renewables in the power system, including for grid expansion and interconnection, storage technologies and sector coupling. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly important role in the HighRE pathway.

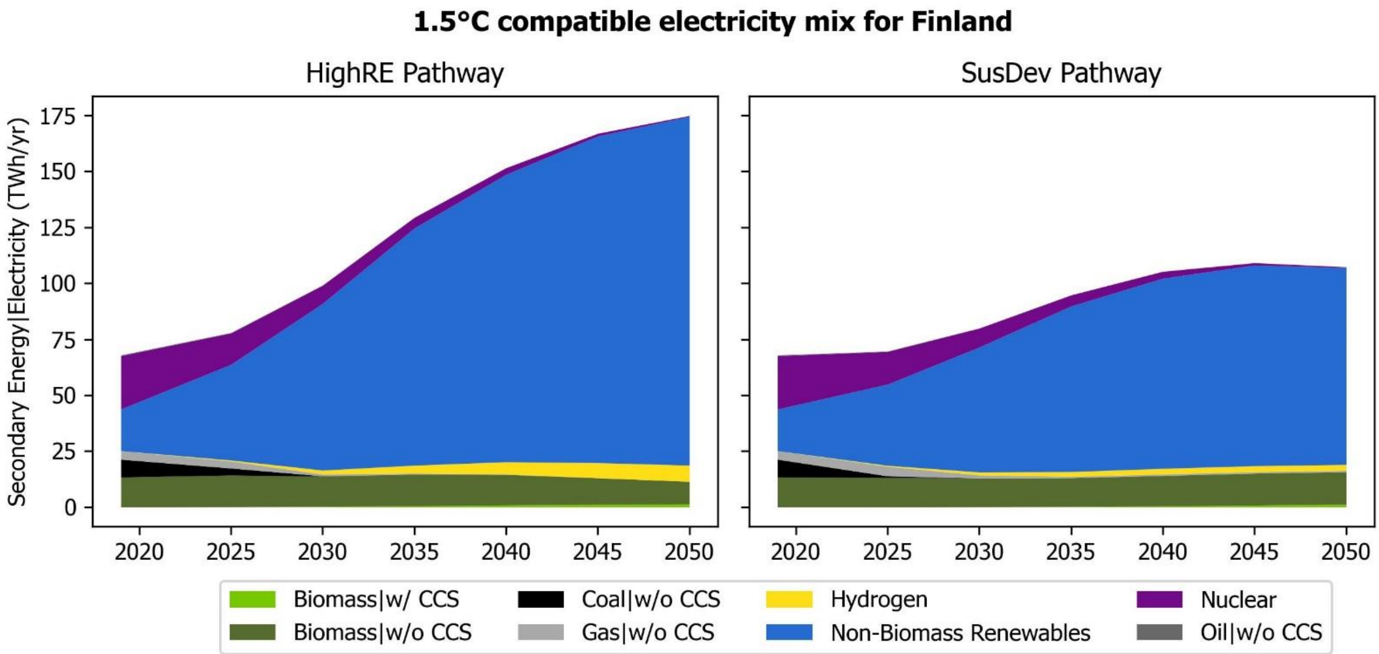


Figure 16 | 1.5°C compatible electricity generation mix for Finland

Both illustrative pathways demonstrate a diminishing role of nuclear in the future power mix. New nuclear power generation is not competitive compared to renewables, and no new capacity is installed in Finland. The share of electricity from nuclear falls to 8-10% by 2030 and is phased out by 2050[6].

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand more than doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand growth is more limited across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables growing strongly.

According to the pathways, there is no space for coal in Finland's power mix after 2030. The assessed pathways also envisage a rapid reduction in gas consumption in the

[6] Lifetime extensions on existing nuclear power plants could enable a greater contribution of nuclear in future Finnish electricity generation (IEA 2019). However, the viability of lifetime extensions may be limited by safety concerns and by continued cost reduction in renewables.

power sector, with gas effectively phased out by 2028-30 in the HighRE and SusDev pathways respectively. Consequently, Finland achieves 100% clean power generation by 2030.

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways the transport sector is decarbonised by a mix of electricity, hydrogen and biofuels. **Electricity provides 10-14% of final energy by 2030 and 42-47% by 2050.** Hydrogen could also become increasingly important in the transport sector decarbonisation. Based on the two assessed illustrative pathways, the share of hydrogen in the transport sector reaches 2.5% by 2030 and 1-9% by 2050. Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

In the assessed pathways based on IPCC AR6, the share of biofuels in the transport sector reaches 12-16% by 2030, and 39-45% by 2050. While this is still a large level of biofuel consumption, it is lower than in previously assessed IAM pathways from the IPCC's Special Report on 1.5°C. Transportation decarbonisation pathways based on higher-resolution and sectoral-specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019), instead relying on direct electrification, hydrogen and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops and negative biodiversity impacts (Energy Transitions Committee 2021). Finland's current target is for biofuels to provide 30% of final energy in the transport sector by 2030. This high reliance on biofuels could be reduced by greater uptake of electric vehicles in surface transport, and hydrogen/synthetic fuels in long-distance applications where electrification is challenging.

Electricity, hydrogen and biofuels all displace oil consumption in the transport sector. Oil provides 69-75% by 2030 and 6-9% by 2050. Remaining oil demand is largely confined to the aviation sector and could be further reduced by the introduction of renewable-based synthetic fuels, which are not included in the assessed model pathways. **The share of renewables in total transport final energy use including renewable electricity, hydrogen, biomass and renewable heat reaches 24-30% by 2030 and 90-93% by 2050**.

Buildings sector decarbonisation pathways

Finland's buildings sector is already heavily decarbonised, with electricity, district heating and biomass consumption providing over 90% of final energy demand in 2019. In the illustrative 1.5°C compatible pathways, three key dynamics occur.

First, the limited remaining oil consumption (7% of final energy in 2019) is phased out before 2040. Secondly, there is a transition away from direct biomass consumption in the buildings sector towards electrification. Electricity provides up to 50% of final energy in the buildings sector by 2030 and 58-68% by 2050, an increase on today's levels of 43%. Thirdly, there is a relatively constant level of district heating, which provides 30-32% of final energy demand in 2050, similar to today's levels. However, the source of energy for district heating moves from a mixture of fossil and renewable sources to entirely renewable sources (biomass and geothermal). As a result of these changes, **the total share of renewables in the buildings sector reaches 89-90% by 2030 and 100% by 2050.**

Industry sector decarbonisation pathways

The electrification of industrial processes can reduce both energy intensity and industrial emissions. In the illustrative 1.5°C compatible pathways considered here, electricity provides 19-41% of final energy demand in industry by 2030 and 52-56% by 2050.

The share of hydrogen in industry use reaches up to 3% by 2030 and 1-15% by 2050. Current biofuel consumption in the Finnish industrial sector is high, with bioenergy providing 39% of industrial final energy in 2019. In 1.5°C compatible pathways, this share rises slightly until 2030, when biomass provides 36-45% of final energy, before declining to represent 12-28% of industrial final energy demand in 2050. In the HighRE pathway, renewable heat and hydrogen become the second largest energy source in industry, displacing biofuels, which fall to 12% of industrial final energy by 2050. The SusDev pathway has slower scale-up of hydrogen production, and displays greater biofuel reliance, with biofuels providing 28% of industrial demand in 2050. In both cases, greater consumption of hydrogen or synthetic fuels, as often shown in detailed energy system modelling, could further reduce biofuel reliance.

Unabated coal is effectively phased out before 2030 in 1.5 °C compatible pathways for the industry sector in Finland. A coal-free industrial sector by 2030 would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling via electric arc furnaces. Any coal-based industry that remains post-2030 would either need to be prematurely retired or lead to increased reliance on CCS deployment in the industrial sector. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls by 43-56% by 2030 relative to 2019 levels, and **gas use is phased out of industry by 2044 at the latest.**

3.3.3 Key characteristics of Finland's 1.5°C compatible pathways and comparison with other analyses

Table 8 below provides a summary of key derived 1.5°C compatible economy-wide and sectoral benchmarks for Finland in 2030 and 2050, compared against recent historical values and country targets.

Table 8 | 1.5°C compatible benchmarks for Finland

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	53 MtCO2	64-70% below 1990	98-100% below 1990	60% below 1990	90-95% below 1990
	Share of renewables in electricity production	47%	88-91%	99-100%	-	-
	Renewable share of final energy demand	56%	70-79%	95-99%	-	-
	Change in final energy demand (relative to 2019)	0%	+7% to +12%	+10% to -15%	-	–
	Electrification of final energy demand	30%	26-40%	53-59%	-	
Sectoral perspective	Transport sector electrification rate	2%	10-14%	42-47%	-	-
	Transport sector renewable share	11%	24-30%	90-93%	-	-
	Buildings sector electrification rate	43%	43-50%	58-68%	-	-
	Buildings sector renewable share	69%	89-90%	99-100%	-	-
	Industry sector electrification rate	30%	19-41%	52-56%	-	-
	Industry sector renewable share	64%	71-87%	93-99%	-	

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases except for oil demand in transport, **fossil fuels are effectively**

phased out prior to 2050 in 1.5°C-compatible pathways for Finland. Table 9 highlights effective fossil fuel phase-out dates by sector and fuel type for the selected pathways.

Table 9 | Effective fossil fuel phase-out dates for Finland

*In these sectors the phase-out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase-out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	2025-2027	2028*	N/A
Industry	2023	2030-2032	2039*
Buildings	N/A	N/A	2036-2040
Transport	N/A	N/A	Post-2050

Comparison with the Finnish Climate Change Panel study

The Finnish Climate Change Panel has explored how Finland could achieve net zero GHG emissions by 2035 and further decarbonisation by 2050. Its report does not produce detailed energy system modelling, but instead applies equity principles to derive a carbon budget for Finland, and then explores emissions pathways compatible with this budget (Finnish Climate Change Panel 2021). This study suggested that Finland's globally fair carbon budget, using the ability-to-pay principle, is 79MtCO_2 from 2020-2050.

On this basis, the Panel suggest that Finland should reduce GHG emissions (excluding LULUCF) emissions to at least 60% below 1990 levels by 2030. Net zero GHG emissions (including LULUCF) should be achieved in 2035. At the same time, the Panel notes that the (already substantial) LULUCF sink in Finland must urgently be expanded to reach -21MtCO_2/y by 2035 and be sustained at this level in the future. By 2050, GHG emissions should be between 90-95% below 1990 levels (excluding LULUCF), and including the land sink, Finland's GHG emissions would be net-negative.

These targets are slightly below the emissions reductions envisioned in the downscaled illustrative pathways, where emissions fall 64-70% below 1990 levels by 2030, and 98-100% below 1990 levels in 2050 (excluding LULUCF). This suggests that there are technically feasible routes to further reduce emissions in Finland. This could either enable Finland to achieve a more stringent total carbon budget and lower its contribution to global warming or reduce its reliance on the LULUCF sink.

3.4 National Results: France

3.4.1 1.5°C compatible emissions pathways: France

France aims to reduce its GHG emissions to 40% below 1990 levels (excluding LULUCF) by 2030, and achieve net zero GHG emissions by 2050 (including LULUCF). This corresponds to GHG emissions (excluding LULUCF) reaching 85% below 1990 levels by 2050. 1.5°C compatible pathways that demonstrate the highest plausible ambition for the EU27 are more ambitious than these current targets. In these pathways, emissions reach 42-57% below 1990 levels by 2030 (excluding LULUCF). This leaves an emissions gap of 40-70MtCO_2e in 2030 between the current NDC and 1.5°C compatible action as assessed in this report. These pathways identify technically feasible routes to higher near-term decarbonisation. Under current policies (with existing measures), France's emissions in 2030 are projected to be only 33% below 1990 levels, 80-110MtCO_2e higher than the 1.5°C compatible pathways

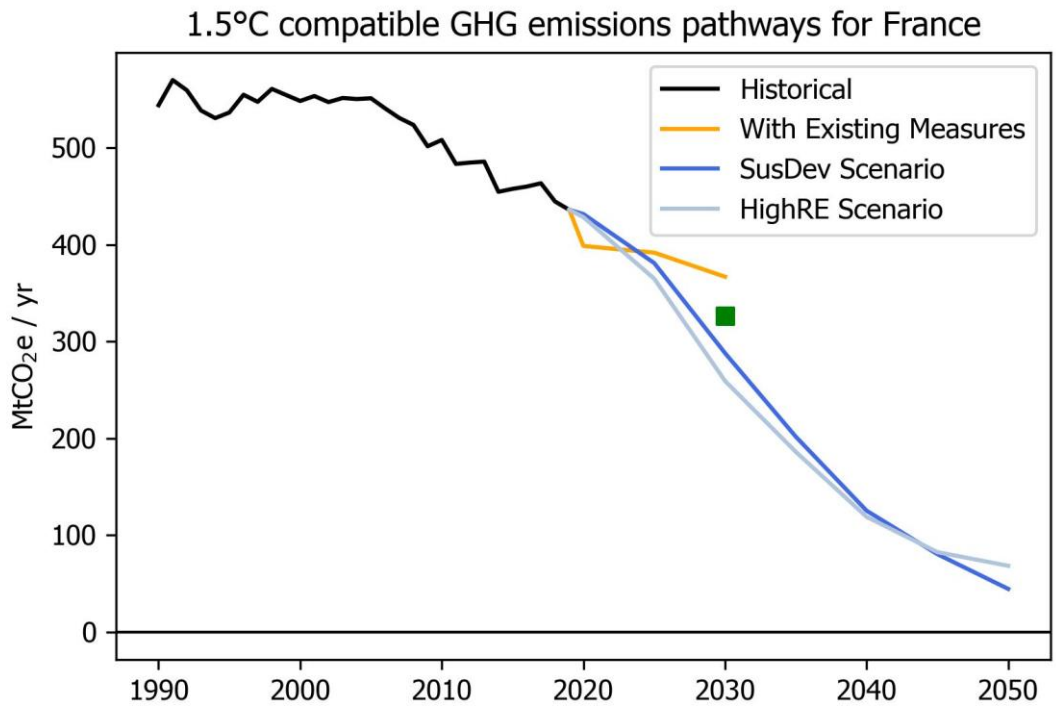


Figure 17 | 1.5°C compatible emissions pathways for France

3.4.2 1.5°C compatible sectoral transformation pathways: France

Figure 18 displays 1.5°C compatible pathways for total final energy demand in France. In both pathways, total energy demand falls across the time horizon. At the same time, renewable energy is rapidly deployed to displace fossil fuels from the energy system.

In both pathways, energy demand electrification is crucial to achieving the 1.5°C goal. **Electricity provides 65-73% of final energy demand in 2050, up from 28% today**. There is also limited but non-negligible use of renewable fuels, particularly renewable heat (from geothermal and biomass), biofuels, and green hydrogen. **Together, renewables provide 38-45% of final energy demand by 2030 and 94-97% by 2050**. France's current target is to meet 32% of final energy demand by renewables in 2030. These pathways demonstrate the potential to increase the ambition of this target further.

Final energy demand falls in both illustrative pathways. In 2030, final energy demand is 10% below 2019 levels, and falls further to reach 26-46% below 2019 levels in 2050 in the HighRE and the SusDev pathway respectively. This reduction in energy demand is broadly aligned with France's current target of 8% by 2030 relative to 2019 levels. However, this target will have to be strengthened and extended post-2030 for France to remain aligned with 1.5°C compatible action as assessed by these pathways. As discussed previously, reductions in final energy demand can be achieved by incremental improvements in energy efficiency (observed in both pathways), efficiency improvements due to direct electrification (particularly relevant for the HighRE pathway), and reduction in total energy service demands (more relevant in the SusDev pathway).

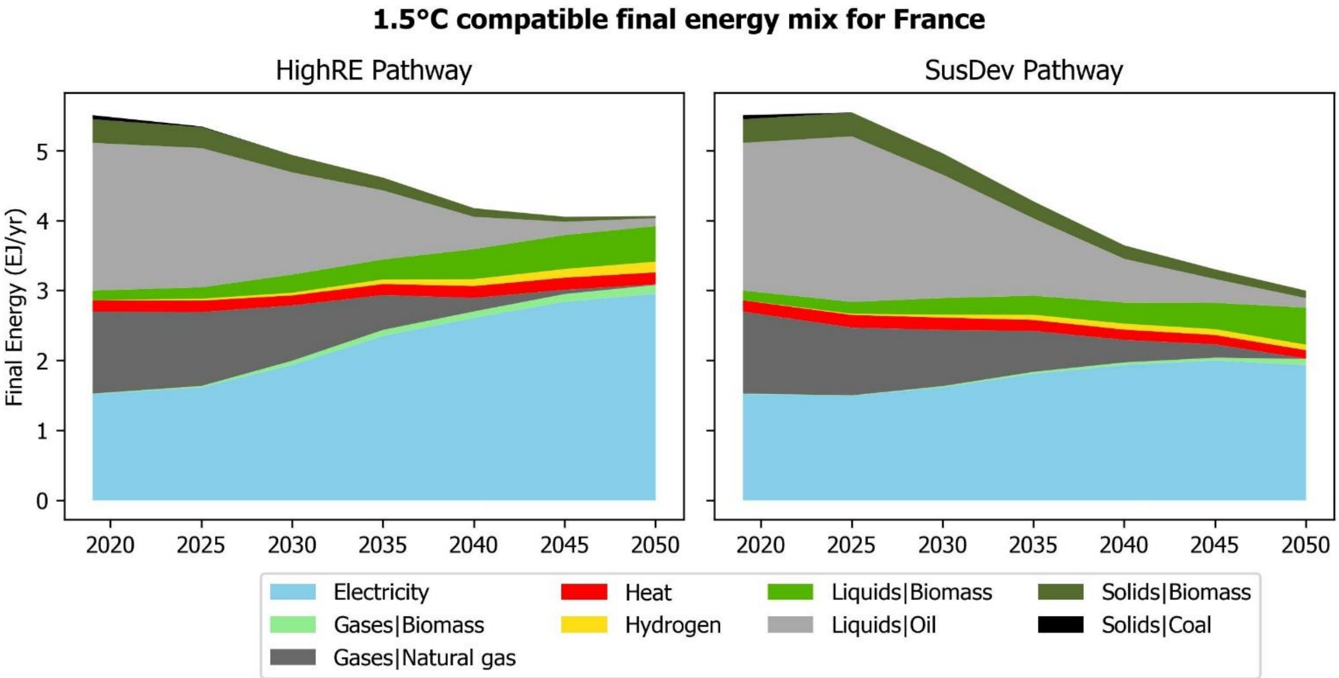


Figure 18 | 1.5°C compatible final energy pathways for France

Electricity sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, non-biomass renewables provide the vast majority of future electricity demand in France. The share of non-biomass renewables (mainly wind and solar) increases from nearly 19% today to 66-74% by 2030 and 96-99% by 2050

(Figure 16). Further innovation and investment would be required to accommodate this high share of variable renewables in the power system, including for grid expansion and interconnection, storage technologies and sector coupling. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly key role in the HighRE pathway.

In the illustrative pathways, no new nuclear capacity is installed. As a result, nuclear generation declines slowly over the time horizon as existing plants retire, and nuclear generation is phased out by 2050. Nuclear provides 23-29% of electricity generation by 2030, with total generation falling by 61% over the 2020s. This represents a historic transformation in the French power sector. A transition toward a 100% renewables power sector has been proposed before in France (Reuters 2019), but seems less likely in the current political climate, where concerns around energy security have led to the pronouncement of a "nuclear renaissance" (Serova 2022). Other studies have further assessed the relative role of renewables and nuclear in the French power sector, and these are further discussed in Section 3.4.3.

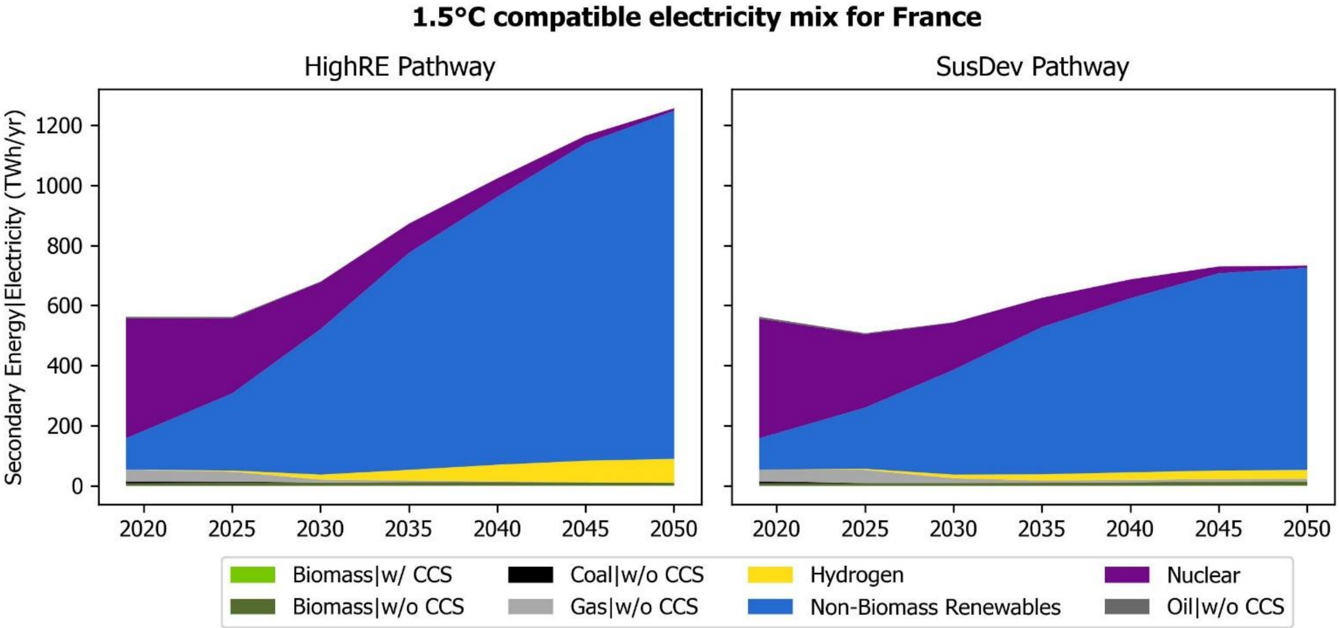


Figure 19 | 1.5°C compatible electricity generation mix for France

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand approximately doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand growth is more limited across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables growing strongly.

The assessed pathways envisage a rapid reduction in gas consumption in the power sector. **Gas is effectively phased out of the power sector between 2029-2031 in France.** As a result, France achieves close to 100% clean electricity generation from 2030 onwards.

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways the transport sector is decarbonised by a mix of electricity, hydrogen and biofuels. Electricity provides 11-15% of final energy by 2030 and 45-50% by 2050. Hydrogen could also become increasingly important in the transport sector decarbonisation. Based on the two assessed illustrative pathways, the share of hydrogen in the transport sector reaches up to 2.5% by 2030 and up to 9% by 2050. Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

There is also an expansion in biofuel consumption in these pathways. The share of biofuels in the transport sector reaches 9-12% by 2030, and 34-40% by 2050. While this is still a high level of biofuel consumption, it is lower than in previously assessed IAM pathways from the IPCC's Special Report on 1.5°C. Transportation decarbonisation pathways based on higher-resolution and sectorally specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019), instead relying on direct electrification, hydrogen and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops and negative biodiversity impacts (Energy Transitions Committee 2021).

Electricity, hydrogen and biofuels all displace oil consumption in the France's transport sector. Oil provides 73-78% by 2030 and 9-12% by 2050. Remaining oil demand is largely confined to the aviation sector and could be further reduced by the introduction of renewable-based synthetic fuels, which are not included in the assessed model pathways. **The share of renewables in total transport final energy use including renewable electricity, hydrogen, biomass and renewable heat reaches 19-23% by 2030 and 87-91% by 2050**.

Buildings sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the buildings sector is predominantly decarbonised through direct electrification. Electricity provides 50-53% of final energy in the buildings sector by 2030 and 78-89% by 2050. The remaining demand is met by limited deployment of district heating and biomass consumption. While some analyses have proposed hydrogen as an option to decarbonise buildings heating, neither pathway uses hydrogen at all in the buildings sector. The total share of renewables in the buildings sector reaches 51-56% by 2030 and 97-99% by 2050.

Gas provides around 30% of final energy demand in the buildings sector. In 1.5°C compatible pathways, this share falls to 22% by 2030, and **gas is effectively phased out of the buildings sector before 2050** in both pathways.

Electrification can reduce final energy demand in the buildings sector due to the much higher efficiency of electric technologies, such as heat pumps. Final energy demand in the buildings sector falls by 20-40% by 2050 in the HighRE and SusDev pathway, respectively.

Industry sector decarbonisation pathways

The electrification of industrial processes can reduce both energy intensity and industrial emissions. In the illustrative 1.5°C compatible pathways considered in this report, electricity provides 57-65% of final energy by 2050.

Hydrogen provides up to 3% of industrial energy by 2030 and up to 14% by 2050. Current biofuel consumption in France's industrial sector is comparatively low, with bioenergy providing 5% of final energy in 2019. 1.5°C compatible pathways display a range of possible futures for biomass consumption in the industrial sector. In the HighRE pathway, hydrogen becomes the second largest energy source in industry (after direct electrification. Biomass therefore provides around 11% of final energy by 2050. The SusDev pathway has slower scale-up of hydrogen production, and therefore displays greater biofuel reliance. Bioenergy provides 33% of industrial demand in 2050. In both cases, greater consumption of hydrogen or synthetic fuels could further reduce biofuel reliance (Dena 2018).

Unabated coal is effectively phased out before 2030 in 1.5°C compatible pathways for France's the industry sector. A coal-free industrial sector by 2030 would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling via electric arc furnaces. Any coal-based industry that remains post-2030 would either need to be prematurely retired or lead to increased reliance on CCS deployment in the industrial sector. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls by 35% by 2030 relative to 2019 levels, and **gas use is effectively phased out of industry by 2049 at the latest**.

3.4.3 Key characteristics of France's 1.5°C compatible pathways and comparison with other analyses

Table 10 provides a summary of key derived 1.5°C compatible economy-wide and sectoral benchmarks for France in 2030 and 2050, compared against recent historical values and country targets.

Table 10 | 1.5°C compatible benchmarks for France

*In the SusDev pathway, the share of electricity in the industrial sector falls to 25% in 2030, from 33% today. However, when considering all sectors, there is still an increase in electrification of the energy system in both 2030 and 2050, and by 2050 the electrification rate in industry grown to 56% in the SusDev pathway.

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	435 $MtCO_2e$	42-57% below 1990	87-92% below 1990	40% below 1990 levels	85% below 1990 levels
	Share of renewables in electricity production	20%	68-75%	98-99%	33% domestic generation	-
	Renewable share of final energy demand	17%	38-45%	94-97%	-	-
	Change in final energy demand (relative to 2019)	0%	-10%	-26% to -46%	-	–
	Electrification of final energy demand	28%	33-39%	65-73%	-	
Sectoral perspective	Transport sector electrification rate	2%	11-15%	45-50%	-	-
	Transport sector renewable share	7%	19-23%	87-91%	-	-
	Buildings sector electrification rate	43%	50-53%	78-89%	-	-
	Buildings sector renewable share	24%	50-56%	97-99%	-	-
	Industry sector electrification rate	36%	28*-48%	57-65%	-	-
	Industry sector renewable share	18%	39-53%	96-99%	-	

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases except for oil demand in transport, **fossil fuels are effectively phased out before 2050** in 1.5°C-compatible pathways for France. Table 11 highlights effective fossil fuel phase-out dates by sector and fuel type for the selected pathways.

Table 11 | Effective fossil fuel phase-out dates for France

*In these sectors the phase-out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase-out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	N/A	2029*	N/A
Industry	2022-2023	2047-2049	2036*
Buildings	N/A	2044-2049	2043-2045
Transport	N/A	N/A	Post-2050

Comparison with the RTE 2021 study

The illustrative pathways assessed in this report entirely phase out nuclear generation in the French power sector by 2050. This represents a historic transformation in a power sector which has been historically dominated by nuclear. A recent study conducted by RTE explored how the French power sector would need to evolve to enable France to meet its 2030 climate target and 2050 net zero goal (RTE 2021). To further contextualise our findings, we compare the power sector transition as envisaged by the two downscaled illustrative pathways and the RTE study.

The RTE study models six different power sector transitions for France. In these pathways, the share of nuclear ranges from 0-50%, while the share of renewables ranges from 50-100%, including a maximum share from non-biomass renewables of 97%. The RTE study therefore acknowledges that a 100% renewables power sector is technically feasible in France, a conclusion which is supported by the illustrative pathways in this report, as well as a range of other studies in the literature (Victoria *et al* 2020, Pickering *et al* 2022).

The illustrative pathways produced in this report do not explicitly consider the scope for lifetime extensions on existing nuclear, focusing instead on the installation of new nuclear capacity. In these illustrative pathways, new nuclear is not cost-competitive with renewables as a source of clean electricity, and as such no new nuclear is installed. The RTE study notes that lifetime extensions for existing plants, most of which were built in the 1980s, could allow the existing fleet to provide a continued contribution to the power sector. However, even with lifetime extensions, the existing nuclear fleet will need to be entirely phased out in the 2060s, with many plants needing to retire pre-2050. As such, existing plants provide at most 23% of electricity demand in 2050. Achieving a greater share of nuclear would require successfully deploying new nuclear generation capacity. Due to the long lead-times for nuclear generation, new nuclear would only come online from 2035 onwards, and would need to demonstrate cost competitiveness against alternative sources of clean electricity.

The RTE study makes three key conclusions which are of note when assessing the scenarios produced in this report.

First, it notes that the scenario which achieves 100% renewable electricity by 2050 represents a major industrial challenge. The pace of deployment of offshore wind and solar exceeds the highest deployment rates seen in the UK and Germany respectively, which are two countries which have successfully achieved rapid renewables deployment in recent years. Therefore, while the RTE study acknowledges that 100% renewables is technically feasible, it highlights that the challenge of achieving such a power sector transformation should not be underestimated.

Secondly, the RTE study concludes that there is economic space for continued nuclear generation in France, and that a total phaseout is not necessary or cost-effective. However, it argues that this is because achieving 100% renewables in the power sector requires very rapid deployment of renewables in the 2020s, which leads to correspondingly large investment requirements before technologies such as floating offshore wind (which will be crucial in the French context) have come down the learning curve. The RTE study is conducted in the context of achieving the EU27's current 2030 NDC of reducing emissions by 55% in 2030 relative to 2019 levels. In this analysis, the illustrative pathways achieve much greater emissions reductions in order to align with 1.5°C, reducing emissions by 64-67%. In this context, where rapid deployment of renewables is required regardless, then the cost advantage of retaining nuclear generation may be diminished.

Finally, the RTE study concludes that the cost of an electricity system powered predominantly or entirely by renewables can approach the cost of a system with large-scale nuclear generation. It highlights that if there are cost reductions in floating offshore wind of a similar level to those seen in fixed-base offshore wind, if the cost of capital provided to renewables is lower than that provided to nuclear, and if hydrogen infrastructure can be built and successfully integrated into the power sector, that a highly renewable electricity system could emerge as the least-cost option. This aligns strongly with the illustrative pathways, which envisage strong and sustained cost reductions in renewables, and highlight the key role of hydrogen in the power sector to provide long duration energy storage.

Overall, the RTE study presents a range of conclusions which are aligned with the illustrative pathways in this report. It notes that achieving 100% renewables in the French power sector is technically feasible, and could results in lower system costs under certain assumptions. While the illustrative pathways demonstrate one possible system configuration, the RTE study still sees a case to be made for nuclear generation in the French power sector. Therefore further evidence may need to be gathered before final decisions are made on the relative role of nuclear and renewables in aligning France with the 1.5°C temperature limit.

3.5 National Results: Belgium

3.5.1 1.5°C compatible emissions pathways: Belgium

Belgium's National Energy and Climate Plan (NECP) aims to reduce emissions from non EU-ETS sectors by 35% below 2005 levels by 2030, to 52.7 $MtCO_2e$ (European Commission 2020a). At the time of drafting the NECP[7], Belgium's emissions covered by the EU ETS were expected to fall from 66.6 $MtCO_2e$ in 2005 to 59 $MtCO_2e$ in 2030. This would lead 111.7 $MtCO_2e$ emissions in 2030, 23% below 1990 levels. Belgium will have to outperform this 2030 target, as both the Effort Sharing Regulation (ESR) and EU ETS targets will be strengthened by the legislation of the 'Fit for 55' package at the European level. However, absent data on how Belgium envisages playing its part in achieving the EU's NDC, we retain the NECP as the most recent official target. In the illustrative pathways assessed in this report, Belgium's emissions fall to 44-50% below 1990 levels by 2030 (excluding LULUCF) and 92% by 2050. Such pathways identify technically feasible routes to higher near-term decarbonisation. Under current policies (with existing measures), emissions in 2030 are projected to be only 13% below 1990 levels, and would need to fall an additional 40-50 $MtCO_2e$ to be compatible with the Paris Agreement's LTTG (Figure 20).

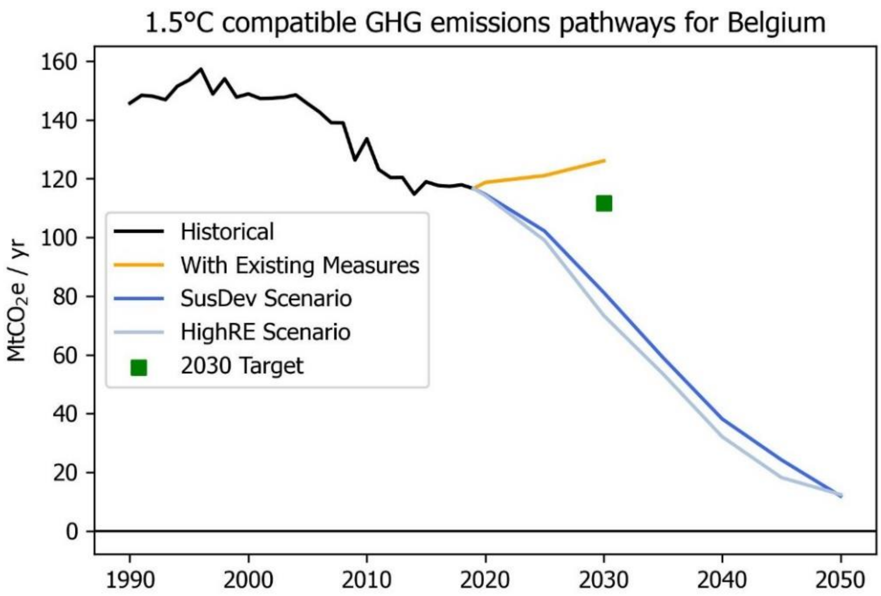


Figure 20|1.5°C compatible GHG emissions pathways for Belgium

[7] NECPs have been adopted before the FF55 and RepowerEU. The NECPs are to be updated 2023/2024 to reflect EU's new goals.

3.5.2 1.5°C compatible sectoral transformation pathways: Belgium

Figure 21 displays 1.5°C compatible pathways for total final energy demand in Belgium. In both pathways, final energy demand declines across the time horizon. At the same time, renewable energy is rapidly deployed to displace fossil fuels from the energy system.

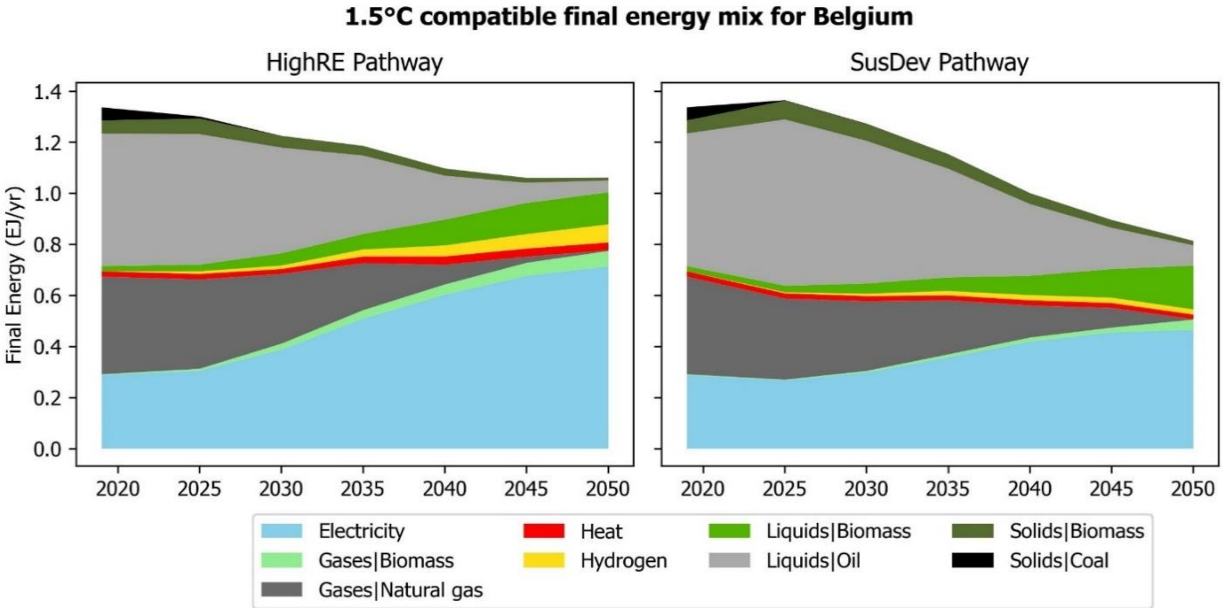


Figure 21|1.5°C compatible final energy pathways for Belgium

These pathways show the potential for ambitious reductions in final energy demand in Belgium. Demand falls by 21-39% by 2050 relative to 2019 levels. However, this reduction in final energy demand is achieved in different ways. In the HighRE pathway, the majority of final energy demand reduction is due to the efficiency gains from direct electrification, with electricity consumption more than doubling over the time horizon. Electric technologies such as heat pumps and EVs are much more efficient than their fossil fuel-based alternatives. As a result, as heat pumps and EVs replace gas boilers and petrol/diesel vehicles, final energy demand falls, even if overall demand for energy services remains unchanged. In the SusDev pathway, some of the reduction in final energy demand is still driven by electrification, with electricity consumption growing 62% across the time horizon. However, this is coupled with ambitious lifestyle shifts that reduce demand, and hence the level of final energy in the pathway.

Both pathways exhibit increased electrification of demand. Electricity provides 57-67% of final energy demand in 2050, up from 21% today. This is coupled with increased biomass consumption, particularly in the transport sector, as well as limited consumption of hydrogen and renewable heat. **As a result, renewables provide 27-36% of final energy demand by 2030 and 87-95% by 2050**.

Electricity sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, non-biomass renewables provide the vast majority of future electricity demand in Belgium. In these pathways, the share of non-biomass renewables (mainly wind and solar) increases from nearly 16% today to 58-67% by 2030 and 82-89% by 2050 (Figure 22). There is a relatively constant level of electricity generation from biomass of around 7-10 TWh/yr across the time horizon. Accounting for this limited contribution from biomass, **the total share of electricity produced by renewables reaches to 67-76% by 2030 and 94-100% by 2050**. Further innovation and investment would be required to accommodate this high share of variable renewables in the power system, including for grid expansion and interconnection, storage technologies and sector coupling. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly key role in the HighRE pathway.

Both illustrative pathways demonstrate a declining role of nuclear in the future power mix with a 17-20% share by 2030 and phase-out around 2045. No new nuclear capacity is installed in these pathways, as renewables represent a more cost competitive option to decarbonise the power sector[8].

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand more than doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand growth is more limited across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables growing strongly.

[8] Lifetime extensions on existing nuclear power plants could enable a greater contribution of nuclear to the future power system (IEA 2019). However, the viability of lifetime extensions may be limited by safety concerns and by continued cost reduction in renewables.

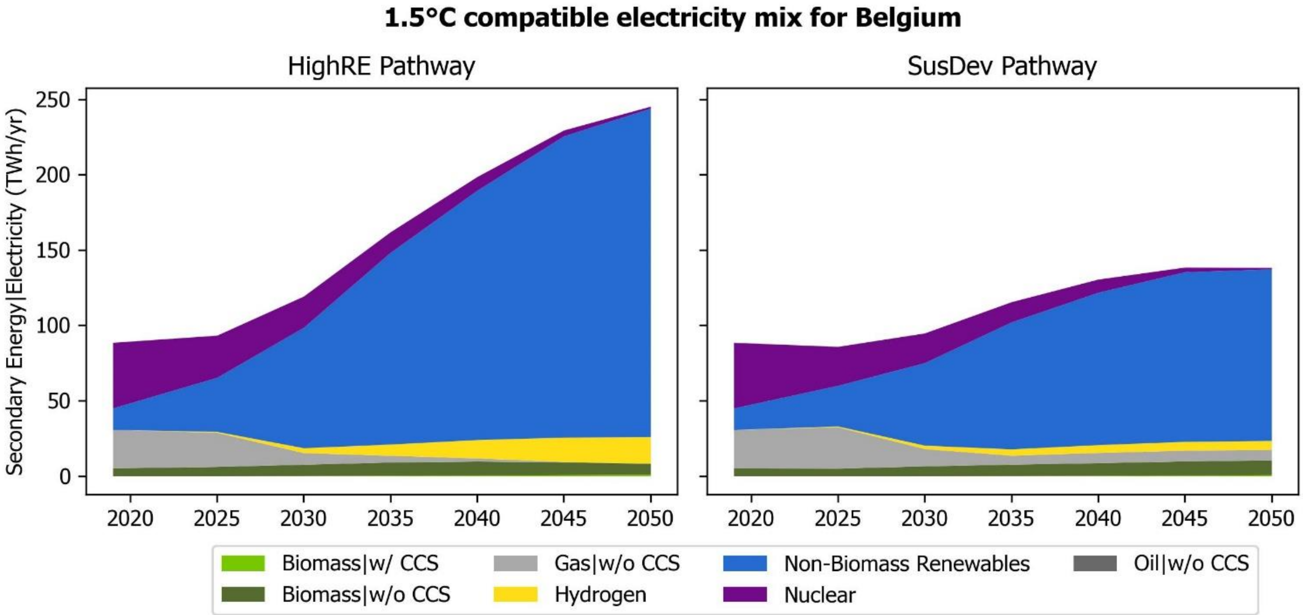


Figure 22|1.5 °C compatible electricity generation mix for Belgium

Belgium has already phased out coal in the power sector, with the last power plant closing in 2016. The assessed pathways also envisage a rapid reduction in gas consumption in the power sector, with phase-out by 2036 in the HighRE pathway. In the SusDev pathway, there is a slightly slower reduction in gas-fired power generation. However, gas demand still falls 73% across the time horizon, and post-2035, gas provides only 5% of Belgium's electricity generation. This difference is due to the larger carbon budget in the SusDev pathway. As the SusDev pathway envisages faster reductions in non-CO_2 emissions due to dietary shifts towards sufficient, healthy and sustainable diets, it is possible to limit warming to 1.5°C with slightly relaxed constraints on CO_2 emissions. The SusDev pathway, therefore, demonstrates a slower phase-out of fossil fuels from the energy sector. It is important to emphasise that this is contingent on making deep cuts in non-CO_2 emissions in the agricultural sector. Without these cuts, the pace of fossil fuel reduction would have to be accelerated. Large scale reductions in animal agriculture and meat consumption would have substantial health benefits, as well as climate benefits (Willett *et al* 2019). However, the socio-political feasibility of such a transition remains unclear. Therefore, a precautionary approach to deep decarbonisation would suggest that gas should be phased out of the power sector by the mid-2030s, to avoid relying on emissions reductions elsewhere.

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways the transport sector is decarbonised by a mix of electricity, hydrogen and biofuels. Electricity provides 10-14% of final energy in the transport sector by 2030 and 43-48% by 2050. Hydrogen could also become increasingly important in the transport sector decarbonisation, providing 2.5% of final energy by 2030 and up to 9% by 2050 in the illustrative pathways. Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

In these pathways, the share of biofuels in the transport sector reaches 7-9% by 2030, and 32-39% by 2050. While this is still a large level of biofuel consumption, it is lower than in previously assessed IAM pathways from the IPCC's Special Report on 1.5°C. Transportation decarbonisation pathways based on higher-resolution and sectorally specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019), instead relying on direct electrification, hydrogen and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops and negative biodiversity impacts (Energy Transitions Committee 2021).

Electricity, hydrogen and biofuels all displace oil consumption in the transport sector. Oil provides 76-81% by 2030 and 11-15% by 2050. Remaining oil demand is largely confined to the aviation sector and could be further reduced by the introduction of renewable-based synthetic fuels, which are not included in the assessed model pathways. **The share of renewables in total transport final energy use including renewable electricity, hydrogen, biomass and renewable heat reaches 16-20% by 2030 and 82-89% by 2050**.

Buildings sector decarbonisation pathways

Fossil fuels provide 65% of final energy in the buildings sector in Belgium, with oil providing a quarter of all final energy demand. **In the illustrative 1.5°C compatible pathways, the buildings sector is predominantly decarbonised through direct electrification**. Electricity provides 33-35% of final energy in the buildings sector by 2030 and 70-84% by 2050, up from 28% today. This is coupled with limited use of biomass. As a result, **the total share of renewables in the buildings sector reaches 30-36% by 2030 and 90-95% by 2050.** The remaining non-renewable section in 2050 is some residual oil consumption which is only phased out post-2050, and (in the case of the SusDev pathway) some fossil-based electricity. While some have proposed hydrogen as an option to decarbonise buildings heating, neither pathway uses hydrogen at all in the buildings sector.

Electrification can reduce final energy demand in the buildings sector, due to the much higher efficiency of electric technologies such as heat pumps. Final energy demand falls by 22-39% by 2050 in the HighRE and SusDev pathway, respectively.

Industry sector decarbonisation pathways

The electrification of industrial processes can reduce both energy intensity and industrial emissions. In the illustrative 1.5°C compatible pathways considered here, electricity provides up to 43% of final energy demand in industry by 2030 and 52-63% by 2050, up from 31% today.

The share of hydrogen in industry use reaches up to 3% by 2030 and up to 16% by 2050. Current biomass consumption in the Belgium's industrial sector is comparatively low, with bioenergy providing 6% of industrial final energy in 2019. In 1.5°C compatible pathways, this share rises slightly out to 2030, where biomass provides 11-13% of final energy. In 2050, there is a range of possible futures for biomass consumption in the industrial sector. In the HighRE pathway, hydrogen becomes the second largest energy source in industry (after direct electrification). Biomass therefore provides around 13% of final energy by 2050. The SusDev pathway has slower scale-up of hydrogen production, and therefore displays greater biofuel reliance. Bioenergy provides 32% of industrial demand in 2050. In both cases, greater consumption of hydrogen or synthetic fuels could further reduce biofuel reliance (Dena 2018).

Unabated coal is effectively phased out before 2030 in 1.5 °C compatible pathways for the industry sector in Belgium. A coal-free industrial sector by 2030 would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling via electric arc furnaces. Any coal-based industry that remains post-2030 would either need to be prematurely retired or lead to increased reliance on CCS deployment in the industrial sector. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls by 32-34% by 2030 relative to 2019 levels, and **gas use is phased out of industry by 2048-2049 at the latest**.

3.5.3 Key characteristics of Belgium's 1.5°C compatible pathways and comparison with other analyses

Table 12 provides a summary of key derived 1.5°C compatible benchmarks for Belgium in 2030 and 2050, compared against recent historical values and country targets.

Table 12 | 1.5°C compatible benchmarks for Belgium

*In the SusDev pathway, the share of electricity in the industrial sector falls to 25% in 2030, from 33% today. However, when considering all sectors, there is still an increase in electrification of the energy system in both 2030 and 2050, and by 2050 the electrification rate in industry grown to 56% in the SusDev pathway.

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	117 $MtCO_2e$	44-50% below 1990	92% below 1990	23% below 1990	Belgium's long-term strategy does not define a clear 2050 goal at the national level
Whole economy	Share of renewables in electricity production	21%	67-76%	94-100%	37.4%	-
Whole economy	Renewable share of final energy demand	12%	27-36%	87-95%	-	-
Whole economy	Change in final energy demand (relative to 2019)	0%	-5% to -8%	-21% to -39%	-	-
Whole economy	Electrification of final energy demand	21%	23-32%	57-67%	-	
Sectoral perspective	Transport sector electrification rate	2%	10-14%	43-48%	-	-
Sectoral perspective	Transport sector renewable share	6%	16-20%	82-89%	-	-
Sectoral perspective	Buildings sector electrification rate	28%	33-35%	70-84%	-	-
Sectoral perspective	Buildings sector renewable share	12%	30-36%	90-95%	-	-
Sectoral perspective	Industry sector electrification rate	31%	22*-43%	52-63%	-	-
Sectoral perspective	Industry sector renewable share	17%	32-51%	86-98%	-	

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases except for oil demand in transport, **fossil fuels are effectively phased out prior to 2050** in 1.5°C-compatible pathways for Belgium. Table 13 highlights effective fossil fuel phaseout dates for Belgium.

Table 13 | Effective fossil fuel phase-out dates for Belgium

*In these sectors the phase-out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase-out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	N/A (Already phased out in 2016)	2036*	N/A
Industry	2024-2025	2045-2049	2044*
Buildings	N/A	2044-2049	Post-2050
Transport	N/A	N/A	Post-2050

Comparison with CLIMACT study

CLIMACT conducted a recent study, which provides insights into pathways and actions Belgium could deploy to reaching net zero GHG emissions by 2050 (FPS Public Health - DG Environment 2021). A series of pathways have been built on the basis of the Belgium's '2050 Pathways Explorer', which is an energy accounting model that covers energy, land and food systems. The main climate neutral pathway 'CORE 95' leads to a 97% reduction of GHG emissions in 2050 below 1990 levels, with the LULUCF sector contributing the remaining 3% required to reach net zero GHG emissions. For comparison, the illustrative pathways assessed in this report lead to around 92% reduction of Belgium's GHG emissions below 1990 levels (excluding LULUCF) – slightly below the levels envisaged by the CLIMACT report.

In the 'CORE 95' pathway, the total renewable share reaches 72% in 2030 and 100% by 2050. Fossil fuels in power generation are phased out by 2035. This aligns well with the HighRE pathway used in this report, in which renewables provide 76% of electricity in 2030 and 100% by 2050, with gas phase-out by 2036. In the SusDev pathway, there is a slightly slower reduction in gas-fired power generation and renewable scale-up, due to the larger carbon budget for this pathway. However, gas provides only ~5% of electricity generation from 2035 onwards, and renewable generation in 2050 is 94%.

In the 'CORE 95' pathway, direct electrification rate of buildings final energy reaches to 38% by 2030. Fossil fuels are completely or almost completely phased out by 2050, while electricity becomes the most important energy vector, providing more than 80% of building's final energy demand in 2050. Biofuels (9%) and synthetic fuels (9%) complete the energy mix in 2050. The illustrative pathways assessed in this report envisage a similar level of electrification, with 33-35% of building's final energy electrified by 2030, and 70-84% by 2050. The main difference between the 'CORE 95' pathway and the downscaled IAM pathways is that in the downscaled pathways, there is a residual level of oil consumption of 4-6% in 2050. This could be displaced by synthetic fuels, which are represented in the 'CORE 95' pathway, but not in the IAM pathways.

In the 'CORE 95' pathway, the direct electrification of transport reaches 15% by 2030 and 50% by 2050. The illustrative pathways assessed in this report envisage a similar level of electrification, with 43-48% direct electrification rate of 2050 transport's final energy demand. However, in the 'CORE 95' pathway, oil is phased out of the transport sector by 2050, with electricity, biofuels, hydrogen and synthetic fuels providing 100% of final energy demand. In the illustrative pathways in this report, electricity, biofuels and hydrogen provide 85-90% of transport's final energy demand in 2050. Again, introducing synthetic fuels into the transport sector could accelerate the phase-out of oil, as well as reducing reliance on biofuels.

Finally, in the 'CORE 95' pathway, electricity provides 20% of industrial final energy by 2030, and 30% by 2050. The illustrative pathways assessed in this report envisage a greater level of electrification, with 22-43% of industry's final energy demand met by electricity in 2030, and 52-63% in 2050. In the 'CORE 95' pathway, renewables provide 90% of 2050 demand. This is well aligned with the illustrative pathways, in which renewables provide 86-98% of industry's final energy demand in 2050. However, in the illustrative pathways there is greater electrification of industrial energy demand, which compensates for the lack of synthetic fuels in the sector.

3.6 National results: Poland

3.6.1 1.5°C compatible emissions pathways: Poland

Poland's latest policy document, *2040 Poland Energy Policy,* commits the country to reducing GHG emissions to 29% below 1990 levels in 2030, excluding LULUCF (Polish Government 2021). However, in 1.5°C compatible pathways which demonstrate the highest plausible ambition for Europe, Poland's emissions fall to 68-70% below 1990 levels by 2030 (excluding LULUCF) and 93-95% by 2050. Such pathways identify technically feasible routes to higher near-term decarbonisation. Under current policies, emissions in 2030 are projected to be only 15% below 1990 levels and would need to fall an additional 250-260MtCO_2e to be compatible with the Paris Agreement's LTTG (Figure 23).

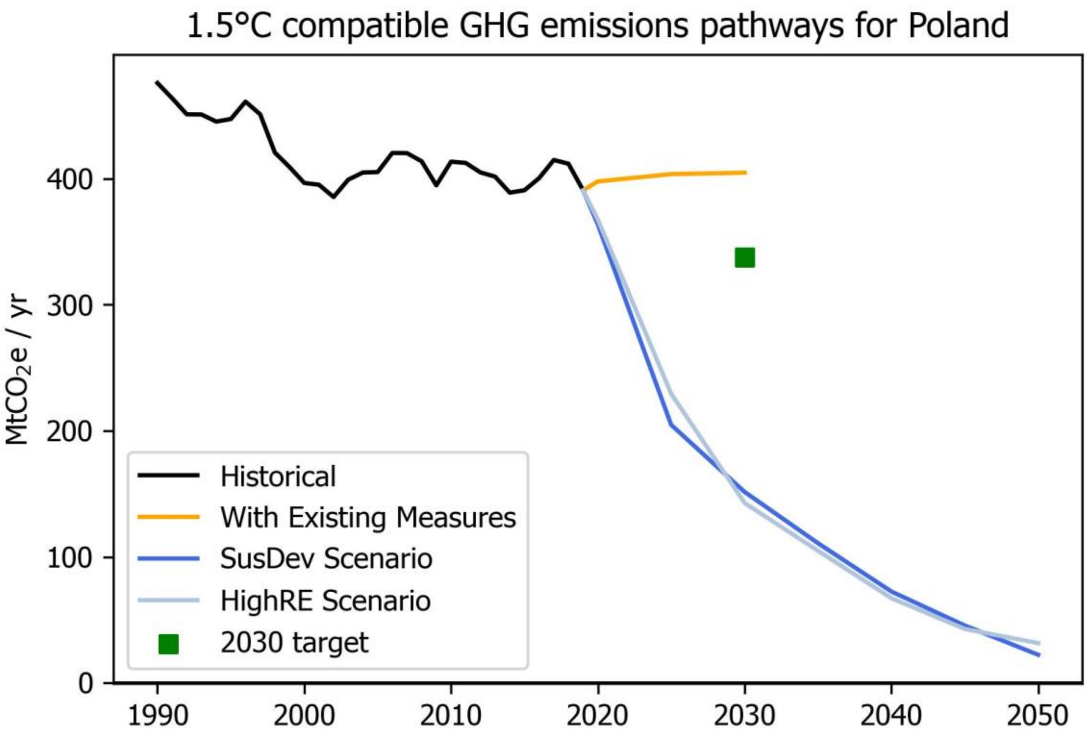


Figure 23|1.5°C compatible GHG emissions pathways for Poland

It is important to note that the downscaling routines used in this report allocate energy and emissions to individual EU27 member states on a cost-effective basis by finding a fuel price equilibrium for the European macro-region as a whole. This is a different allocation basis compared to the Effort Sharing Regulation (ESR) that the EU27 uses to distribute effort amongst sectors not covered by the EU ETS. In the downscaling routine, Poland emerges with one of the most ambitious 2030 targets, only surpassed by Germany, reflecting its current highly carbon-intense (polluting) energy system. This highlights a substantial cost-effective potential for decarbonisation in Poland, which is related to the current large share of coal in the energy sector, where coal provides over 70% of electricity generation, 25% of industrial final energy and 20% of final energy in the buildings sector. This is valuable information, demonstrating techno-economically feasible routes to higher near-term decarbonisation in Poland. However, achieving this would involve Poland substantially exceeding its commitments under the ESR and accelerating emissions reduction in the sectors covered by the EU ETS. For this purpose, Poland can benefit from access to significant funding from the EU funds and the proceeds from the sale of emission certificates in the framework of the EU ETS.

3.6.2 1.5°C compatible sectoral transformation pathways: Poland

Figure 24 displays 1.5°C compatible pathways for total final energy demand in Poland. In both pathways, total energy demand declines (more steeply in SusDev pathway). Final energy demand falls by 31-48% below 2019 levels by 2050. Falling final energy demand is due to a combination of improved energy efficiency and demand reduction. In the HighRE pathway, the majority of final energy demand reduction is due to efficiency gains from direct electrification. As heat-pumps, EVs and other electric technologies replace gas boilers, petrol/diesel vehicles and other fossil alternatives, final energy demand falls, while overall demand for energy services is relatively unchanged. In the SusDev pathway, some of the reduction in final energy demand is still driven by electrification, with electricity consumption growing 45% across the time horizon. However, this is coupled with ambitious lifestyle shifts that reduce demand and, hence, the level of final energy in the pathway.

At the same time, renewable energy is rapidly deployed to displace fossil fuels from the energy system. The electricity system is largely decarbonised by the mid-2030s, and electricity provides 52-58% of final energy demand in 2050, up from 18% today. There is also a substantial role for district heating in the buildings and industrial sector. **Together, renewables provide 48-52% of final energy demand by 2030 and 91-95% by 2050**.

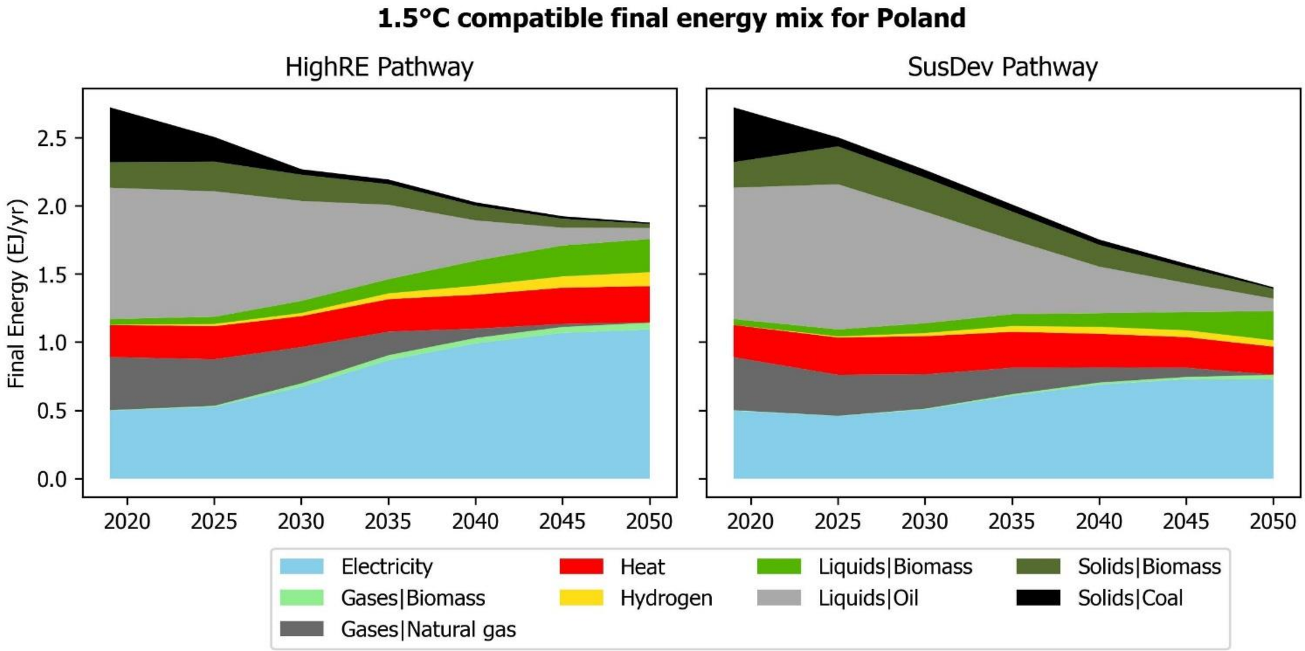


Figure 24 | 1.5°C compatible final energy pathways for Poland

Electricity sector decarbonisation pathways

Poland's target is to increase the share of renewable power to 32% by 2030. The national target also increases the PV capacity target to 7.3 GW and offshore win to 3.8 GW. For onshore wind, only a slight increase in capacity to 9.6 GW was targeted. The capacity of hydropower, biogas, and biomass should also increase. Since the publication of the government's strategy, the capacity of the solar PV significantly exceeded the target planned for 2030 and reached 10.2GW by mid-2022 (Rynek Elektryczny 2022).

In the illustrative 1.5°C compatible pathways, non-biomass renewables provide the vast majority of future electricity demand in Poland. In these pathways, the share of non-biomass renewables (mainly wind and solar) increases from nearly 11% today to 81-85% by 2030 and 86-96% by 2050 (

Figure 25). There is a relatively constant level of electricity generation from biomass of around 5-9 TWh/yr across the time horizon. Accounting for this limited contribution from biomass, **the total share of electricity produced by renewables reaches to 92-94% by 2030 and 98-100% by 2050**. This range is far above Poland's target stated above. Further innovation and investment for grid expansion and interconnection, storage technologies, and sector coupling would be required to accommodate this high share of variable renewables in the power system. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly key role in the HighRE pathway.

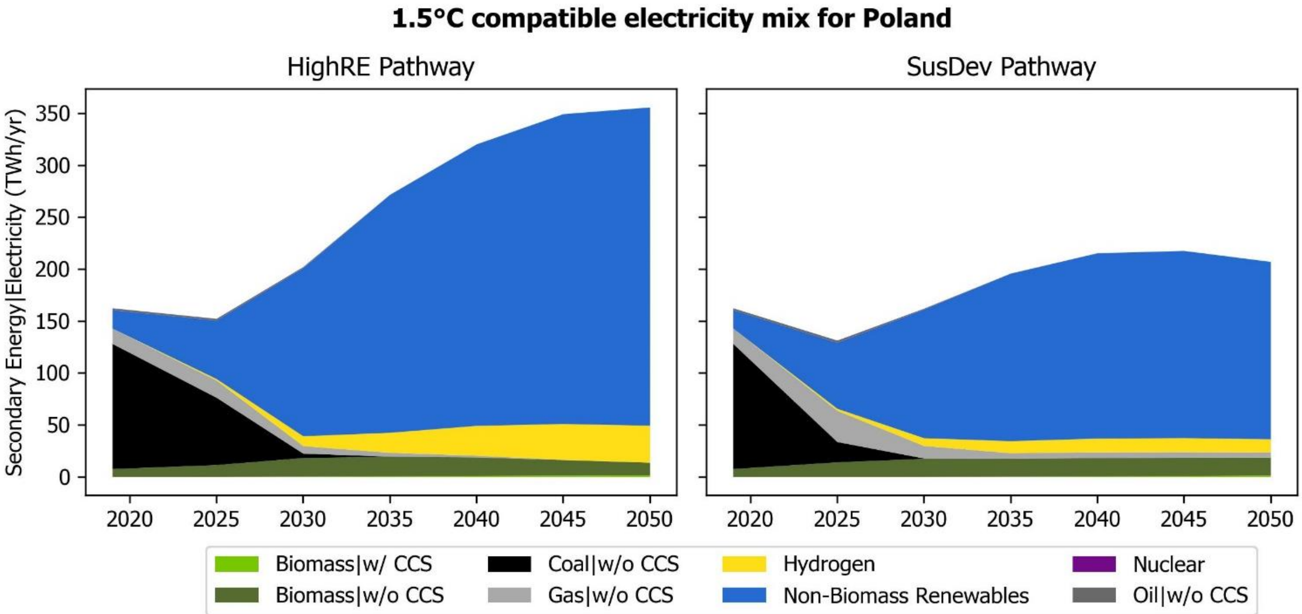


Figure 25 | 1.5°C compatible electricity generation mix for Poland

In these illustrative pathways, coal is effectively phased out of the power sector by 2030. This is almost two decades ahead of the agreed phase-out date of 2049. The pathways also envisage a rapid reduction in gas consumption in the power sector, with gas effectively phased out by 2033 and by 2044 in the HighRE and SusDev pathways, respectively. In the SusDev pathway, there is a slightly slower reduction in gas-fired power generation.

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand approximately doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand growth is more limited across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables growing strongly.

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the transport sector is decarbonised by a mix of electricity, hydrogen, and biofuels. Electricity provides 8-10% of final energy by 2030 and 36-41% by 2050. Hydrogen could also become increasingly important in the transport sector decarbonisation, providing up to 2.5% of final energy by 2030 and up to 10% by 2050.

Hydrogen could also be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

In the illustrative pathways, the share of biofuels in the transport sector reaches 6-8% by 2030, and 34-43% by 2050. While this is still a large level of biofuel consumption, it is lower than in previously assessed IAM pathways from the IPCC's Special Report on 1.5°C. Transportation decarbonisation pathways based on higher-resolution and sectoral-specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019) and instead rely on direct electrification, hydrogen, and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is thereforeis an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops, and negative biodiversity impacts (Energy Transitions Committee 2021).

Electricity, hydrogen, and biofuels all displace oil consumption in the transport sector. Oil provides 81-84% by 2030 and 15-20% by 2050. Remaining oil consumption could be further reduced by the introduction of renewable-based synthetic fuels, which are not included in the assessed model pathways. **The share of renewables in total transport final energy use including renewable electricity, hydrogen, biomass, and renewable heat reaches 15-18% by 2030 and 79-85% by 2050**. Poland's target is to achieve 14% share of renewables in transport final energy consumption by 2030 including 7% conventional biofuels, which is just below the range derived from 1.5°C compatible pathways assessed here. To be aligned with 1.5°C in transport decarbonisation, Poland should accordingly achieve this target and continue to strongly increase the share of renewables in transport post-2030.

Buildings sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the buildings sector is predominantly decarbonised through direct electrification and district heating. Electricity provides 33-38% of final energy in the buildings sector by 2030 and 55-67% by 2050, up from 26% in 2019. The second main driver of decarbonisation is district heating, which provides 28-29% of final energy in 2050. In the HighRE pathway, rapid electrification and greater district heating means that these technologies provide 94% of final energy by 2050, with a small residual consumption of biomass/coal. In the SusDev pathway, there is slightly reduced electrification. This is compensated for by greater biomass consumption, which provides 14% of final energy in 2030, and 15% in 2050. While some have proposed hydrogen as an option to decarbonise buildings heating, neither pathway uses hydrogen at all in the buildings sector. The total share of renewables in the buildings sector reaches 72-74% by 2030 and 97-100% by 2050.

Poland still uses coal in the buildings sector, with coal providing 21% of final energy in 2019. This is rapidly reduced, with coal consumption falling 75-85% by 2030, and with coal effectively phased out of the buildings sector between 2043-2049.

Electrification can reduce final energy demand in the buildings sector due to the much higher efficiency of electric technologies such as heat pumps. Final energy demand in the buildings sector falls by 27% and 43% by 2050 below 2019 levels in the HighRE and SusDev pathway, respectively.

Industry sector decarbonisation pathways

The electrification of industrial processes can reduce both energy intensity and industrial emissions. In the illustrative 1.5°C compatible pathways considered here, electricity provides 27-46% of final energy demand in industry by 2030 and 62-63% by 2050.

The share of hydrogen in industry use reaches 3% by 2030 and rises to 17% by 2050. In 1.5°C compatible pathways, share of biofuel consumption in the Poland’s industrial sector rises from 11% today to 18-28% by 2030, before declining to meet to 11-25% of industrial final energy demand in 2050.

Unabated coal is phased out before 2030 in 1.5°C compatible pathways for the industry sector in Poland. A coal-free industrial sector by 2030 would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling via electric arc furnaces. Any coal-based industry that remains post-2030 would either need to be prematurely retired or lead to increased reliance on CCS deployment in the industrial sector. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls by 31-35% by 2030 relative to 2019 levels. **Gas use is effectively phased out of industry by 2045 in the HighRE pathway, and by 2049 in the SusDev pathway**.

3.6.3 Key characteristics of Poland's 1.5°C compatible pathways and comparison with other analyses

Table 14 provides a summary of key 1.5°C compatible benchmarks for Poland in 2030 and 2050, compared against recent historical values and country targets.

Table 14 | 1.5°C compatible benchmarks for Poland

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	391 $MtCO_2e$	68-70% below 1990	93-95% below 1990	29% below 1990	-
Whole economy	Share of renewable electricity	16%	92-94%	98-100%	32%	16%
Whole economy	Renewable share of final energy demand	20%	48-52%	91-95%	21-23%	-
Whole economy	Change in final energy demand (relative to 2019)	0%	-17%	-31% to -48%	-	–
Whole economy	Electrification of final energy demand	18%	22-30%	52-58%	-	-
Sectoral perspective	Transport sector electrification rate	1%	8-10%	36-41%	14% by 2030	-
Sectoral perspective	Transport sector renewable share	5%	15-18%	79-85%	-	-
Sectoral perspective	Buildings sector electrification rate	26%	34%	53-54%	-	-
Sectoral perspective	Buildings sector renewable share	32%	43-66%	49-92%	28.4%	-
Sectoral perspective	Industry sector electrification rate	29%	27-46%	62-63%	-	-
Sectoral perspective	Industry sector renewable share	21%	59-71%	95-99%	-	-

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and sectors. In all cases except for oil demand in transport, **fossil fuels are effectively**

phased out prior to 2050 in 1.5°C-compatible pathways for Poland. Table 15 highlights effective fossil fuel phase-out dates by sector and fuel type for the selected pathways.

Table 15 | Effective fossil fuel phaseout dates for Poland.

*In these sectors the phase out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	2030	2033*	N/A
Industry	2025-2027	2045-2049	2035*
Buildings	2043-2049	2043-2048	2032-2036
Transport	N/A	N/A	Post-2050

Comparison with Instrat modelling

To the authors' knowledge, there is no other 1.5°C compatible pathway for Poland that covers all sectors of the energy system. Therefore, a full comparison of the results against detailed energy system modelling is not possible. However, there is growing analysis that focuses on the power sector transition.

Instrat recently produced a report which explores how to achieve a phase-out of coal in the power sector that accounts for the specific social and technological context for Poland, does not compromise energy security, and is also aligned with the EU27's Fit for 55 package (Czyżak and Wrona 2021). The report used a multi-criteria analysis to determine a unit-by-unit schedule for coal plant phaseout, and ran the PyPSA-PL open source power model to confirm system reliability and performance.

This modelling found that the share of coal in the energy mix could fall from 70% today to 13% in 2030, with a complete phaseout by 2035. The share of renewables reaches 76% in 2030. This is slightly slower than observed in the downscaled IAM pathways, which phase out coal entirely by 2030 and reach above 90% renewables by 2030. However, the Instrat modelling focuses on aligning the Polish power sector transition with the Fit for 55 package which, as observed here, is not fully compatible with 1.5°C in itself. The report notes this, highlighting that achieving the Paris Agreement goals would require the almost complete elimination of coal in the Polish power sector by 2030 (Instrat *et al* 2020).

In general, the Instrat modelling confirms, by a more granular modelling excersize that accounts for the specific Polish context, that rapidly phasing out coal-fired power generation in the power sector is not only feasible, but cheaper than alternatives such as the current

Polish Energy Plan 2040. Phasing out coal in the power sector is not only essential to deliver the Paris Agreement goals, but is accompanied by significant economic benefits.

3.7 National results: Netherlands

3.7.1 1.5°C compatible emissions pathways: Netherlands

The Netherlands' officially legislated climate target aims to reduce GHG emissions to 49% below 1990 levels by 2030 and 95% by 2050 (Netherlands Ministry of Economic Affairs 2019). This is close to, but not aligned with, 1.5°C compatible pathways which demonstrate the highest plausible ambition for Europe. In these pathways, the Netherland's emissions fall to 52-55% below 1990 levels by 2030 (excluding LULUCF) and 91-92% by 2050. However, the coalition agreement in the Netherlands recently included a new climate target for 2030, aiming to reduce emissions to 55% below 1990 levels by 2030 (VVD *et al* 2022). The coalition agreement specifies this should be inscribed in law, strengthening the 49% target in the 2019 Climate Act to 55%. This is an improvement from the previous target, and would be aligned with the globally cost-effective 1.5°C compatible pathways used in this report.

While the intensifying of climate ambition is to be welcomed, the proposed 2030 target needs to be viewed in light of the following context. First, under current policies, emissions in 2030 are projected to be only 33% below 1990 levels. They would need to fall an additional 40-50MtCO_2e to be compatible with the Paris Agreement's LTTG (Figure 26). The Netherland's climate targets will need much greater policy action if they are to be achieved.

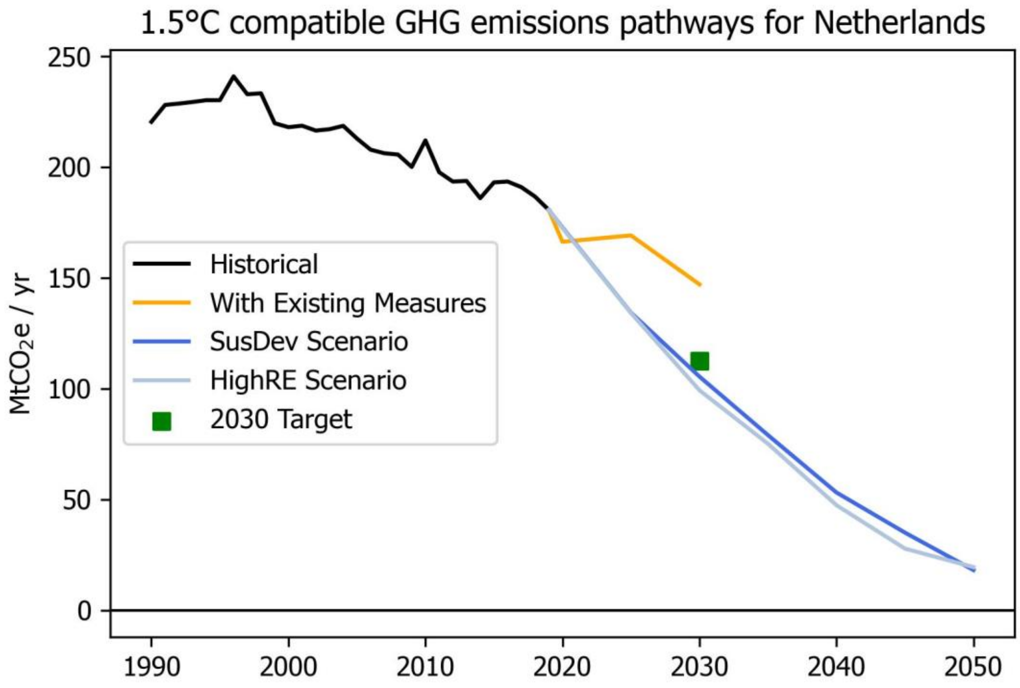


Figure 26|1.5°C compatible GHG emissions pathways for Netherlands[9]

Second, it is plausible that the Netherlands could outperform the target as calculated in this report. For example, the Netherlands has a relatively large potential for offshore wind (ESMAP 2021) of over 200GW. Recent cost reductions in the cost of offshore wind mean that a greater proportion of this potential could be accessed cost effectively by 2030, with current projects in the Netherlands already able to compete without subsidy (Jansen *et al* 2020). It can take time for models to update their cost assumptions in line with the latest evidence (Grant *et al* 2021b). The IAM pathways used to produce these pathways may, therefore, not have fully accounted for the latest cost reductions in offshore wind (Jansen *et al* 2020). In addition, the SIAMESE methodology used to downscale pathways to the national level cannot fully account for the national circumstances of individual countries, instead finding fuel price equilibria for the whole region. As a result, it is highly possible that the Netherlands could reduce emissions faster than shown in these pathways. Given that the fair share climate target for the Netherlands would likely be much more stringent than a 55% reduction below 1990 levels, where the Netherlands can outperform this target, it should consider doing so.

Third, these pathways do not account for the latest geopolitical context in terms of Russia's invasion of Ukraine. This has provided further economic and geopolitical rationale to accelerate the phaseout of natural gas consumption. Natural gas provided around 35% of final energy demand in the Netherlands in 2019, and 60% of power generation. This makes the Netherlands the most gas-reliant country of the EU27 member states considered. These pathways were produced prior to the Russian invasion of Ukraine. Consequently, they do not

[9] The Netherlands' target is based on the current obliged 2030 target of a 49% reduction. The coalition has recently proposed increasing this to 55%.

account for this additional rationale to accelerate the phase-out of natural gas consumption, which would further increase the emission reduction targets of the Netherlands. Finally, while this report focuses on aligning domestic emissions reduction targets with globally cost-effective 1.5°C compatible pathways, wealthy nations such as the Netherlands also need to provide climate finance to support emission reductions in less wealthy countries. Upscaling climate finance flows will be essential if the Netherlands is to contribute its fair share to global climate action (Climate Action Tracker 2022b).

3.7.2 1.5°C compatible sectoral transformation pathways: Netherlands

Figure 27 displays 1.5°C compatible pathways for total final energy demand in Netherlands. In both pathways, total energy demand declines across the time horizon, falling by 26-44% in 2050 relative to 2019 levels. Falling final energy demand is due to a combination of improved energy efficiency and demand reduction. In the HighRE pathway, the majority of final energy demand reduction is caused by efficiency gains from direct electrification. As heat-pumps, EVs and other electric technologies replace gas boilers, petrol/diesel vehicles, and other fossil alternatives, final energy demand falls while overall demand for energy services is relatively unchanged. In the SusDev pathway, some of the reduction in final energy demand is still driven by electrification, with electricity consumption growing 42% across the time horizon. However, this is coupled with ambitious lifestyle shifts that reduce demand and, hence, the level of final energy.

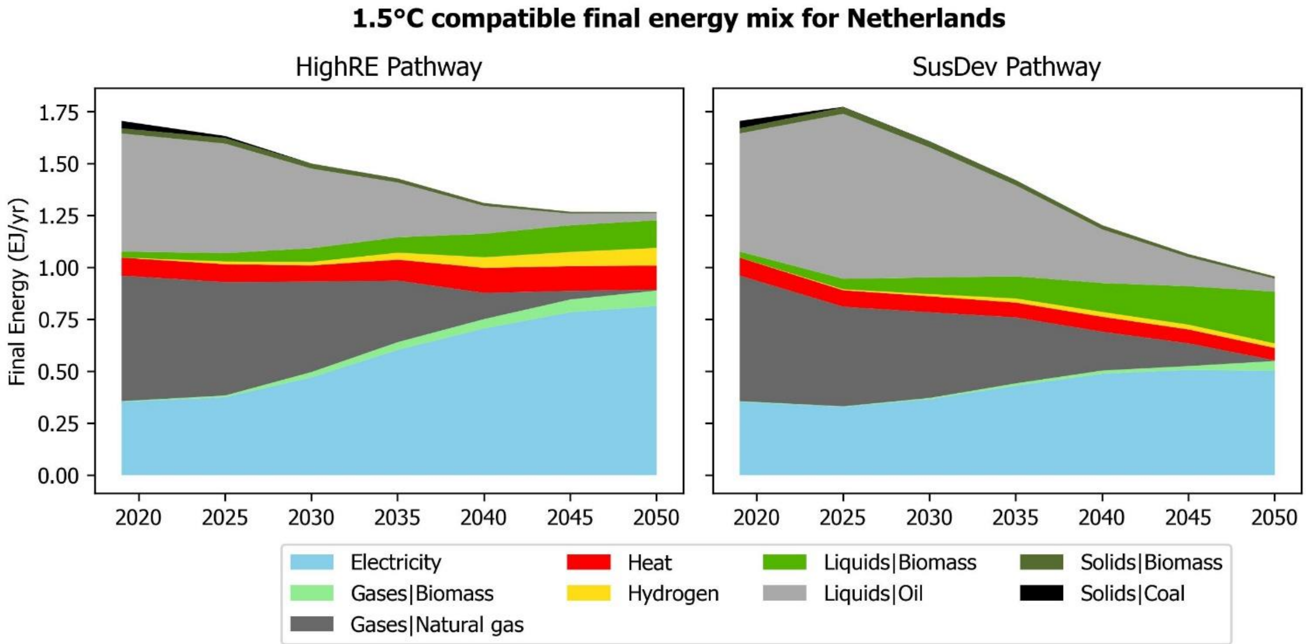


Figure 27|1.5°C compatible final energy pathways for Netherlands

At the same time, renewable energy is rapidly deployed to displace fossil fuels from the energy system. The electricity system is largely decarbonised by the mid-2030s, and electricity provides 53-64% of final energy demand in 2050, up from 21% today. There is also a substantial role for district heating in the buildings and industrial sector. **Together, renewables provide 28-40% of final energy demand by 2030 and 87-97% by 2050**.

Electricity sector decarbonisation pathways

The Netherland's power system is dominated by fossil fuels. Gas provides 59% of electricity generation in 2019, with coal providing 17%. In the illustrative 1.5°C compatible pathways, there is a sustained transition towards a renewable-based power sector. The share of non-biomass renewables (mainly wind and solar) increases from nearly 14% today to 62-75% by 2030 and 82-97% by 2050 (Figure 28). There is a relatively constant level of electricity generation from biomass of around 7-10 TWh/yr across the time horizon. Accounting for this limited contribution from biomass, **the total share of electricity produced by renewables reaches to 69-82% by 2030 and 89-100% by 2050**. Further innovation and investment for grid expansion and interconnection, storage technologies, and sector coupling would be required to accommodate this high share of variable renewables in the power system. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly key role in the HighRE pathway.

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand more than doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand growth is more limited across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables growing strongly, and fossil gas generation being reduced by 50% across the 2020s.

In both illustrative pathways, coal is phased out of the power sector by 2030 at the latest. Both pathways also envisage a considerable reduction in gas consumption in the power sector. In the HighRE pathway, gas demand falls 64% by 2030, and gas is effectively phased out by 2041. The SusDev pathway does not reduce gas demand in the power sector, with gas providing 11% of electricity generation in 2050. However, gas demand still falls 50% by 2030. As mentioned in previous country profiles, the slower phaseout of gas in the SusDev pathway is compensated for by greater action on non-CO_2 emissions, particularly in the agricultural sector. Unabated gas is still phased out of the power sector post-2050 in the SusDev pathway. However, a robust approach to electricity system decarbonisation would not predicate gas phase-out dates on progress in other sectors and, therefore, to be compatible with 1.5°C, the Netherlands should aim to phase out gas-fired generation by the early 2040s

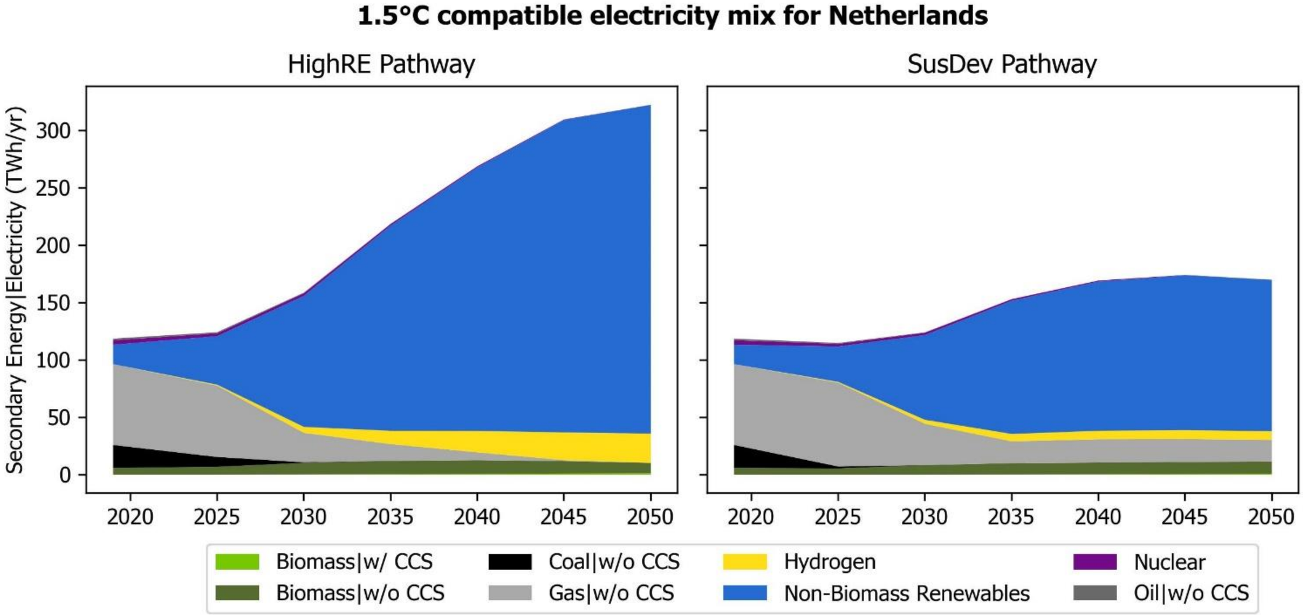


Figure 28 | 1.5°C compatible electricity generation mix for Netherlands

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the transport sector is decarbonised by a mix of electricity, hydrogen, and biofuels. Electricity provides 10-14% of final energy by 2030 and 44-50% by 2050. Hydrogen could also become increasingly important in the transport sector decarbonisation. Based on the two assessed illustrative pathways, the share of hydrogen in the transport sector reaches 2.5% by 2030 and up to 9% by 2050. Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

In the illustrative pathways, the share of biofuels in the transport sector reaches 7-9% by 2030, and 32-38% by 2050. This represents a large-scale reliance on biofuels. It is, however, lower than in previously assessed IAM pathways from the IPCC's Special Report on 1.5°C. Transportation decarbonisation pathways based on higher-resolution and sectoral-specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019) and instead rely on direct electrification, hydrogen and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops, and negative biodiversity impacts (Energy Transitions Committee 2021).

Electricity, hydrogen, and biofuels all displace oil consumption in the transport sector. Oil provides 75-80% by 2030 and 10-15% by 2050. Remaining oil demand is largely confined to the aviation sector and could be further reduced by the introduction of renewable-based synthetic fuels, which are not included in the assessed model pathways. **The share of renewables in total transport final energy use reaches 17-22% by 2030 and 80-90% by 2050**.

Buildings sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the buildings sector is predominantly decarbonised through direct electrification. Electricity provides 41-42% of final energy in the buildings sector by 2030 and 81-88% by 2050. While some have proposed hydrogen as an option to decarbonise building heating, neither pathway uses hydrogen in the buildings sector. Direct electrification is coupled with deployment of district heating and sustainable biomass, with the total share of renewables in the buildings sector reaching 37-44% by 2030 and 90-100% by 2050. The remaining non-renewable share is mainly using gas to produce electricity for direct electrification in the SusDev pathway.

Electrification can reduce final energy demand in the buildings sector due to the much higher efficiency of electric technologies such as heat pumps. Final energy demand in the buildings sector falls 23-44% by 2050 below 2019 levels in the HighRE and SusDev pathway, respectively.

Industry sector decarbonisation pathways

Electrifying industrial processes can reduce both energy intensity and industrial emissions. In the considered illustrative 1.5°C compatible pathways, electricity provides 13-32% of final energy demand in industry by 2030 and 30-48% by 2050.

As well as electrification, the industrial sector is also decarbonised by green hydrogen, renewable-based heat, and biofuel consumption. The share of hydrogen in industrial final energy demand reaches 3% by 2030 and rises to 17% by 2050. In the HighRE pathway, biomass provides 15% of final energy in 2050, with industry predominantly decarbonised by electricity, hydrogen, and district heating. In the SusDev pathway, biofuels provide 51% of industrial demand in 2050. This demonstrates that greater progress on the electrification of end-use demand can reduce reliance on bioenergy. In both cases, greater consumption of hydrogen or synthetic fuelscould further reduce biofuel reliance (Dena 2018).

Unabated coal is phased out before 2030 in 1.5 °C compatible pathways for the industry sector in Netherlands. A coal-free industrial sector by 2030 would represent a transformative shift in coal-reliant industries such as steel production, which would move to greater use of hydrogen for primary steel production and greater steel recycling via electric arc furnaces. Any coal-based industry that remains post-2030 would either need to be prematurely retired or lead to increased reliance on CCS deployment in the industrial sector. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls by 18-33% by 2030 relative to 2019 levels, and **gas use is phased out of industry in the 2040s in both pathways**.

3.7.3 Key characteristics of the Netherlands' 1.5°C compatible pathways and comparison with other analyses

Table 16 provides a summary of key derived 1.5°C benchmarks for Netherlands in 2030 and 2050 compared against recent historical values and country targets.

Table 16 | 1.5°C compatible benchmarks for the Netherlands

*In the SusDev pathway, the share of electricity in the industrial sector falls to 25% in 2030, from 33% today. However, when considering all sectors, there is still an increase in electrification of the energy system in both 2030 and 2050, and by 2050 the electrification rate in industry grown to 56% in the SusDev pathway.

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	181 $MtCO_2e$	52-55% below 1990	91-92% below 1990	49% below 1990 levels.	95% below 1990 levels
Whole economy	Share of renewables in electricity production	19%	69-82%	89-100%	-	-
Whole economy	Renewable share of final energy demand	12%	28-40%	87-97%	-	-
Whole economy	Change in final energy demand (relative to 2019)	0%	-6% to -12%	-26% to -44%	-	–
Whole economy	Electrification of final energy demand	21%	23-31%	53-64%	-	-
Sectoral perspective	Transport sector electrification rate	2%	11-14%	44-50%	-	-
Sectoral perspective	Transport sector renewable share	6%	17-22%	80-90%	-	-
Sectoral perspective	Buildings sector electrification rate	32%	41-42%	81-88%	-	-
Sectoral perspective	Buildings sector renewable share	13%	38-44%	90-100%	-	-
Sectoral perspective	Industry sector electrification rate	22%	13*-32%	30-48%	-	-
Sectoral perspective	Industry sector renewable share	17%	26-49%	88-98%	-	-

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases except for oil demand in transport, **fossil fuels are effectively phased out prior to 2050** in the Netherlands in 1.5°C-compatible pathways. Table 17 highlights effective fossil fuel phase out dates by sector and fuel type for the selected pathways.

Table 17 | Effective fossil fuel phase-out dates for the Netherlands

*In these sectors the phase out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	2025-2029	2041*	N/A
Industry	2023-2024	2046-2049	2045*
Buildings	N/A – already phased out	2048-2050	N/A – already phased out
Transport	N/A	N/A	Post-2050

Comparison with national modelling studies

The study conducted by (Scheepers *et al* 2022) presents two different pathways for the energy system of the Netherlands that achieve the Dutch government's national target of near net-zero greenhouse gas emissions in 2050. They applied the system optimisation model OPERA for analysis, which is a bottom-up, technology-rich energy system optimisation model for the Netherlands. Two pathways were developed in their study: ADAPT and TRANSFORM. Both pathways meet the Dutch Climate Act objectives, reducing GHG emissions in the Netherlands by 95% relative to 1990 levels in 2050. They also reduce GHG emissions by 49% in 2030. However, the pathways differ in the way these goals are achieved. The ADAPT pathway, builds on existing infrastructure and reduces GHG emissions without significant behavioural change or demand reduction. This pathway includes CCS deployment, while CCS is excluded from the TRANSFORM pathway, which also restricts biomass consumption compared to the ADAPT pathway. The TRANSFORM pathway particularly focuses on behavioural changes in Dutch society to support a radical shift to a less energy intensive and more sustainable economy for the Netherlands.

In the pathways modelled by (Scheepers *et al* 2022) renewable energy dominated by solar and wind provides the vast majority of electricity generation, and is projected to account for around 99% of total produced electricity in 2050. This is broadly aligned with the assessed illustrative pathways in this report, where the total share of electricity produced by renewables reaches 69-82% by 2030 and 89-100% by 2050. This share is dominated by non-biomass renewables (mainly wind and solar), whose share increases to 62-75% by 2030 and 82-97% by 2050. The higher end of the range represents the HighRE pathway and therefore increases confidence in HighRE's feasibility as a robust and ambitious guide for power sector decarbonisation. In accordance with Dutch government policy, no coal-fired power plants are used after 2024 in both pathways modelled by (Scheepers *et al* 2022). Coal is also phased out of the power sector by 2030 at the latest in both illustrative pathways.

3.8 National results: Spain

3.8.1 1.5°C compatible emissions pathways: Spain

Spain is aiming to reduce GHG emissions by 23% below 1990 levels, excluding LULUCF (Spanish Government 2020). This follows a significant increase between 1990 and 2007 by 63%, after which the emissions started to decrease. In 2020, Spain's emissions were only 5% below 1990 levels. Spain also aims to reach net zero GHG emissions by 2050 at the latest (European Climate Foundation 2021), meaning that Spain will only emit the amount of GHGs that its sink can absorb. However, in 1.5°C compatible pathways which demonstrate the highest plausible ambition for Europe, Spain's emissions fall to 46-51% below 1990 levels by 2030 (excluding LULUCF) and 87-91% by 2050. Such pathways identify technically feasible routes to higher near-term decarbonisation. Under current policies, emissions in 2030 are projected to stay near 1990 levels, and would need to fall an additional 140-160 $MtCO_2e$ to be compatible with the Paris Agreement's LTTG (Figure 29).

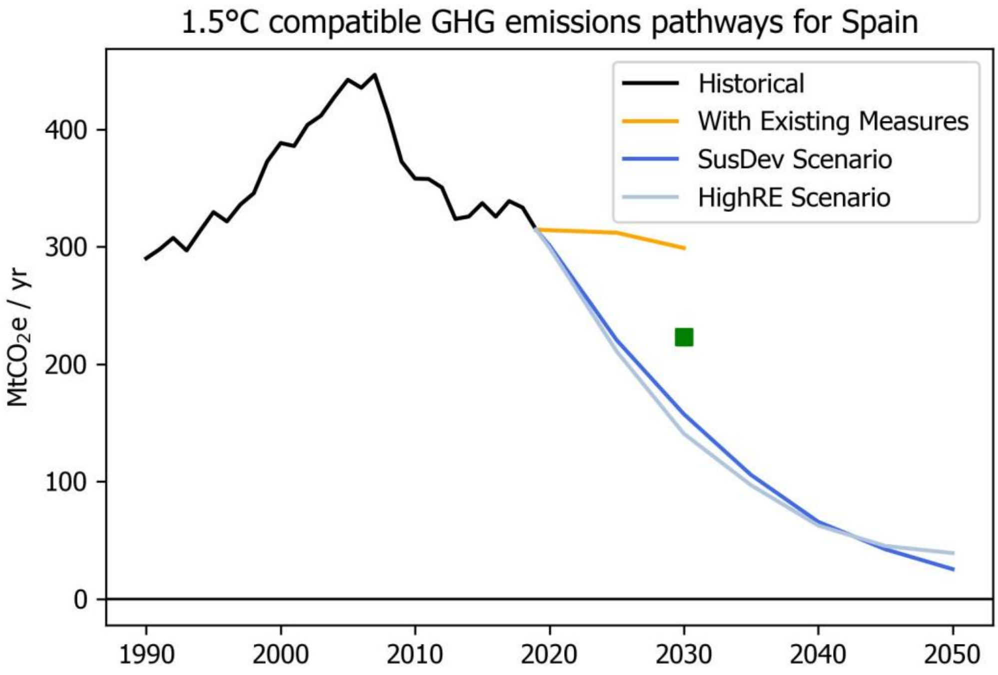


Figure 29 | 1.5°C compatible GHG emissions pathways for Spain

3.8.2 1.5°C compatible sectoral transformation pathways: Spain

Figure 30 displays 1.5°C compatible pathways for total final energy demand in Spain. In both pathways, total energy demand declines strongly across the time horizon, falling by 34-49% in 2050 below 2019 levels. Falling final energy demand is caused by a combination of improved energy efficiency and demand reduction. In the HighRE pathway, the majority of final energy demand reduction is due to efficiency gains from direct electrification. As heat-pumps, EVs, and other electric technologies replace gas boilers, petrol/diesel vehicles, and other fossil alternatives, final energy demand falls, while overall demand for energy services is relatively unchanged. In the SusDev pathway, some of the reduction in final energy demand is still driven by electrification, with electricity consumption growing 14% across the time horizon. However, the reduction in final energy demand is also driven by ambitious lifestyle shifts that reduce demand for final products.

At the same time, renewable energy is rapidly deployed to displace fossil fuels from the energy system. The electricity system is largely decarbonised by the mid-2030s, and electricity provides 57-67% of final energy demand in 2050, up from 25% today. Coupled with biomass and green hydrogen production, **renewables provide 28-40% of final energy demand by 2030 and 89-92% by 2050**.

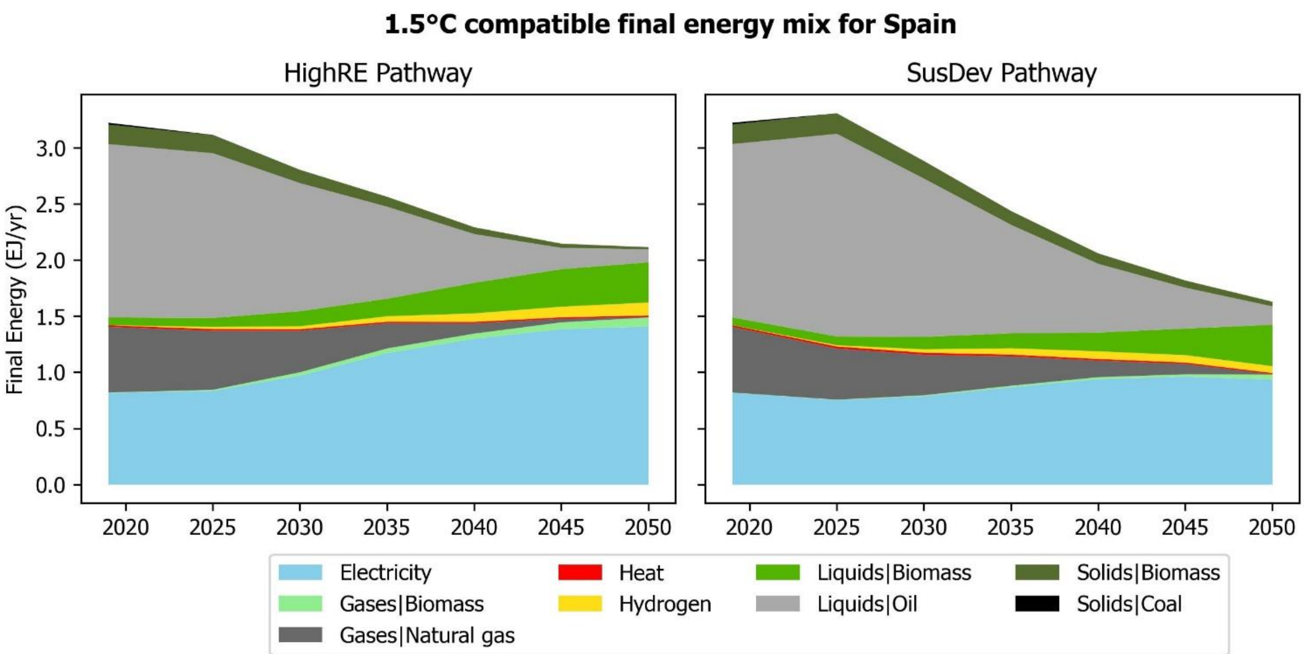


Figure 30 | 1.5°C compatible final energy pathways for Spain

Electricity sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, non-biomass renewables provide the vast majority of future electricity demand in Spain. In these pathways, the share of non-biomass renewables (mainly wind and solar) increases from nearly 35% today to 83-88% by 2030 and 96-99% by 2050 (Figure 28). Accounting for limited contribution from biomass, **the total share of electricity produced by renewables reaches 85-91% by 2030 and 97-100% by 2050**. Further innovation and investment in grid expansion and interconnection, storage technologies, and sector coupling would be required to accommodate this high share of variable renewables in the power system. Hydrogen is used in the power sector to provide long-term energy storage and plays a particularly key role in the HighRE pathway.

Both illustrative pathways demonstrate a declining role of nuclear in the future power mix with the share reaching 4% by 2030 and being phased out by 2040.

While both pathways show a transition to a power sector dominated by renewable electricity, the size of the power sector in the long-term varies strongly between them. In the HighRE pathway, total electricity demand approximately doubles between 2019 and 2050 due to relatively limited progress on energy efficiency/demand reduction, and a strong focus on electrifying final energy demand. In the SusDev pathway, electricity demand growth is more limited across the time horizon as strong reductions in final energy demand lower the need for additional generation. Additional action on the demand-side can reduce the scale of the energy system required, which can help mitigate supply-side challenges, such as those relating to renewables permitting (Bellona 2022). However, in the near-term both pathways display broadly similar behaviour – with generation from non-biomass renewables growing strongly.

Spain aims to phase out its coal fleet by 2025 at the latest. The illustrative pathways assessed here phaseout coal in 2023-2024, aligning well with this date**.** The pathways also envisage a rapid reduction in gas consumption in the power sector, with gas effectively phased out by 2034 in the HighRE pathway. In the SusDev pathway, there is a slightly slower reduction in gas-fired power generation. However, gas provides only 3% of electricity generation by 2050. At this low level, gas will be relegated to the role of a 'peaking technology', operating only to meet electricity demand on limited occasions.

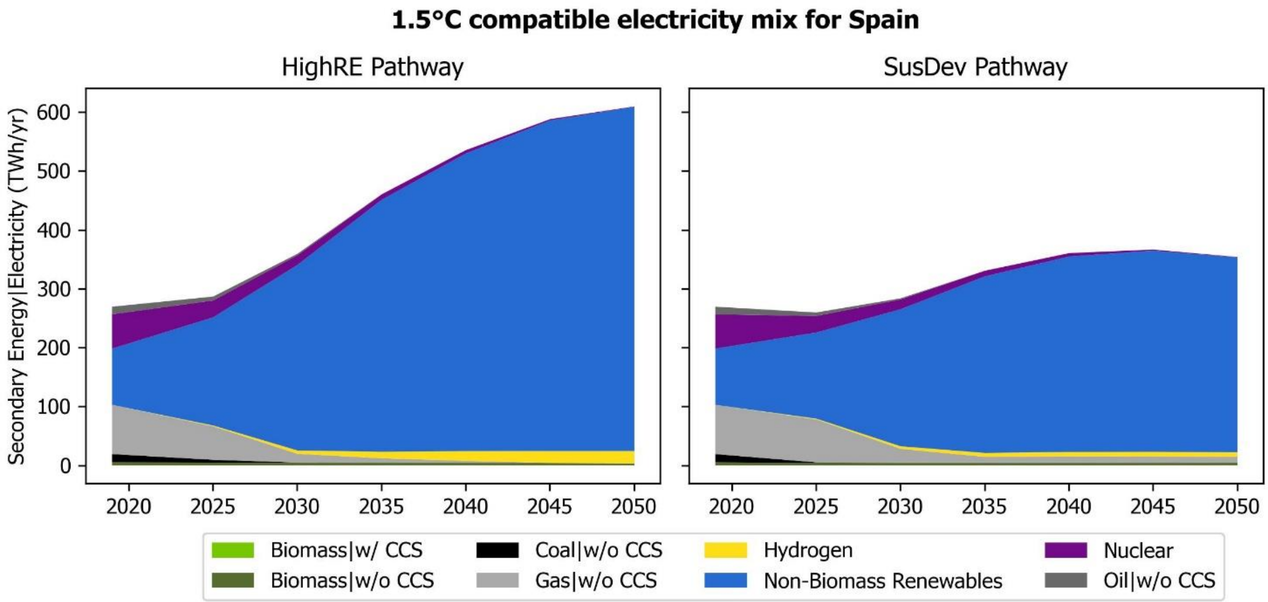


Figure 31 | 1.5°C compatible electricity generation mix for Spain

Transport sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the transport sector is decarbonised by a mix of electricity, hydrogen, and biofuels. Electricity provides 6-9% of final energy by 2030 and 31-36% by 2050. Hydrogen could also become increasingly important in the transport sector decarbonisation. Based on the two assessed illustrative pathways, the share of hydrogen in the transport sector reaches 3% by 2030 and up to 12% by 2050. Hydrogen could be crucial for decarbonising long-distance transport such as aviation, shipping, and long-haul road freight, where electrification is a less competitive option.

In the assessed pathways based on IPCC AR6, the share of biofuels in the transport sector reaches 7-9% by 2030 and 38-48% by 2050, which represents a large-scale reliance on biofuels for transport decarbonisation by 2050. However, this share is lower than in previously assessed pathways from the IPCC's Special Report on 1.5°C. IAMs are beginning to reflect the potential for greater hydrogen and electricity consumption in the transport sector. Transportation decarbonisation pathways based on higher-resolution and sectoral-specific models often indicate the potential to substantially limit biofuel consumption in the transport sector (Luderer *et al* 2021a, Breyer *et al* 2019), and instead rely on direct electrification, hydrogen, and synthetic fuels (which are not represented in these pathways) to reduce emissions. Recent modelling has highlighted the diversity of possible low-carbon futures for Europe, including pathways which eliminate biofuel use entirely (Pickering *et al* 2022). Biofuel use is therefore an option, rather than a necessity, for reducing emissions. Any biomass used to support decarbonisation should be sourced sustainably, avoiding high land-use change emissions, competition with food crops, and negative biodiversity impacts (Energy Transitions Committee 2021)

Electricity, hydrogen, and biofuels all displace oil consumption in the transport sector. Oil provides 82-83% by 2030 and 15-44% by 2050. Remaining oil demand is largely confined to the aviation sector and could be further reduced by introducing renewable-based synthetic fuels, which are not included in the assessed model pathways. **The share of renewables in total transport final energy use reaches 14-17% by 2030 and 78-84% by 2050**.

Buildings sector decarbonisation pathways

In the illustrative 1.5°C compatible pathways, the buildings sector is predominantly decarbonised through direct electrification. Electricity provides 57-60% of final energy in the buildings sector by 2030 and 83-93% by 2050. This is accompanied by limited consumption of sustainable biomass and district heating. While some have proposed hydrogen as an option to decarbonise buildings heating, neither pathway uses hydrogen in the buildings sector. The total share of renewables in the buildings sector reaches 60-66% by 2030 and 94-96% by 2050.

Electrification can reduce final energy demand in the buildings sector due to the much higher efficiency of electric technologies such as heat pumps. Final energy demand falls by 24% and 40% by 2050 below 2019 levels in the HighRE and SusDev pathway, respectively.

Industry sector decarbonisation pathways

Industrial processes electrification can reduce both energy intensity and industrial emissions. In the considered illustrative 1.5°C compatible pathways, electricity provides 22-44% of final energy demand in industry by 2030 and 52-67% by 2050.

Hydrogen provides up to 3% of industrial final energy by 2030 and up to 16% by 2050. Bioenergy provided 8% of industrial final energy in 2019. In 1.5°C compatible pathways, this share rises slightly by 2030, where biomass provides 12-22% of final energy. In the HighRE pathway, renewable heat and hydrogen become the second largest energy source in industry, displacing biofuels, which account for 14% of industrial final energy by 2050. The SusDev pathway has slower scale-up of hydrogen production and, therefore, displays greater biofuel reliance, with biofuels providing 36% of industrial demand in 2050. In both cases, greater consumption of hydrogen or synthetic fuels could further reduce biofuel reliance (Dena 2018).

Coal already provides a relatively low share in Spain's industrial final energy demand (1.5% in 2019), and this needs to be further reduced to zero. The pathways also project a rapid reduction in gas demand. Industrial gas demand falls 36-40% by 2030 below 2019 levels, and **gas use is effectively phased out of industry by 2048-2050.**

3.8.3 Key characteristics of Spain's 1.5°C compatible pathways

Table 18 provides a summary of key derived 1.5°C compatible benchmarks for Spain in 2030 and 2050 compared to recent historical values and country targets.

Table 18 | 1.5°C compatible benchmarks for Spain

		Historical	1.5°C compatible benchmarks		Country targets	
		2019	2030	2050	2030	2050
Whole economy	Total GHG excl. LULUCF	290 $MtCO_2e$	46-51% below 1990	87-91% below 1990	23% reduction relative to 1990 levels.	90% below 1990 levels
	Share of renewables in electricity production	37%	85-91%	97-100%	74%	-
	Renewable share of final energy demand	18%	34-43%	88-94%	-	-
	Change in final energy demand (relative to 2019**)**	0%	-11% to -13%	-34% to -49%	-	–
	Electrification of final energy demand	25%	27-35%	57-67%	-	-
Sectoral perspective	Transport sector electrification rate	1%	6-8%	31-36%	-	-
	Transport sector renewable share	5%	14-17%	79-85%	28%	-
	Buildings sector electrification rate	51%	57-60%	83-93%	-	-
	Buildings sector renewable share	31%	61-67%	96-99%	-	-
	Industry sector electrification rate	33%	22-44%	52-67%	-	-
	Industry sector renewable share	20%	31-52%	88-98%	-	-

In the assessed pathways, there is a rapid reduction in fossil fuel consumption across all fuels and all sectors. In all cases except for oil demand in transport, **fossil fuels are effectively phased out prior to 2050** in 1.5°C-compatible pathways for Spain. Table 19 highlights effective fossil fuel phase out dates by sector and fuel type for the selected pathways.

Table 19 | Effective fossil fuel phase-out dates for Spain.

*In these sectors the phase out dates are based on the HighRE pathway only, with the SusDev pathway demonstrating a slower phase out of fossil fuels in this sector.

Sector	Coal	Gas	Oil
Power	2023-2024	2034*	N/A
Industry	N/A - Already phased out	2048-2050	2044*
Buildings	N/A - Already phased out	2042-2047	2044-2048
Transport	N/A	N/A	Post-2050

At the time of submission, no national studies for Spain could be identified which provide the necessary level of detail for comparison and aligned with either the Spanish net zero target or broader interpretations of the Paris Agreement. Country-specific roadmaps are of considerable value and would enable further evaluation of the illustrative pathways produced in this report, as well as accounting for the unique context that should help guide decision making at the national level.

4. Discussion

This report makes two key analytical contributions. It first quantifies and classifies the level of transformation in a set of eight 1.5°C compatible pathways from the IPCC's Sixth Assessment Report for the EU27 and seven selected member states. It then takes two of these pathways and performs an in-depth analysis of energy system transformations at the sectoral level. The report presents a range of new methodological and conceptual advancements in the field of assessing transformation pathways, as well as a range of key country-specific findings. In this section, some relevant caveats are highlighted to help contextualise the findings of this analysis, as well as avenues for further work.

First, when classifying pathways based on the level of transformation observed, we use a relative approach that scores pathways against one another. This is a valuable approach, as it can help identify the pathways which are most or least transformative and inform further analysis. However, it does not provide information on the absolute level of transformation required by the scenarios. As such, all eight pathways could be highly transformative, but some would be ranked "low" as they have slightly lower transformation relative to the ensemble as a whole. Further work could develop absolute thresholds for transformative change across each indicator to identify whether the ensemble as a whole represents high levels of absolute transformation when measured by an external benchmark. Thresholds developed in the literature could be developed and extended to enable this (Warszawski *et al* 2021, Brutschin *et al* 2021).

Second, the report explores how different dimensions of transformation relate to one another. It does this by both clustering the pathways into "landing zones", where pathways have similar levels of transformative change in particular dimensions of the transition, and by conducting further in-depth analysis into the correlation between underlying indicators. While this has value, the robustness of the analysis is limited by the small sample size of eight 1.5°C compatible pathways. This sample size is governed by data availability and the strict sustainability and climate criteria that are used to select pathways for analysis. However, as new pathways are produced, they could be integrated into this framework to further improve the robustness of the analysis.

In addition, the sample is dominated by pathways produced by the REMIND integrated assessment model, which provides 75% of the pathways. In some underlying dimensions, such as the share of renewables in the power sector, these REMIND pathways are relatively homogeneous, which could skew the results of analysis. Expanding the set of pathways under consideration to improve pathway diversity or developing statistical techniques to identify and remove pathways which are highly similar would be a potential avenue for future research. At the same time, the six pathways produced by REMIND differ strongly in many dimensions due to the diverse scenario narratives across the pathway set (Appendix B). Therefore, scenario bias is not deemed to be a critical weakness in the results as presented.

Third, the scenario quantification we perform is limited by the availability of data for required indicators. Some metrics of interest, such as around the level of demand-side response or the level of cost reduction in key technologies, could not be determined from the IAM pathways. However, the tool we develop and apply in this report provides a flexible framework for quantification, comparison, and classification of pathways. Additional dimensions and indicators could, therefore, be added in the future depending on data availability.

Fourth, scenario quantification and classification in this report is broadly conducted at a whole-system level, focusing on the overall level of electrification, demand reduction, and hydrogen consumption across the whole energy system. This is valuable as it gives a systemic perspective on the level of transformative change observed in pathways. However, it would be interesting to extend this approach to explore the level of transformative change at a sectoral level, exploring how transformation in one sector compares and relates to transformation in other sectors.

In the second analytical contribution, the report uses two illustrative pathways to provide in-depth analysis of the transformation required in each member state to align with the Paris Agreement's 1.5°C temperature limit. The illustrative pathways are chosen because they represent the "highest plausible ambition" for the EU27 as a whole. This is defined as 1.5°C compatible pathways which are technically and economically feasible, demonstrate the steepest GHG emissions reductions by 2030, and do not violate sustainability criteria as laid out in Section 2.2. Aiming for the highest plausible ambition is aligned with the EU27's historic responsibility for climate change and economic/regulatory capacity to reduce emissions rapidly. These illustrative pathways do not explicitly consider the political or social feasibility of the transformations they envisage and focus instead on producing pathways which are techno-economically feasible and cost-effective. Further analysis could use additional metrics to explore the socio-political feasibility challenges that these scenarios face (Jewell and Cherp 2020, Brutschin *et al* 2021). However, identifying technically feasible pathways to achieve greater emissions reductions can provide motivation to address remaining socio-political barriers to implementation. The transformative change envisaged by all pathways in this report will only be achieved if substantial new political will can be mustered at both the EU27 and member state level. Future work packages in the 4i-TRACTION project will explore how this transformative change could be achieved through new and existing EU climate policy architecture.

It is also important to note that the pathways produced in this report use a cost-effective approach to allocate energy consumption and emissions at the member state level. They highlight where it would be most cost-effective to reduce emissions, but therefore does not account for EU27 policies such as the Effort Sharing Regulation (ESR), which attempts to ensure a fair allocation of emissions reductions across member states. In some cases, such as Poland, the emissions reductions that we obtain are much more ambitious than what would be allocated under the ESR. While it is unlikely that the EU will move away from the ESR entirely, cost-effectiveness analysis remains a valuable tool, as it can help identify substantial mitigation potential that could otherwise be overlooked. This analysis demonstrates that Poland and Germany have particularly large cost-effective mitigation potentials, due to the high share of coal in their total energy mix. This information can help inform the EU27's climate action as a whole and potentially unlock greater ambition in the 2020s.

We also compared the results of our analysis against various EU-level and national studies. For instance, the illustrative pathways produced for this analysis report greater levels of renewable consumption in 2030 than the scenarios produced for the European Commission to support the Fit for 55 package. This suggests that there are feasible routes for the EU to accelerate the transition in the 2020s faster than envisaged by the PRIMES modelling. The results of a recent EU study (Ember 2022) also broadly align with the power sector transitions for the illustrative pathways we assessed in this report. Further in-depth comparison of our results against various national modelling studies also shows a high consistency at member state level, while the differences have been thoroughly explained in the corresponding country chapters.

5. Conclusions and outlook

In this report, we have developed and applied a new framework for assessing and classifying the pathways with respect to four core challenges of the transformation. We applied this framework to assess the latest pathways from the IPCC's AR6, exploring what transformation may be necessary for the EU27 and selected seven member states to achieve the goals of the Paris Agreement. We have quantified and classified pathways based on the level of transformation observed in the four cross-cutting core challenges at the heart of the long-term transformation effort, **the 4i's:** fostering **innovation**, mobilising **investment** and finance, rolling out the **infrastructure**, and enabling greater **integration** across sectors. In addition, we used two illustrative mitigation pathways to perform an in-depth assessment of 1.5°C compatible energy and emissions pathways for the EU27 and seven selected member states: Germany, Finland, France, Belgium, Poland, the Netherlands and Spain. This was then compared to the current set of targets and other national pathways and modelling studies. The results of this analysis will be fed into the other work packages of this project to assess how existing and new policy measures could help achieve this level of ambition.

The report finds that the EU27 and member states could reduce emissions in the 2020s much faster than planned. The report identifies technically feasible routes for the EU27 to reduce emissions in 2030 by 64-67% below 1990 levels by 2030, which is more than the submitted NDC of 53.9% (excluding LULUCF). While the recently released REPowerEU plan accelerates the bloc's energy transition, it remains incompatible with the 1.5°C target as assessed by this report, leading to emissions reductions of 57-58% in 2030 below 1990 levels. Therefore, the **EU's current 2030 targets cannot be seen as compatible with 1.5°C** and would need to be increased to align with the Paris Agreement's temperature goal. In addition, further strong reductions in GHG emissions are required post-2030, with emissions reaching 85-86% below 1990 levels by 2040 (excluding LULUCF).

The report then explores how this transition could be achieved at the sectoral level. Rapid power sector decarbonisation is crucial to achieving the 1.5°C goal. In the vast majority of pathways, this is driven by wind and solar deployment. In the most ambitious pathways, renewables provide over 80% of electricity generation in 2030 in the EU27, growing to 100% by 2050. Non-biomass renewables such as wind and solar are key technologies, providing around 70-83% of electricity in 2030 and 88-98% in 2050 in the EU27. There is variation in individual member states, but in all countries the share of renewables approaches at least 70% in 2030 and 90% in 2050. Rapid power sector decarbonisation driven by renewables emerges as a robust strategy across member states and pathways.

In all member states, coal is effectively phased out of the power sector by 2030, while in the most ambitious pathways, gas is effectively phased out in the 2030s. Alongside electricity decarbonisation, the electrification of buildings, transport, and industry emerges as a robust decarbonisation option. In the most ambitious pathways, electricity provides up 57-66% of final energy in 2050 at the EU27 level. Electrification of end-use sectors and efficiency improvements, coupled with some reductions in demand for final products, lead to a strong reduction in final energy demand in most pathways and countries. Achieving such levels of renewable electricity will require shifting investment from fossil fuels to renewables, while simultaneously scaling up total investment. In addition, accelerating the permitting process for onshore renewables (particularly wind), can help achieve this rapid expansion of renewables.

This report helps to identify an emerging consensus on the form of transformation needed to align with 1.5°C – renewable-based electrification, efficiency improvements, and some changes in the level of demand for final products. However, in other areas of the transformation, there remains scope for diverse energy system pathways. For instance, the level of hydrogen demand, CCS reliance, and energy storage deployment varies strongly across the pathways. This highlights that choices remain to be made about the shape of the EU27's energy transition. However, this variety should not be seen as a reason to relax the pace of decarbonisation. Rather it highlights that there are key decisions that must be made by decisionmakers about the type of decarbonisation pathway the EU27 is going to embark upon. These decisions are needed urgently to guide investments and infrastructure development. Transformative change is necessary to align the EU27 and member states with the 1.5°C goal. It remains to be seen whether such change will emerge in this critical decade for climate action.

The report also finds that transformation in one dimension can entail transformation in another dimension. For example, there is a strong correlation between total infrastructure needs and total investment needs in the EU27. Pathways that have high/low investment needs often also have high/low levels of transformation in integration. This highlights that developing a large-scale and well-integrated energy system requires strong levels of investment. When assessing the underlying indicators for the EU27, it was found that pathways which envisage greater transformation in the level of renewables deployment and demand reduction can reduce their reliance on CCS deployment, while increasing hydrogen deployment can facilitate higher levels of electrification. The 4i's should be viewed as a joint challenge rather than as separate and isolated issues to be engaged with by policymakers.

The results of the analysis provide insights into the timing and sectoral scope of the 4i's of the transition. The illustrative pathways in this report show that key to achieving transformative change is a clean power sector. Reducing power sector emissions via renewables deployment is a key challenge for the 2020s. Electrification then emerges as a second pillar of transformative change, with a huge growth of electrification rate of end-use sectors in the post-2030 period. While growth in electrification is modest in the 2020s, it rapidly accelerates in the 2030-2050 period. Infrastructure deployment to facilitate end use electrification thus becomes key post-2030. Therefore, while some of the infrastructure needed to support end-use electrification (such as reinforcement of local grids) is more important to be ready for the 2030s, the infrastructure to facilitate renewables deployment in the power sector is needed immediately.

Key innovations can help drive transformative change. While many of the technologies required to drive deep decarbonisation, such as solar and wind, exist at scale today, others require further innovation support. In particular, renewable hydrogen plays an important role in the power, industrial, and transport sectors. Continued innovation support for hydrogen production and use will be essential. As well as infrastructure improvements, a highly renewable power sector will require demand-side innovation. Demand-side flexibility offers considerable potential in Europe to balance variable renewables at low cost, as 15–30% of the peak load can be shifted on average (Söder et al 2018).

In the illustrative pathways, remaining fossil demand in 2050 is concentrated in long-distance transport and in non-energy use. Innovation into sustainable aviation fuels and renewable feedstocks are therefore promising avenues to displace remaining fossil fuels in 2050 and achieve a fossil-free European Union.

The report also explores the energy system transformation for seven selected member states. This gives a perspective on how the EU27's total contribution to global climate action could be distributed across individual countries. The nation level results further support the key messages of this report. **None of the seven member states has a legislated 2030 target which is 1.5°C aligned, as assessed in this report.** There is, therefore, an urgent need to increase action at the member state level if the EU27 is to take the role as a global leader in driving climate action.

Transformation pathways in all member states involve substantial electrification of demand. Further policies must support closer integration of the power sector and the demand sectors of buildings, transport, and industry through smart grids, digitization, electric vehicle charging infrastructure, and system flexibility. Furthermore, in all selected seven member states excluding Finland, final energy demand declines across the horizon. Importantly, this is driven not only by changes in demand patterns, but also by the efficiency of direct electrification as a decarbonisation option. An electrified energy system can be smaller in terms of energy consumption while still providing the same amount of energy service demands.

Germany's new renewables target of 80% is also to be welcomed but, to align with 1.5°C, it should consider aiming for a 91-94% share of renewables. Finland has made strong steps towards decarbonisation, with over 50% of its energy coming from renewable sources in 2019. However, to align with 1.5°C, Finland would need to target a 64-70% reduction in GHG emissions in 2030, rather than the proposed 60%. In France, renewable based electrification leads to GHG emissions reaching 42-57% below 1990 levels in 2030. Belgium has committed to a 23% reduction in GHG emissions relative to 1990 levels compared to 44-50% in 1.5°C compatible pathways. The Netherlands' updated target would align it with the illustrative pathways in this report. However, it may be plausible for the Netherlands to outperform this target, particularly given recent cost reductions in offshore wind. For Spain, the strength of the 2030 target has not been increased, remaining at a 23% reduction relative to 1990 levels. This is not aligned with 1.5°C and makes achieving the 2050 target much more challenging.

This report has demonstrated that 1.5°C consistent action for the EU27 and individual member states will require transformative change towards a zero-carbon energy system and economy. They show a rapid reduction in fossil fuel consumption, effectively phasing coal out of the energy system by 2030, and fossil gas by 2050 at the latest. Historical precedents and existing international best practices in accelerating technology deployment shows that this rapid change is possible. For instance, UK grew its renewables share by 35% in a decade from 2010 to 2020 (Climate Action Tracker 2022a), while EV sales share went from 1.6% in 2019 to 12.1% in 2021 (IEA 2022). The Danish power system has been undergoing a rapid transformation, moving from a highly centralised to a decentralised electricity system with a significant increase of renewable energy sources (Agora Energiewende and DTU Management Engineering 2015). However, existing barriers related to public acceptance and lack of political will need to be overcome to make this transformative change happen. Highlighting that technically feasible and cost-effective pathways to higher ambition exist can provide motivation to identify and address these barriers, and thus achieve the necessary transformation to align with 1.5°C.

However, current policies and targets are inadequate to spur this transformation. To align itself with the 1.5°C goal, the EU27 would need to rapidly increase its 2030 targets and provide global leadership on climate action. EU member states are due to revisit and update their national energy and climate plans (NECPs) in 2023. This provides a key opportunity for each country to demonstrate global leadership and accelerate transformative change. It remains to be seen whether such transformative leadership will be provided in this critical decade.

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Appendix A: Member State pathway classification

Appendix A1: Germany

A1.1 Pathway classification with respect to 4i's – Germany

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. Figure A1 displays the results for Germany.

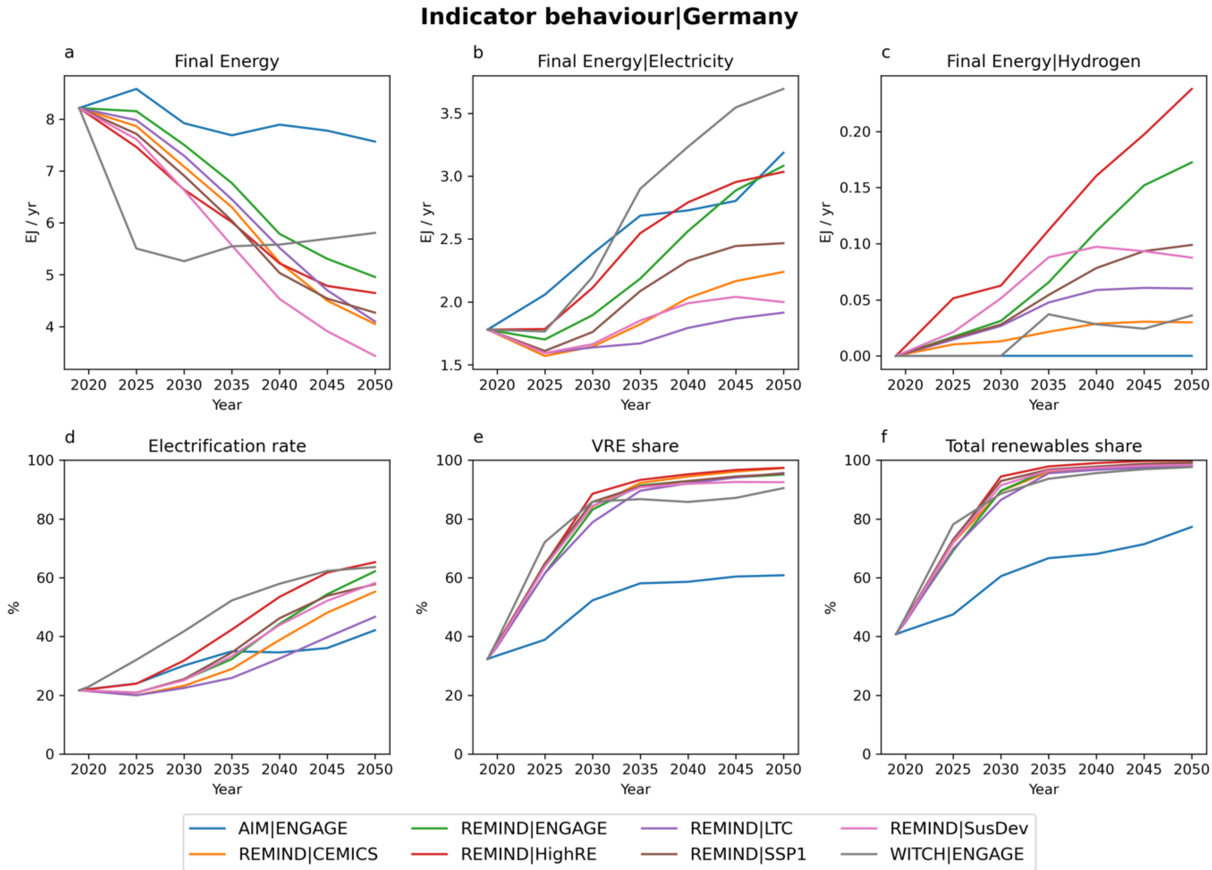


Figure A1|Indicator performance for Germany.

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

The 8 pathways selected represent a diversity of possible 1.5°C compatible futures for Germany. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. The area where there is less variation across pathways is in the power sector. Here all but one pathways envisages a rapid transition towards 100% renewable electricity. Renewables provide 86-94% of electricity in 2030, rising to 98-100% by 2050. Non-biomass renewables such as wind and solar are key technologies, providing around 79-89% of electricity in 2030 and 89-97% in 2050. The one exception is the pathway produced by AIM/CGE 2.2, in which nuclear and fossil fuels equipped with CCS are also used as sources of low-carbon electricity. These sources provide around 25% of electricity generation in 2050 in this pathway, which explains the distinct behaviour. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for Germany involves a transition towards 100% renewable electricity by 2050, with strong growth by 2030.

In the next step, we classify the pathways into different levels of transformation for each of the 4i's.

We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway (Figure A2).

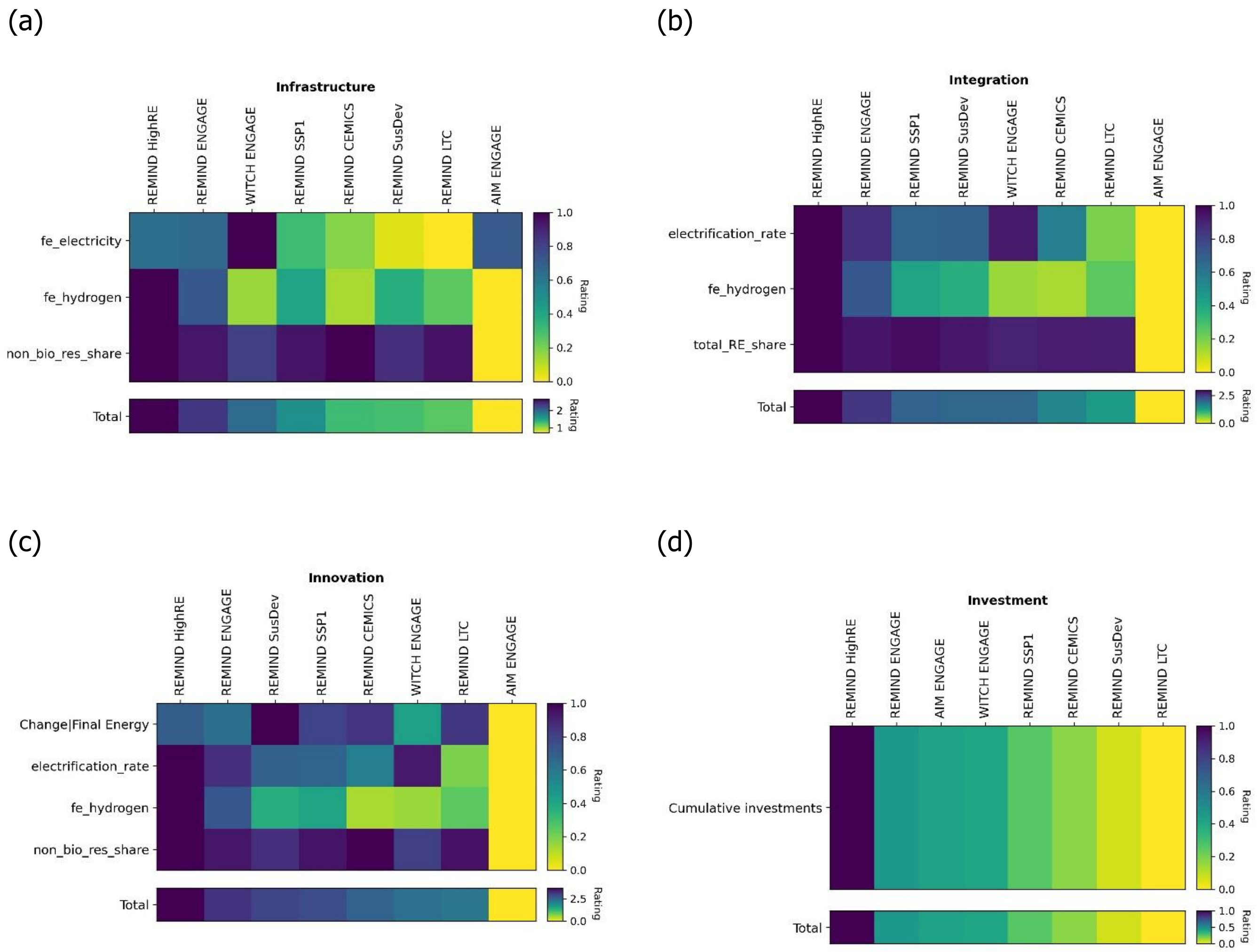


Figure A2|Pathway rating for each 4i dimension (Germany).

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then define the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These pathway classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A1 shows which pathways are assessed as low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A1|Pathway classification into low/medium/high categories (Germany)

This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment

model	pathway	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	high
REMIND	CEMICS	medium	low	medium	low
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	high	medium	medium
	SusDev	low	medium	high	low
WITCH	ENGAGE	high	medium	low	medium

Finally, we cluster the pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A3 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	0	1
Medium	0	1	1
Low	1	1	1

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	2	0	1
Medium	0	2	0
Low	1	0	2

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	0	1
Low	0	1	2

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	1	0	1
Low	0	1	2

Figure A3|Pathway classification into landing zones with respect to the 4i's (Germany)

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A number of results can be highlighted from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are relatively consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in integration and infrastructure as well. There is also some correlation between the level of transformation required in infrastructure and innovation, with 75% of pathways sitting on the diagonal. This is partly due to the use of shared underlying indicators, but highlights that there are strong interlinkages between the transformative challenges facing the EU27 and member states. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate issues to be engaged with by policymakers.

A1.2 Relationship between the underlying indicators

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for Germany, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. Table A2 highlights the correlation (r-value) between each pair of underlying indicators.

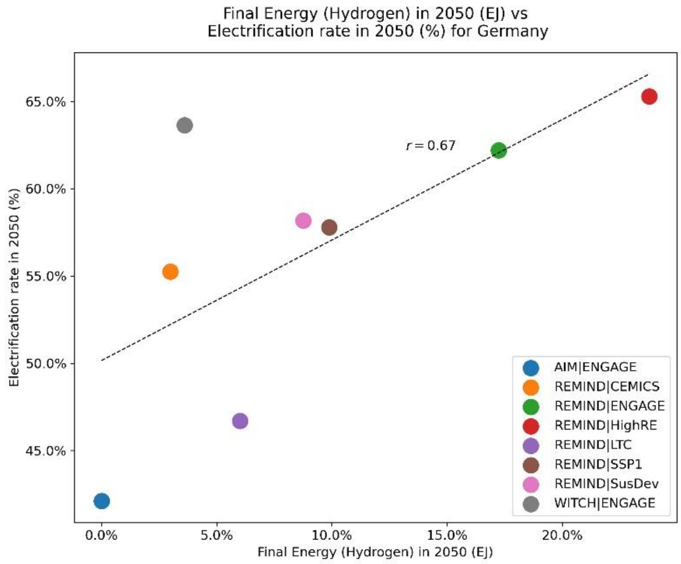
Table A2|Correlations between different underlying indicators (Germany).

The darker the colour, the stronger the relationship between the two variables.

	Change| Final Energy	Cumulative investments	Electrification rate	fe_ electricity	fe_ hydrogen	non_bio_ res_share	total_RE_ share
Change| Final Energy	1.00	0.35	-0.38	0.74	-0.34	-0.86	-0.85
Cumulative investments	0.35	1.00	0.49	0.67	0.67	-0.04	-0.03
electrification _rate	-0.38	0.49	1.00	0.33	0.67	0.66	0.73
fe_electricity	0.74	0.67	0.33	1.00	0.10	-0.37	-0.30
fe_hydrogen	-0.34	0.67	0.67	0.10	1.00	0.52	0.53
non_bio_res_ share	-0.86	-0.04	0.66	-0.37	0.52	1.00	0.99
total_RE_ share	-0.85	-0.03	0.73	-0.30	0.53	0.99	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.20[10]. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states down a particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the ensuing level of electricity generation), but others merit further investigation. Two relationships are highlighted here.

[10] This is excluding the self-correlations shown on the diagonal of Table A2



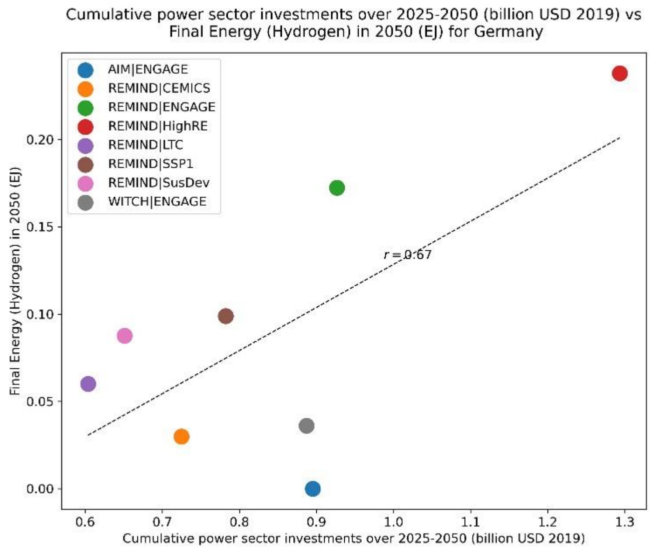


Figure A4|Relationship between selected underlying indicators (Germany)

Shows (a) Final Energy|Hydrogen in 2050 vs. Electrification rate in 2050 and (b) Cumulative investment vs. Final Energy|Hydrogen in 2050

Hydrogen can enable increased electrification of demand

Figure A4a shows the relationship between the level of hydrogen consumption in final energy in 2050, and the level of electrification in 2050. The positive correlation here suggests that, in the underlying pathways, hydrogen is an enabling factor in electrification. Greater deployment of hydrogen leads to greater levels of electrification of energy demand. This in turn increases the level of transformation across all three dimensions of infrastructure, integration and innovation.

Hydrogen integration linked to electricity system investments

Figure A4b shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here again indicates that there is a relationship between the level of hydrogen demand, and the scale of transformation in the power sector. Hydrogen and electrification can therefore be seen as supporting, rather than competing, decarbonisation options.

Appendix A2: Finland

A2.1 Pathway classification with respect to 4i's: Finland

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. **Figure A5** displays the results for Finland.

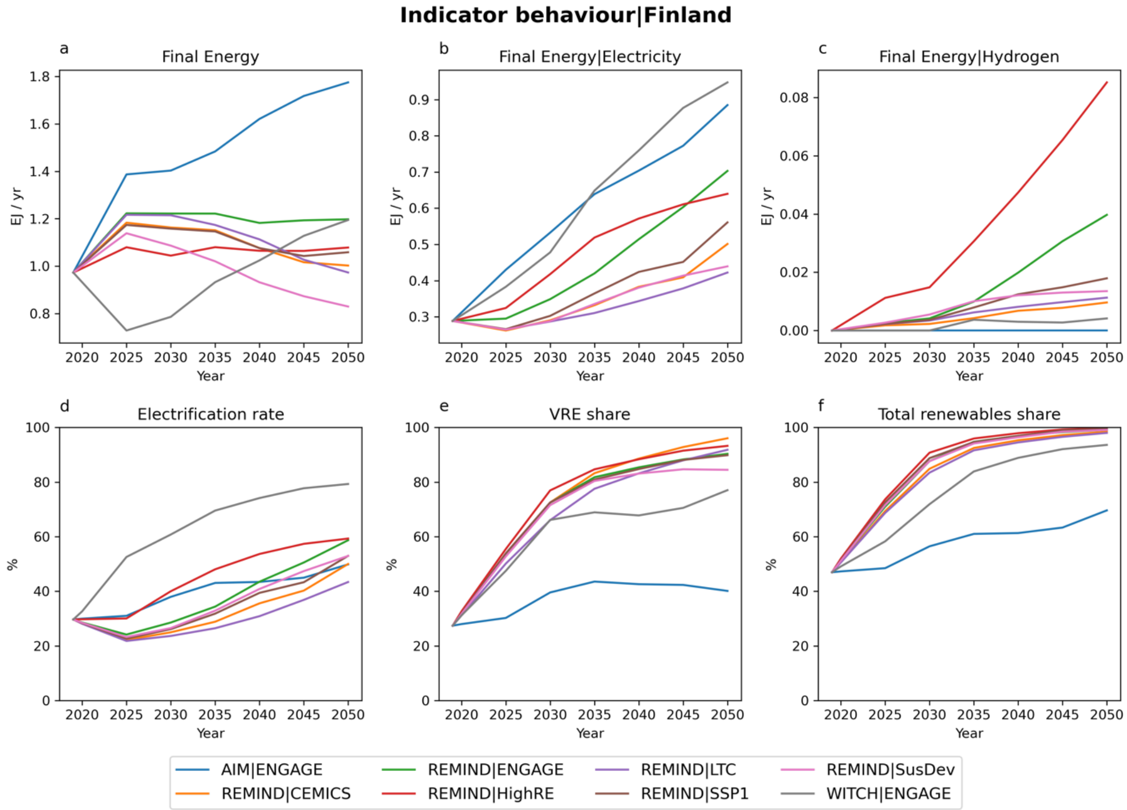


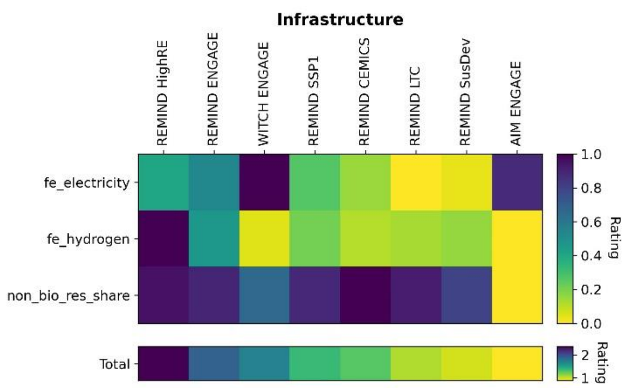
Figure A5|Indicator performance (Finland)

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

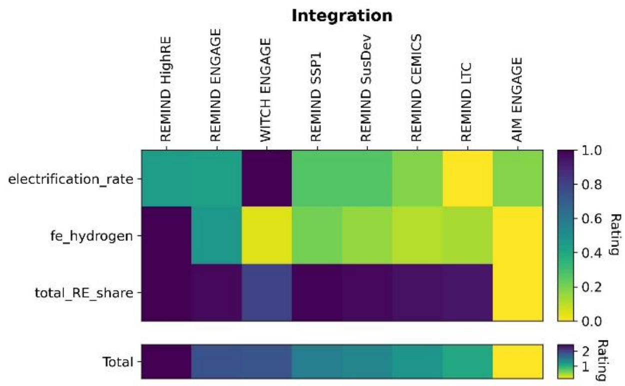
The 8 pathways selected represent a diversity of possible 1.5°C compatible futures for Finland. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. The area where there is less variation across pathways is in the power sector. Here all but one pathway envisages a rapid transition towards 100% renewable electricity, with non-biomass renewables providing around 72-91% of electricity by 2030, rising to 94-100% by 2050. Non-biomass renewables such as wind and solar are key technologies, providing around 66-77% of electricity in 2030 and 73-96% in 2050. The one exception is the pathway produced by AIM/CGE 2.2, in which nuclear and fossil fuels equipped with CCS are also used as sources of low-carbon electricity. These sources provide around 30% of electricity generation in 2050 in this pathway, which explains the distinct behaviour. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for Finland involves a transition towards 100% renewable electricity by 2050, with strong growth already achieved by 2030.

In the next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway. Figure A6 shows the results in the case of Finland.

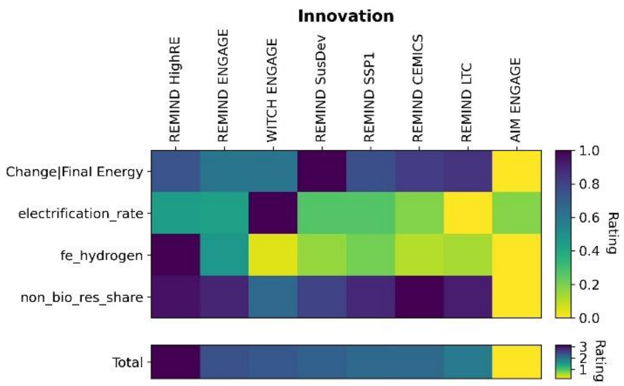
(a)



(b)



(c



(d)

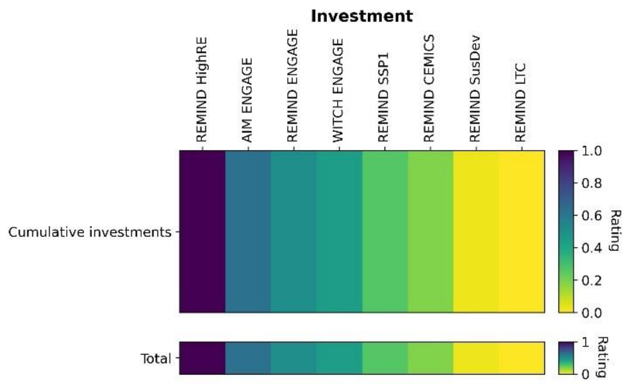


Figure A6|Pathway rating for each 4i dimension (Finland).

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by

AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then define the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These pathway classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A3 shows which pathways are assessed as requiring low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A3|Pathway classification into low/medium/high categories (Finland).

This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment.

model	pathway	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	high
REMIND	CEMICS	medium	low	low	low
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	medium	medium	medium
	SusDev	low	medium	medium	low
WITCH	ENGAGE	high	high	high	medium

Finally, we cluster the pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A7 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	3	0	0
Medium	0	2	0
Low	0	0	3

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

Figure A7|Pathway classification into landing zones with respect to the 4i's (Finland).

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A range of results can be seen from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in integration and infrastructure as well. There is also strong correlation between the level of innovation that occurs in the pathway, and the level of integration observed. All pathways sit on the diagonal. There is also some correlation between the level of transformation required in infrastructure and innovation, with 75% of pathways sitting on the diagonal. A similar interlinkage can be observed between pathways with high/low integration needs and high/low infrastructure needs. This is partly due to the use of shared underlying indicators but highlights that there are strong interlinkages between the transformative challenges facing the EU27 and member States. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate, isolated issues to be engaged with by policymakers.

A2.2 Relationship between the underlying indicators: Finland

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for Finland, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. Table A4 highlights the correlation (r-value) between each pair of underlying indicators.

Table A4: Finland results: Correlations between different underlying indicators.

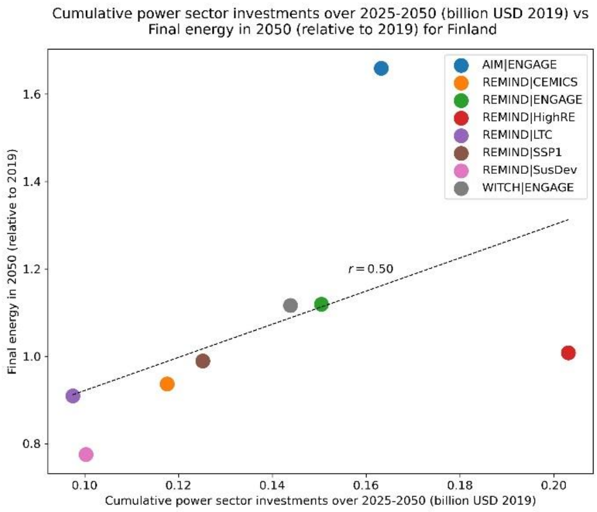
The darker the colour, the stronger the relationship between the two variables.

	Change|Final Energy	Cumulative investments	Electrification rate	fe_electricity	fe_hydrogen	non_bio_res_share	total_RE_share
Change|Final Energy	1.00	0.50	0.07	0.77	-0.20	-0.88	-0.92
Cumulative investments	0.50	1.00	0.38	0.60	0.69	-0.25	-0.27
electrification_rate	0.07	0.38	1.00	0.69	0.11	-0.03	0.08
fe_electricity	0.77	0.60	0.69	1.00	-0.10	-0.65	-0.61
fe_hydrogen	-0.20	0.69	0.11	-0.10	1.00	0.43	0.41
non_bio_res_share	-0.88	-0.25	-0.03	-0.65	0.43	1.00	0.98
total_RE_share	-0.92	-0.27	0.08	-0.61	0.41	0.98	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.30. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states on any particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the level of electricity production), but others merit further investigation. One relationship is highlighted here.

Demand reduction can reduce energy system investments

Figure A8a shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of final energy demand in 2050. The correlation between these indicators suggests that reducing final energy demand can help minimize investment needs (calculated here for the power sector alone). Therefore, greater transformation on the innovation dimension can reduce the scale of transformation required in investment dimension, if this innovation is focused on the demand-side.



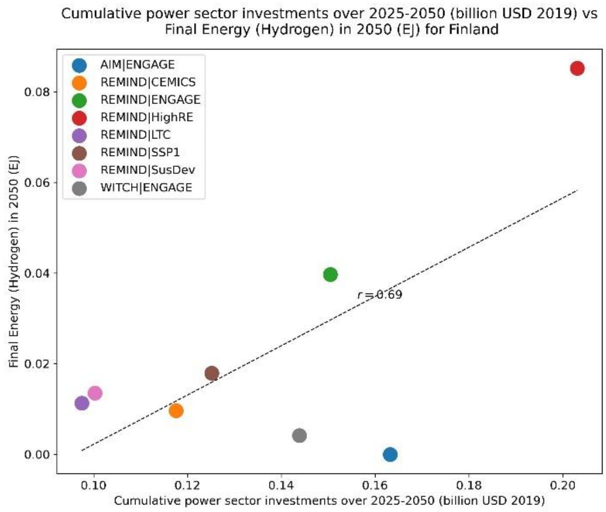


Figure A8| Relationship between selected underlying indicators (Finland).

Shows (a) Cumulative investments vs. Final Energy in 2050 and (b) Cumulative investment vs. Final Energy|Hydrogen in 2050

Hydrogen integration linked to electricity system investments

Figure A8b shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here again indicates that there is a relationship between the level of hydrogen demand, and the scale of transformation in the power sector. Hydrogen and electrification can therefore be seen as supporting, rather than competing, decarbonisation options.

Appendix A3: France

A3.1: Pathway classification with respect to 4i's: France

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. Figure A9 displays the results for France.

The eight pathways selected represent a diversity of possible 1.5°C compatible futures for France. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. There is also a range of possible low-carbon futures in the power sector. Here the majority of pathways, produced by REMIND, envisage a rapid transition towards 100% renewable electricity. This involves a phaseout of the existing large nuclear fleet in France, which is replaced by wind and solar. However, the pathways produced by WITCH and AIM show smaller levels of renewables deployment. They instead rely on a continued contribution from nuclear in the power. Nuclear provides around 19% of electricity generation in 2050 in the WITCH pathway, and 63% in the AIM/CGE pathway. This explains the distinct behaviour of these pathways.

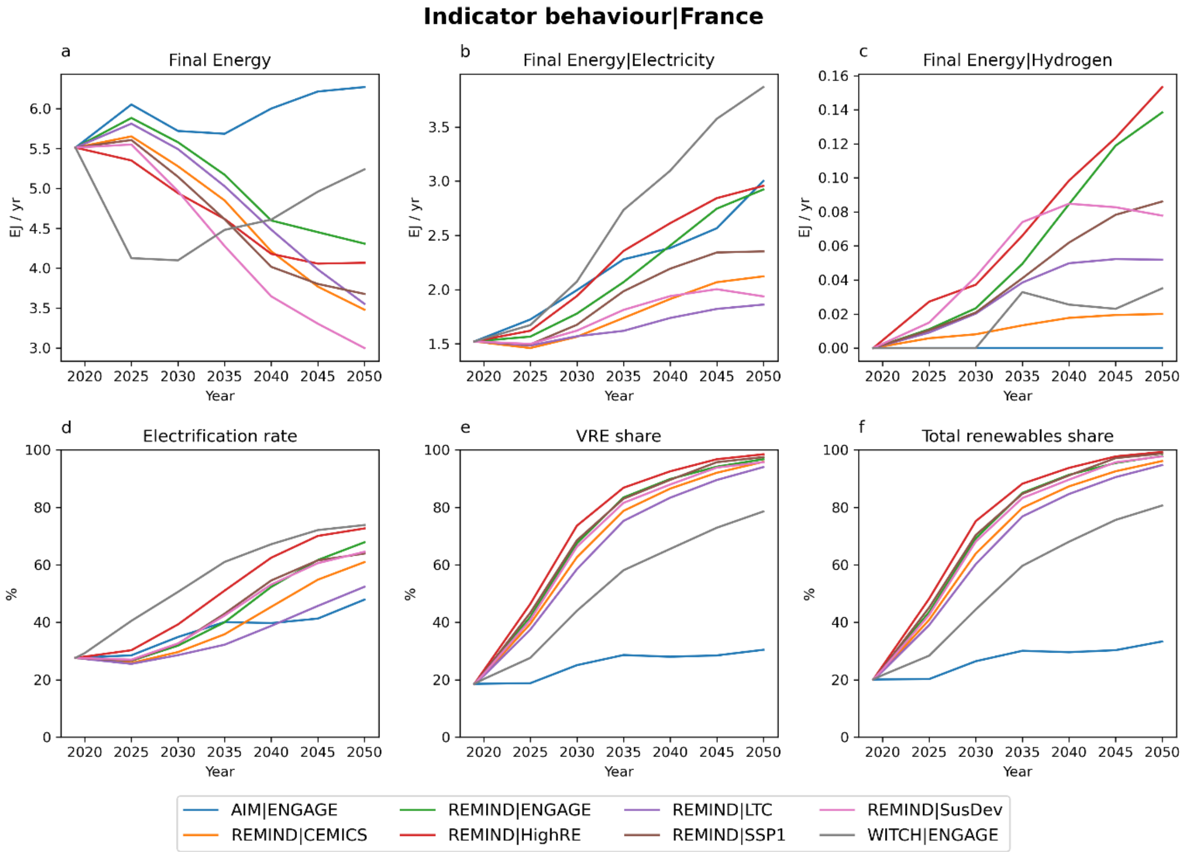


Figure A9|Behaviour of underlying indicators (France).

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

In the next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway. Figure A10 shows the results in the case of France.

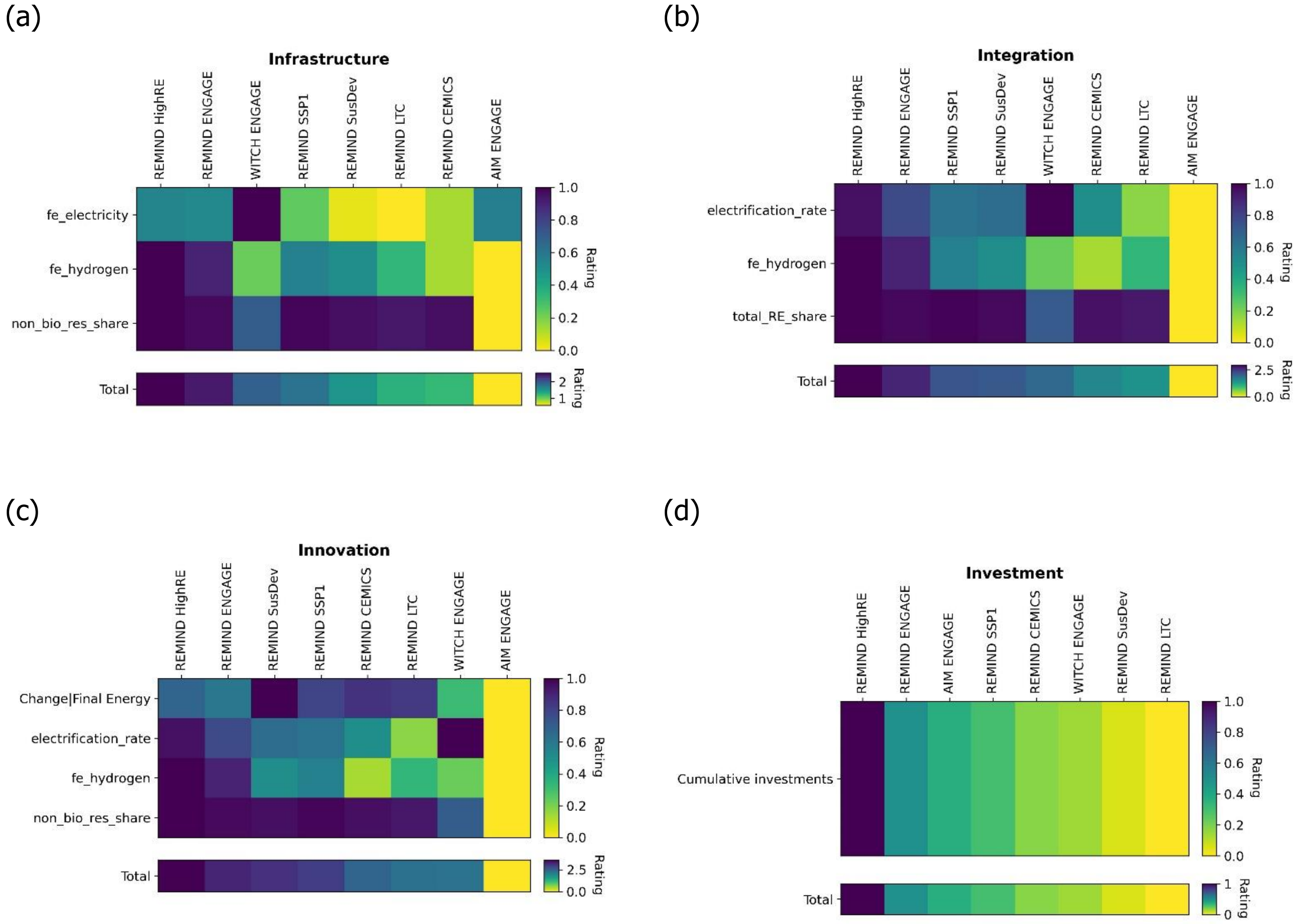


Figure A10|Pathway rating for each 4i dimension (France)

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then classify the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These pathway classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A5 shows which pathways are assessed as requiring low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A5|Pathway classification into low/medium/high categories (France)

This is done with respect to the level of transformation in infrastructure, innovation, integration and investment needs.

model	pathway	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	high
REMIND	CEMICS	low	low	medium	medium
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	high	medium	medium
	SusDev	medium	medium	high	low
WITCH	ENGAGE	high	medium	low	low

Finally, we cluster pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A11 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	0	0	2
Low	1	1	1

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	2	0	1
Medium	0	1	1
Low	1	1	1

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	0	1
Medium	0	2	0
Low	1	0	2

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	2	0	1
Medium	1	1	0
Low	0	1	2

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	0	1
Low	0	1	2

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	1	1	0
Low	0	0	3

Figure A11|Pathway classification into landing zones with respect to the 4i's (France).

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A range of results can be seen from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in the innovation dimension. There is also strong correlation between the level of infrastructure deployment in the pathway and the level of integration observed, with 75% of pathways sitting on the diagonal. This is partly due to the use of shared underlying indicators, but highlights that there are strong interlinkages between the transformative challenges facing the EU27. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate, isolated issues to be engaged with by policymakers.

A3.2 Relationship between the underlying indicators: France

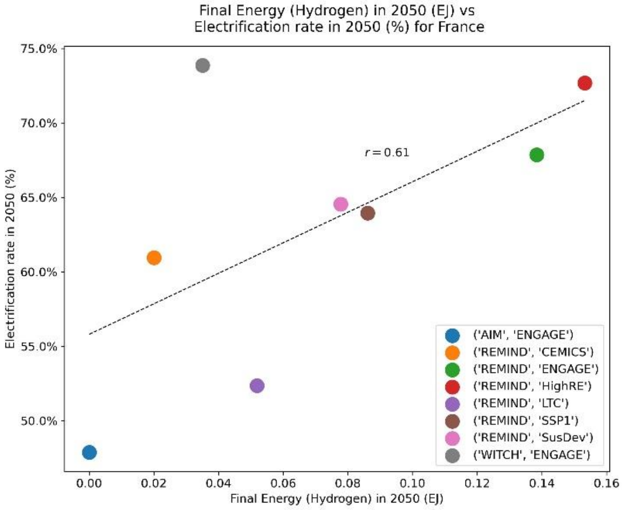
This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for France, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. Table A6 highlights the correlation (r-value) between each pair of underlying indicators.

Table A6| Correlations between different underlying indicators (France).

The darker the colour, the stronger the relationship between the two variables.

	Change| Final Energy	Cumulative investments	Electrification rate	fe_ electricity	fe_ hydrogen	non_bio_ res_share	total_RE_ share
Change| Final Energy	1.00	0.20	-0.22	0.76	-0.38	-0.88	-0.88
Cumulative investments	0.20	1.00	0.39	0.38	0.66	0.04	0.03
electrification _rate	-0.22	0.39	1.00	0.46	0.61	0.57	0.58
fe_electricity	0.76	0.38	0.46	1.00	0.03	-0.39	-0.39
fe_hydrogen	-0.38	0.66	0.61	0.03	1.00	0.62	0.63
non_bio_res_ share	-0.88	0.04	0.57	-0.39	0.62	1.00	1.00
total_RE_ share	-0.88	0.03	0.58	-0.39	0.63	1.00	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.30. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states on any particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some key relationships of interest are highlighted here.



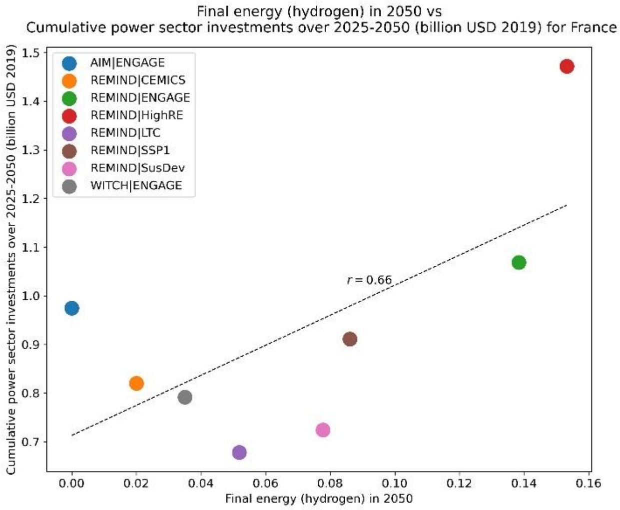


Figure A12|Relationship between selected underlying indicators (France).

Shows (a) Final Energy|Hydrogen in 2050 vs. Electrification rate in 2050 and (b) Final Energy|Hydrogen in 2050 vs. Cumulative power sector investments in 2050

Hydrogen can enable increased electrification of demand

Figure A12a shows the relationship between the level of hydrogen consumption in final energy in 2050, and the level of electrification in 2050. The positive correlation here suggests that, in the underlying pathways, hydrogen is an enabling factor in electrification. Greater deployment of hydrogen leads to greater levels of electrification of energy demand. This in turn increases the level of transformation across all three dimensions of infrastructure, integration and innovation.

Hydrogen integration linked to electricity system investments

Figure A12b shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here indicates that to enable integration of hydrogen playing a key role in the future energy system closely relates to additional investment needs in the power sector.

Appendix A4: Belgium

A4.1: Pathway classification with respect to 4i's: Belgium

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. Figure A13|Behaviour of underlying indicators (Belgium) displays the results for Belgium.

The 8 pathways selected represent a diversity of possible 1.5°C compatible futures for Belgium. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. The area where there is less variation across pathways is in the power sector. Here all but one pathway envisages a rapid transition towards 100% renewable electricity, with non-biomass renewables providing around 48-70% of electricity by 2030, rising to 75-96% by 2050. The one exception is the pathway produced by AIM/CGE 2.2, in which nuclear and fossil fuels equipped with CCS are also used as sources of low-carbon electricity. These sources provide around 58% of electricity generation in 2050 in this pathway, which explains the distinct behaviour. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for Belgium involves a transition towards 100% renewable electricity by 2050, with strong growth already achieved by 2030.

In the next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway. **Figure A14** shows the results in the case of Belgium.

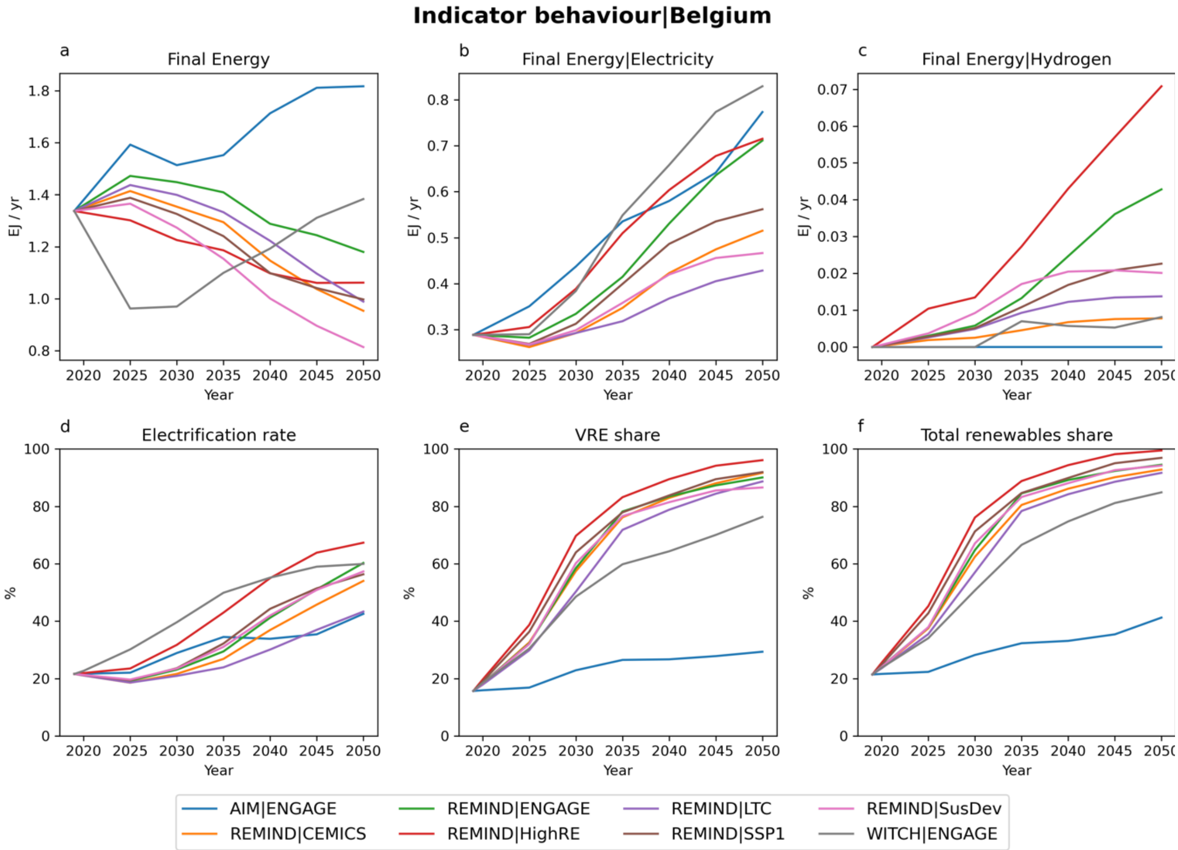


Figure A13|Behaviour of underlying indicators (Belgium).

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

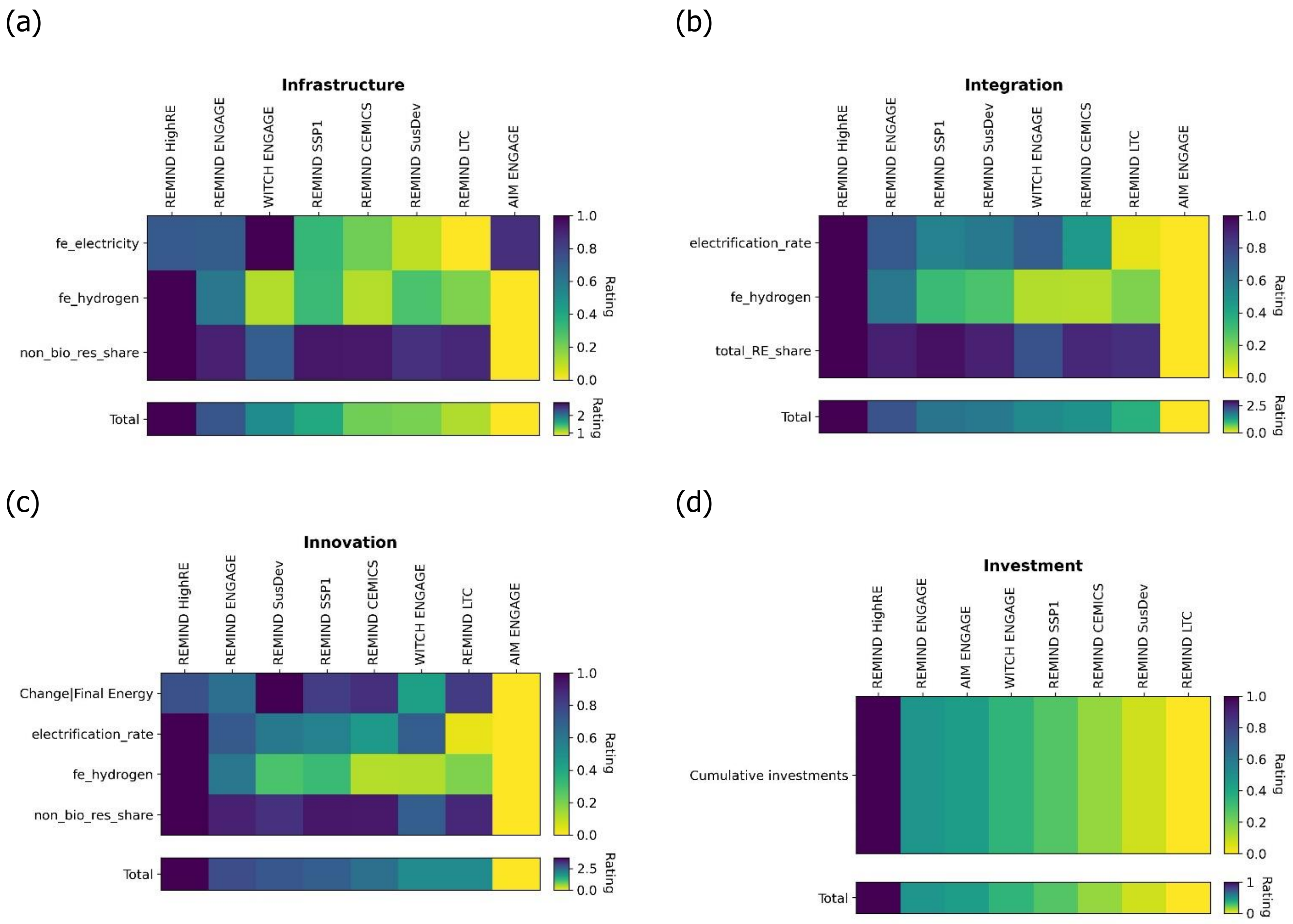


Figure A14|Pathway rating for each 4i dimension (Belgium)

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then classify the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These pathway classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A7 shows which pathways are assessed as requiring low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A7|Pathway classification into low/medium/high categories (Belgium)

This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment.

model	scenario	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	high
REMIND	CEMICS	medium	low	medium	low
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	high	medium	medium
	SusDev	low	medium	high	low
WITCH	ENGAGE	high	medium	low	medium

Finally, we cluster pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A15 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	0	1
Medium	0	1	1
Low	1	1	1

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	2	0	1
Medium	0	2	0
Low	1	0	2

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	0	1
Low	0	1	2

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	1	0	1
Low	0	1	2

Figure A15|Pathway classification into landing zones with respect to the 4i's (Belgium).

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A range of results can be seen from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in integration and infrastructure as well. There is also strong correlation between the level of innovation that occurs in the pathway, and the level of integration observed. All pathways sit on the diagonal. There is also some correlation between the level of transformation required in infrastructure and innovation, with 75% of pathways sitting on the diagonal. A similar interlinkage can be observed between pathways with high/low integration needs and high/low infrastructure needs This is partly due to the use of shared underlying indicators, but highlights that there are strong interlinkages between the transformative challenges facing the EU27 and Member States. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate, isolated issues to be engaged with by policymakers.

A4.2 Relationship between the underlying indicators: Belgium

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for Finland, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. Table A8 highlights the correlation (r-value) between each pair of underlying indicators.

Table A8| Correlations between different underlying indicators (Belgium).

The darker the colour, the stronger the relationship between the two variables.

	Change| Final Energy	Cumulative investments	Electrification rate	fe_ electricity	fe_ hydrogen	non_bio_ res_share	total_RE_ share
Change| Final Energy	1.00	0.30	-0.37	0.77	-0.33	-0.90	-0.89
Cumulative investments	0.30	1.00	0.59	0.67	0.76	-0.02	-0.02
electrification _rate	-0.37	0.59	1.00	0.30	0.74	0.60	0.64
fe_electricity	0.77	0.67	0.30	1.00	0.14	-0.47	-0.44
fe_hydrogen	-0.33	0.76	0.74	0.14	1.00	0.54	0.55
non_bio_res_ share	-0.90	-0.02	0.60	-0.47	0.54	1.00	0.99
total_RE_ share	-0.89	-0.02	0.64	-0.44	0.55	0.99	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.19. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states on any particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the level of electricity production), but others merit further investigation. One key relationship is highlighted here.

Hydrogen integration linked to electricity system investments

Figure A16 shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here indicates that to enable integration of hydrogen playing a key role in the future energy system closely relates to additional investment needs in the power sector.

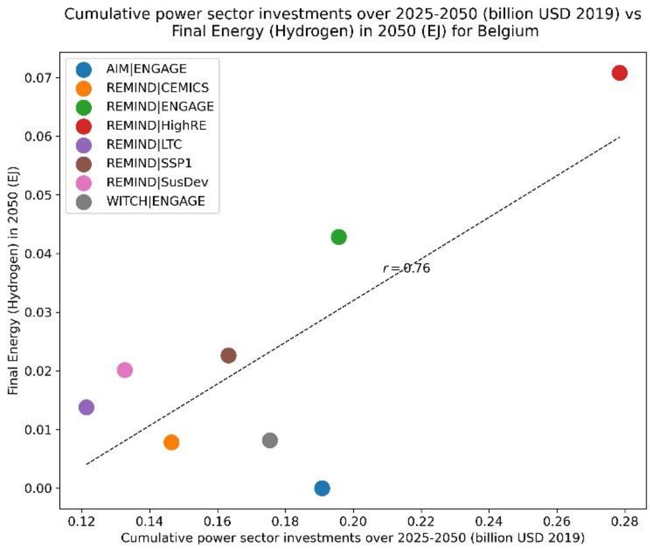


Figure A16|Relationship between selected underlying indicators (Belgium).

Shows cumulative investment vs. Final Energy|Hydrogen in 2050

Appendix A5: Poland

A5.1: Pathway classification with respect to 4i's: Poland

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. Figure A17 displays the results for Poland.

The 8 pathways selected represent a diversity of possible 1.5°C compatible futures for Poland. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. The area where there is less variation across pathways is in the power sector. Here all but one pathway envisages a rapid transition towards 100% renewable electricity, with non-biomass renewables providing around 69-98% of electricity by 2030, rising to 82-89% by 2050. The one exception is the pathway produced by AIM/CGE 2.2, in which nuclear and fossil fuels equipped with CCS are also used as sources of low-carbon electricity. These sources provide around 34% of electricity generation in 2050 in this pathway, which explains the distinct behaviour. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for Poland involves a transition towards 100% renewable electricity by 2050, with strong growth already achieved by 2030.

In the next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway. **Figure A18** shows the results in the case of Poland.

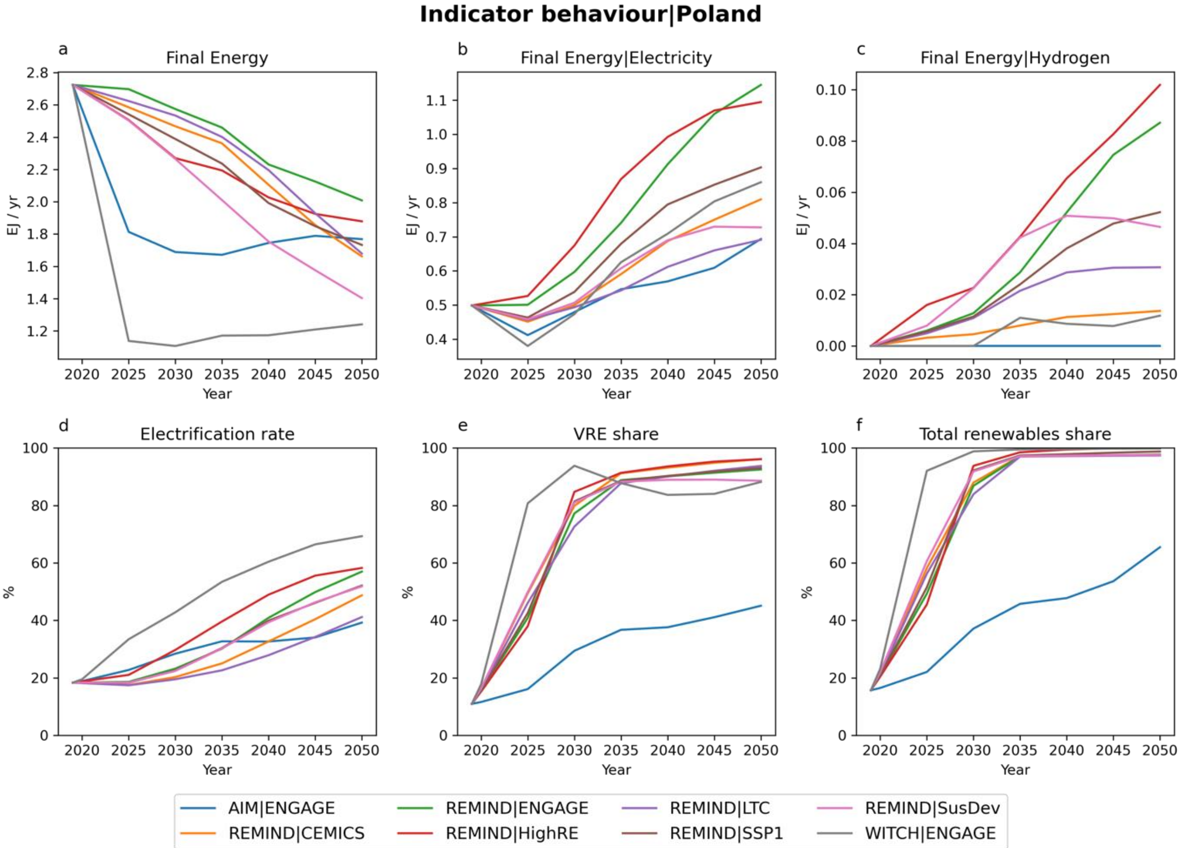
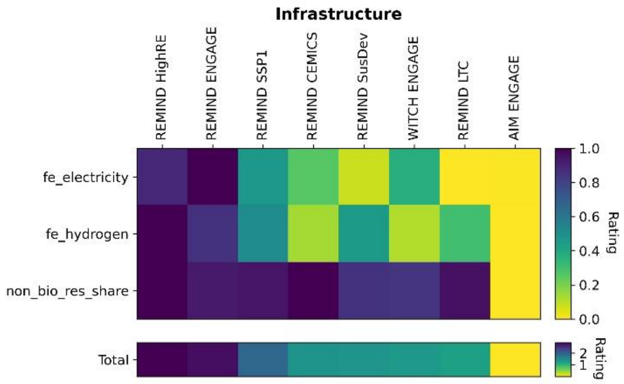


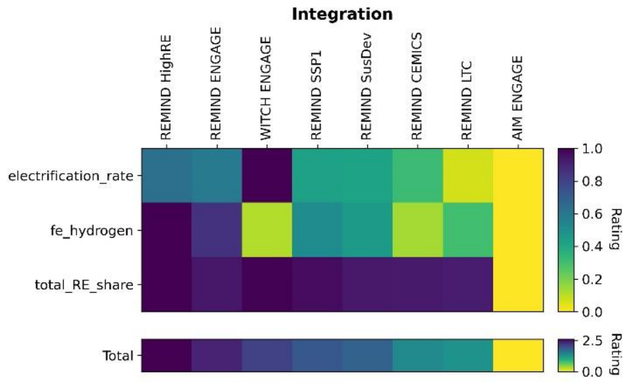
Figure A17|Behaviour of underlying indicators (Poland)

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

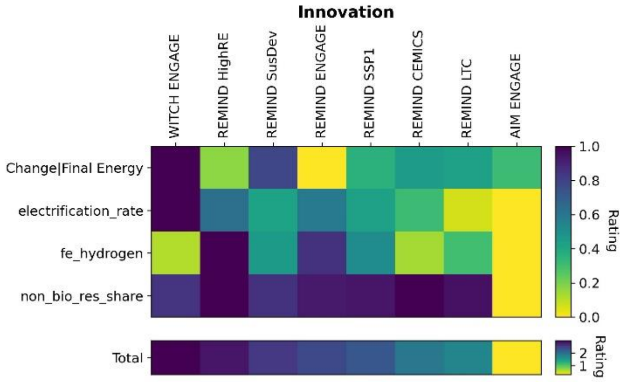
(a)



(b)



(c)



(d)

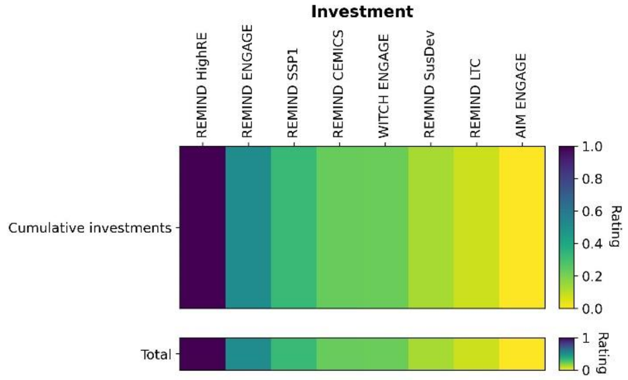


Figure A18| Pathway rating for each 4i dimension (Poland)

Showing (a), Infrastructure (b) Integration (c) Innovation and (d) Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then classify the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A9 shows which pathways are assessed as requiring low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A9|Pathway classification into low/medium/high categories (Poland).

This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment.

model	scenario	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	low
REMIND	CEMICS	medium	low	low	medium
	ENGAGE	high	high	medium	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	high	medium	medium	high
	SusDev	medium	medium	high	low
WITCH	ENGAGE	low	high	high	medium

Finally, we cluster pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A19 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	0	1
Low	0	1	2

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	1	1	1
Medium	2	0	0
Low	0	1	2

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	1	2	0
Medium	1	0	1
Low	1	0	2

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	1	0
Low	0	0	3

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

Figure A19|Pathway classification into landing zones with respect to the 4i's (Poland).

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A range of results can be seen from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in integration and infrastructure as well. There is also strong correlation between the level of innovation that occurs in the pathway, and the level of integration observed. All pathways sit on the diagonal. There is also some correlation between the level of transformation required in infrastructure and innovation, with 75% of pathways sitting on the diagonal. A similar interlinkage can be observed between pathways with high/low integration needs and high/low infrastructure needs This is partly due to the use of shared underlying indicators but highlights that there are strong interlinkages between the transformative challenges facing the EU27 and Member States. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate, isolated issues to be engaged with by policymakers.

A6.2 Relationship between the underlying indicators: Netherlands

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for Netherlands, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead.

Table A10 highlights the correlation (r-value) between each pair of underlying indicators.

Table A10|Correlations between different underlying indicators (Poland).
The darker the colour, the stronger the relationship between the two variables.

	Change| Final Energy	Cumulative investments	Electrification rate	fe_ electricity	fe_ hydrogen	non_bio_ res_share	total_RE_ share
Change| Final Energy	1.00	0.48	-0.34	0.55	0.57	-0.03	-0.17
Cumulative investments	0.48	1.00	0.49	0.87	0.86	0.47	0.44
electrification _rate	-0.34	0.49	1.00	0.59	0.34	0.47	0.60
fe_electricity	0.55	0.87	0.59	1.00	0.83	0.44	0.43
fe_hydrogen	0.57	0.86	0.34	0.83	1.00	0.52	0.49
non_bio_res_ share	-0.03	0.47	0.47	0.44	0.52	1.00	0.98
total_RE_ share	-0.17	0.44	0.60	0.43	0.49	0.98	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.47. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states on any particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the level of electricity production), but others merit further investigation. A few relationships are highlighted here.

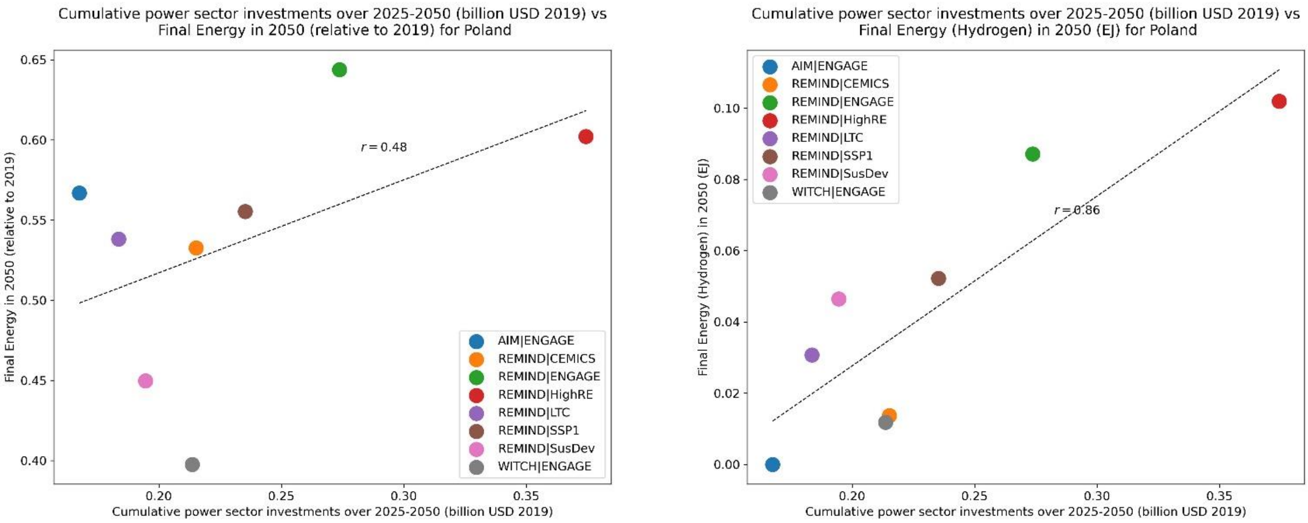


Figure A20|Relationship between selected underlying indicators (Poland).

Shows (a) Cumulative investments vs. Final Energy in 2050 and (b) Cumulative investment vs. Final Energy|Hydrogen in 2050

Demand reduction can reduce energy system investments

Figure A20a shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of final energy demand in 2050. The correlation between these indicators suggests that reducing final energy demand can help minimise investment needs (calculated here for the power sector alone). Therefore, greater transformation on the innovation dimension can reduce the scale of transformation required in investment dimension, if this innovation is focused on the demand-side.

Hydrogen integration linked to electricity system investments

Figure A20b shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here indicates that to enable integration of hydrogen playing a key role in the future energy system closely relates to additional investment needs in the power sector.

Appendix A6: Netherlands

A6.1: Pathway classification with respect to 4i's: Netherlands

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. Figure A21 displays the results for Netherlands.

The 8 pathways selected represent a diversity of possible 1.5°C compatible futures for Netherlands. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. The area where there is less variation across pathways is in the power sector. Here all but one pathway envisages a rapid transition towards 100% renewable electricity, with non-biomass renewables providing around 49-91% of electricity by 2030, rising to 82-97% by 2050. The one exception is the pathway produced by AIM/CGE 2.2, in which nuclear and fossil fuels equipped with CCS are also used as sources of low-carbon electricity. These sources provide around 40% of electricity generation in 2050 in this pathway, which explains the distinct behaviour. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for Netherlands involves a transition towards 100% renewable electricity by 2050, with strong growth already achieved by 2030.

In the next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway. **Figure A22** shows the results in the case of Netherlands.

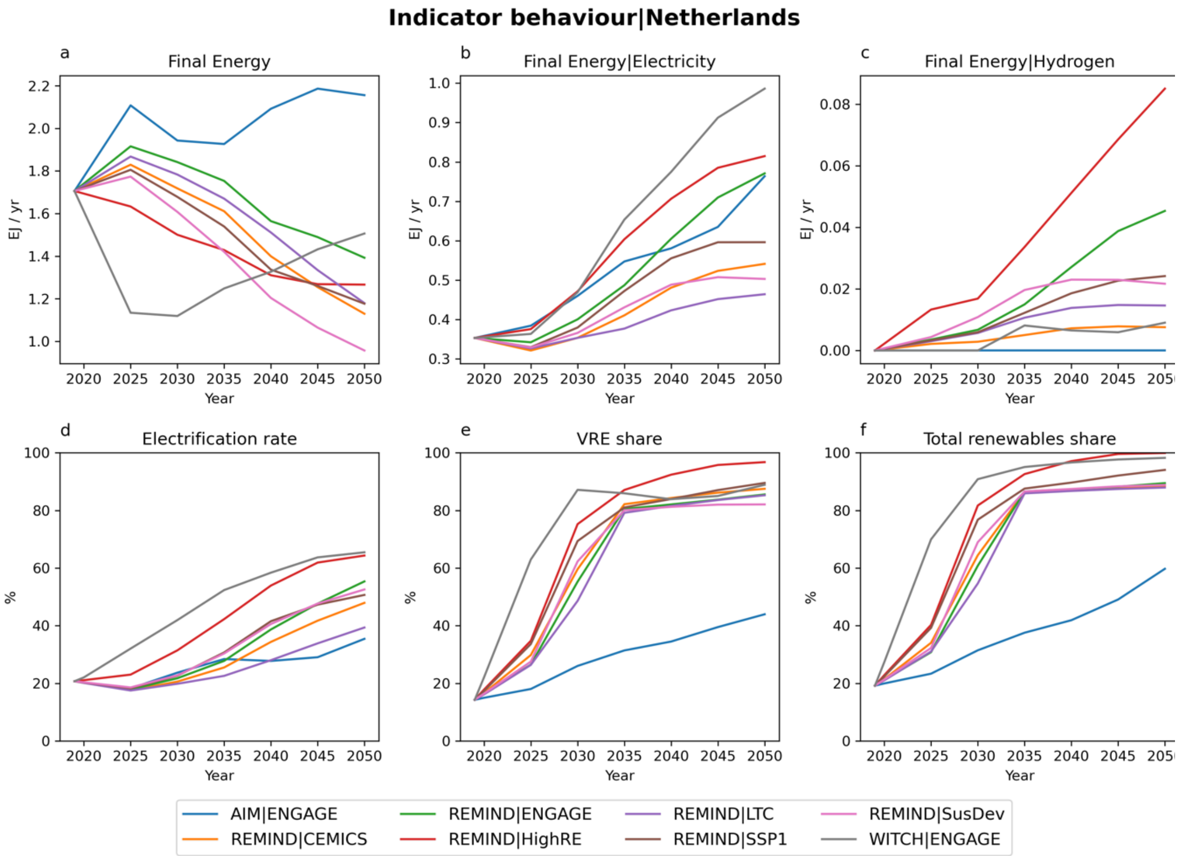


Figure A21|Behaviour of underlying indicators (Netherlands).

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

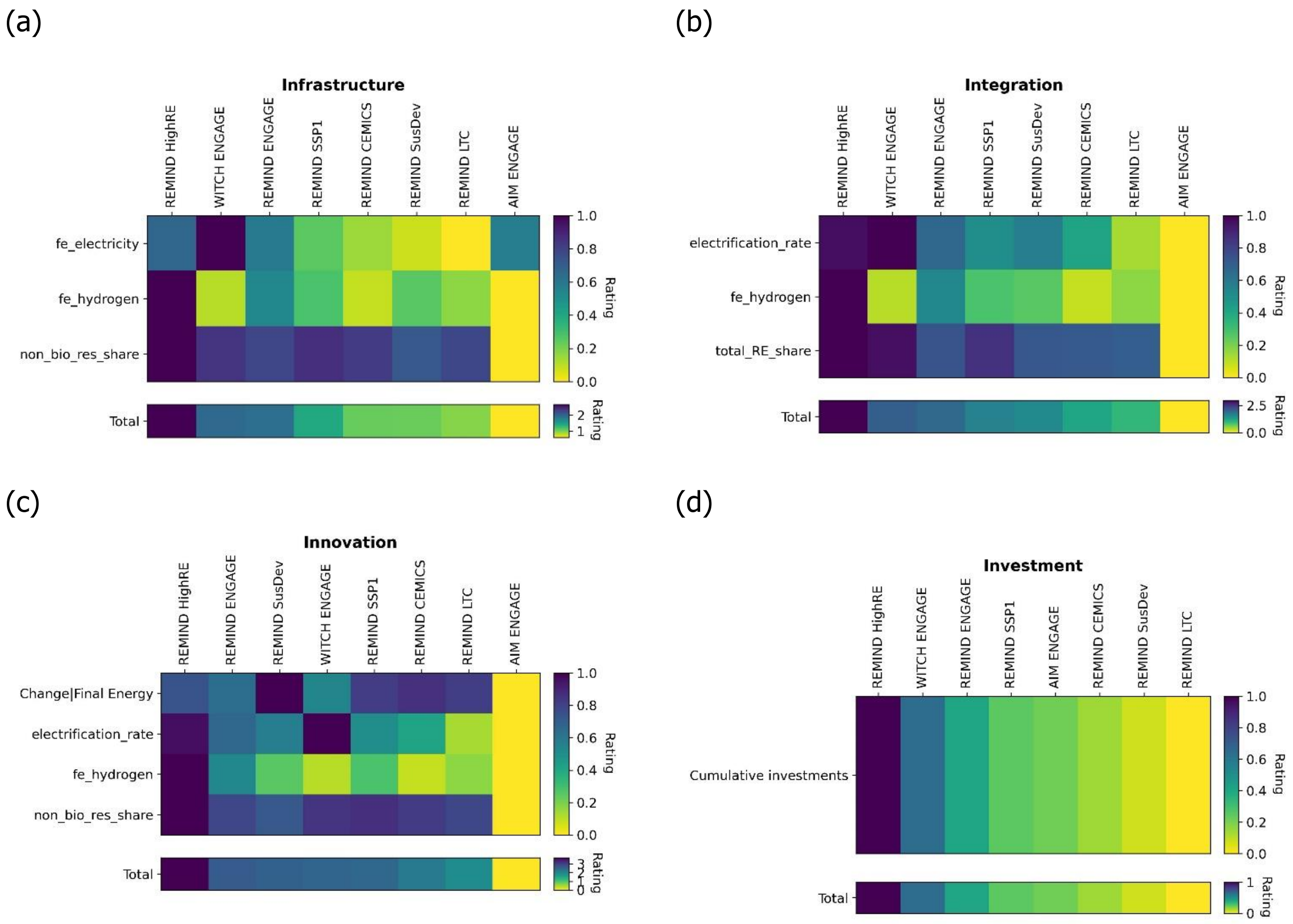


Figure A22|Pathway rating for each 4i dimension (Netherlands).

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then classify the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A11 shows which pathways are assessed as requiring low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A11|Pathway classification into low/medium/high categories (Netherlands)

This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment.

model	scenario	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	medium
REMIND	CEMICS	medium	low	low	low
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	medium	medium	medium
	SusDev	low	medium	high	low
WITCH	ENGAGE	high	high	medium	high

Finally, we cluster pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A23 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	0	1
Medium	1	1	0
Low	0	1	2

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	1	0
Low	0	0	3

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	1	1
Low	0	1	2

Figure A23|Pathway classification into landing zones with respect to the 4i's (Netherlands).

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructure, (e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A range of results can be seen from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in integration and infrastructure as well. There is also strong correlation between the level of innovation that occurs in the pathway, and the level of integration observed. All pathways sit on the diagonal. There is also some correlation between the level of transformation required in infrastructure and innovation, with 75% of pathways sitting on the diagonal. A similar interlinkage can be observed between pathways with high/low integration needs and high/low infrastructure needs This is partly due to the use of shared underlying indicators, but highlights that there are strong interlinkages between the transformative challenges facing the EU27 and Member States. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate, isolated issues to be engaged with by policymakers.

A6.2 Relationship between the underlying indicators: Netherlands

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for Netherlands, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. **Table A12** highlights the correlation (r-value) between each pair of underlying indicators.

Table A12| Correlations between different underlying indicators (Netherlands)

The darker the colour, the stronger the relationship between the two variables.

	Change| Final Energy	Cumulative investments	Electrification rate	fe_ electricity	fe_ hydrogen	non_bio_ res_share	total_RE_ share
Change| Final Energy	1.00	0.14	-0.33	0.55	-0.28	-0.81	-0.74
Cumulative investments	0.14	1.00	0.79	0.78	0.73	0.37	0.47
electrification _rate	-0.33	0.79	1.00	0.59	0.59	0.70	0.81
fe_electricity	0.55	0.78	0.59	1.00	0.24	-0.04	0.11
fe_hydrogen	-0.28	0.73	0.59	0.24	1.00	0.53	0.53
non_bio_res_ share	-0.81	0.37	0.70	-0.04	0.53	1.00	0.98
total_RE_ share	-0.74	0.47	0.81	0.11	0.53	0.98	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.32. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states on any particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the level of electricity production), but others merit further investigation. A few relationships are highlighted here.

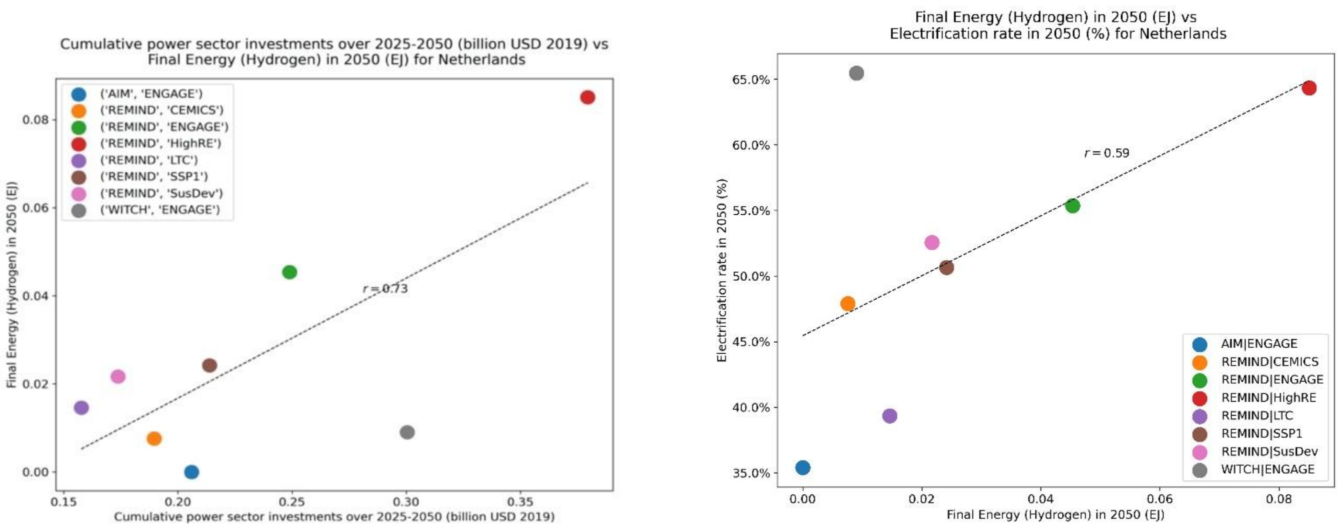


Figure A 24|Relationship between selected underlying indicators (Netherlands)

Shows (a) Cumulative investment vs. Final Energy|Hydrogen in 2050 and (b) Final Energy|Hydrogen vs. Electrification rate in 2050

Hydrogen integration linked to electricity system investments

Figure A24a shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here indicates that to enable integration of hydrogen playing a key role in the future energy system closely relates to additional investment needs in the power sector.

Hydrogen can enable increased electrification of demand

Figure A24b shows the relationship between the level of hydrogen consumption in final energy in 2050, and the level of electrification in 2050. The positive correlation here suggests that, in the underlying pathways, hydrogen is an enabling factor in electrification. Greater deployment of hydrogen leads to greater levels of electrification of energy demand. This in turn increases the level of transformation across all three dimensions of infrastructure, integration and innovation.

Appendix A7: Spain

A7.1: Pathway classification with respect to 4i's: Spain

In this section, we explore how the pathways perform across the four cross-cutting dimensions of transformation, the 4i's. To start with, we show how the underlying indicators which are used to evaluate the 4i's vary across the eight 1.5°C compatible pathways selected. Figure A25 displays the results for Spain.

The 8 pathways selected represent a diversity of possible 1.5°C compatible futures for Spain. Pathways vary strongly in the level of final energy demand, electricity and hydrogen consumption in the end-use sectors. The area where there is less variation across pathways is in the power sector. Here all but one pathway envisages a rapid transition towards 100% renewable electricity, with non-biomass renewables providing around 76-89% of electricity by 2030, rising to 94-99% by 2050. The one exception is the pathway produced by AIM/CGE 2.2, in which nuclear and fossil fuels equipped with CCS are also used as sources of low-carbon electricity. These sources provide around 32% of electricity generation in 2050 in this pathway, which explains the distinct behaviour. However, the emerging consensus from the assessed pathways is that 1.5°C compatible action for Netherlands involves a transition towards 100% renewable electricity by 2050, with strong growth already achieved by 2030.

In the next step, we classify the pathways into different levels of transformation for each of the 4i's. We use the linear ranking described in Section 3.3.2, in which for each underlying indicator, the maximum receives a score of 1 and the minimum level a score of 0. We then aggregate over all relevant indicators for each of the 4i's. This gives a measure of the level of transformation envisaged by each pathway. **Figure A26** shows the results in the case of Spain.

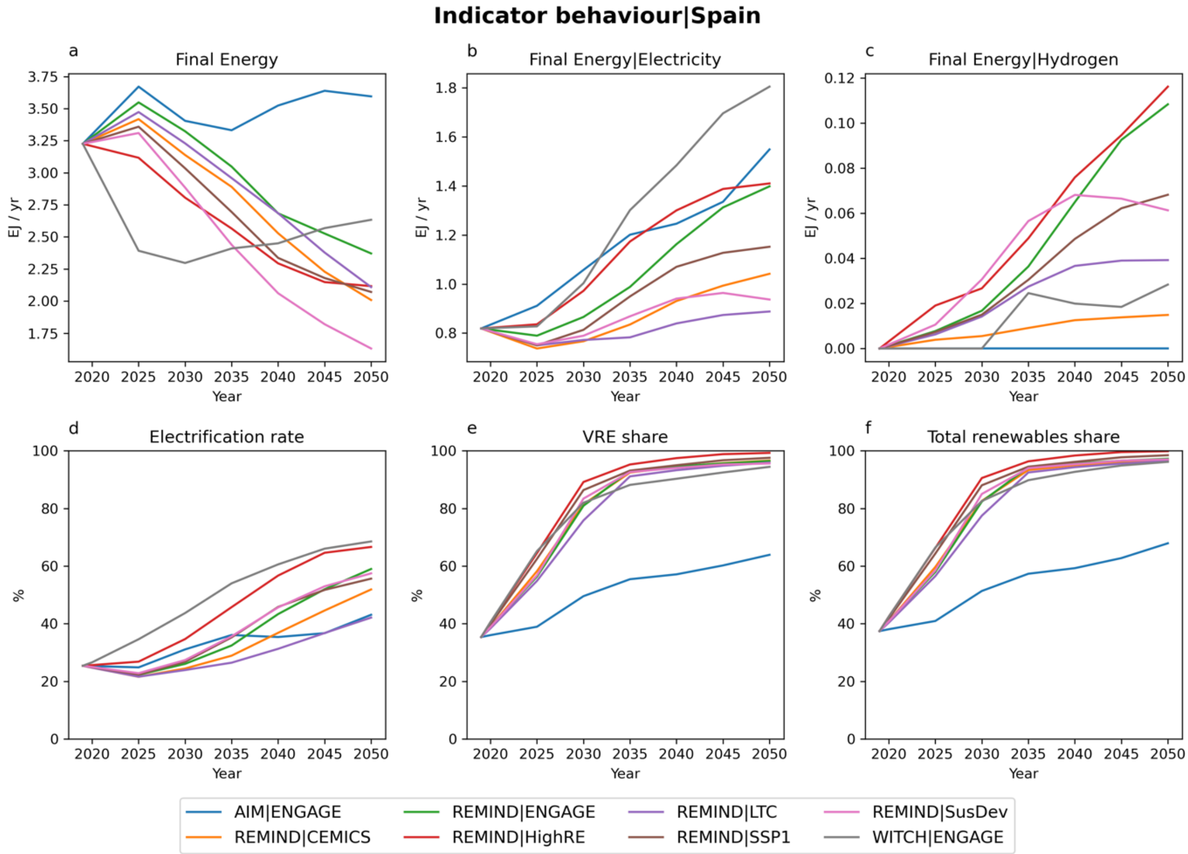


Figure A25|Behaviour of underlying indicators (Netherlands).

Showing (a) Final Energy, (b) Final Energy|Electricity, (c) Final Energy|Hydrogen, (d) Electrification rate (the share of final energy that is electric), (e) VRE share in the power sector, (f) Total renewables share

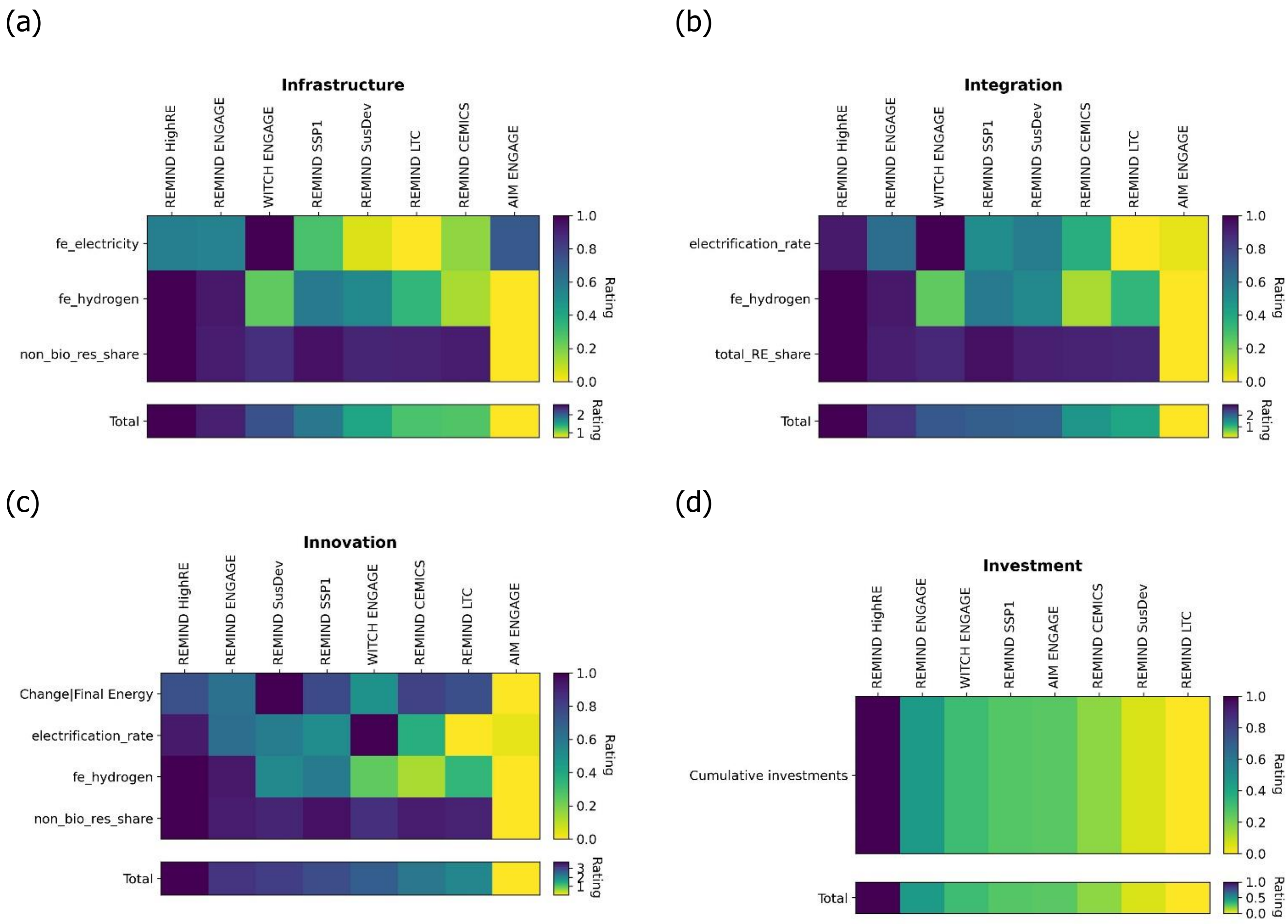


Figure A26| Pathway rating for each 4i dimension (Spain).

Showing (a), Infrastructure (b), Integration (c), Innovation and (d), Investment

This shows that the HighRE pathway produced by REMIND consistently demonstrates the greatest level of transformation across the 4i's, receiving the highest score in each of infrastructure, integration, innovation and investment. Meanwhile the pathway produced by AIM/CGE as part of the ENGAGE inter-model comparison project generally shows lower levels of transformation across the dimensions of infrastructure, integration and innovation, although this does not prevent it requiring large levels of investment in the power sector.

We then classify the pathways as requiring low, medium or high levels of transformation for each of the 4i's. These classifications are defined as follows:

- Low transformation: up to 33rd percentile
- Medium transformation: 33rd to 67th percentile
- High transformation: above 67th percentile.

Table A13 shows which pathways are assessed as requiring low/medium/high, regarding the level of transformation in infrastructure, innovation, integration and investment needs.

Table A13|Pathway classification into low/medium/high categories (Spain)

This is done with respect to the level of transformation in Infrastructure, Innovation, Integration and Investment.

model	scenario	Infrastructure	Integration	Innovation	Investment
AIM	ENGAGE	low	low	low	medium
REMIND	CEMICS	low	low	low	low
	ENGAGE	high	high	high	high
	HighRE	high	high	high	high
	LTC	low	low	low	low
	SSP1	medium	medium	medium	medium
	SusDev	medium	medium	high	low
WITCH	ENGAGE	high	high	medium	high

Finally, we cluster pathways into archetypal 'landing zones' concerning the 4i's. Each landing zone representing a different mode of achieving the Paris Agreement's goals. More pathways present in a particular landing zone means more evidence that this combination of indicators is 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving 1.5°C. Figure A27 shows landing zone plots for each combination of the 4i's.

(a)

Investment(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(b)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	0	1	1
Low	1	0	2

(c)

Investment(X) Innovation (Y)	High	Medium	Low
High	2	0	1
Medium	0	2	0
Low	1	0	2

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	2	1	0
Medium	1	1	0
Low	0	0	3

(e)

Innovation(X) Integration (Y)	High	Medium	Low
High	2	1	0
Medium	1	1	0
Low	0	0	3

(f)

Integration(X) Infrastructure (Y)	High	Medium	Low
High	3	0	0
Medium	0	2	0
Low	0	0	3

Figure A27| Pathway classification into landing zones with respect to the 4i's (Spain).

Showing (a) Investment vs. Integration, (b) Investment vs. Infrastructure, (c) Investment vs. Innovation, (d) Innovation vs. Infrastructur€(e) Innovation vs. Integration and (f) Integration vs. Infrastructure.

A range of results can be seen from these landing zone plots. The first is that there is a diversity of possible pathways that achieve the Paris Agreement goals, with different levels of transformation required. While certain dimensions of the energy transition are consistent across all pathways (e.g., the rapid scale up of renewables in the power sector), in other dimensions a range of possible low-carbon futures still remain. Decisions must still be made by policymakers on the form of transformation pathway that will be embarked upon. Secondly, some correlations can be observed across the 4i's. Pathways that have high/low investment needs often have high/low levels of transformation in integration and infrastructure as well. There is also strong correlation between the level of innovation that occurs in the pathway, and the level of integration observed. All pathways sit on the diagonal. There is also some correlation between the level of transformation required in infrastructure and innovation, with 75% of pathways sitting on the diagonal. A similar interlinkage can be observed between pathways with high/low integration needs and high/low infrastructure needs This is partly due to the use of shared underlying indicators, but highlights that there are strong interlinkages between the transformative challenges facing the EU27 and Member States. Transformation in one dimension can entail transformation in another dimension. Therefore, the challenges of infrastructure, integration, innovation and investment should be viewed as a joint challenge, rather than as separate, isolated issues to be engaged with by policymakers.

A7.2 Relationship between the underlying indicators: Spain

This report explores how transformation pathways differ across four key aspects of the energy transition. As seen above, there are a range of possible low-carbon futures for Spain, with diverse implications across the 4i's. At the same time, some relationships between the 4i's can be observed. The following section explores whether there are relationships between the underlying indicators which can help policymakers navigate through the transformation challenge ahead. Table A14 highlights the correlation (r-value) between each pair of underlying indicators.

Table A14|Correlations between different underlying indicators (Spain).

The darker the colour, the stronger the relationship between the two variables.

	Change| Final Energy	Cumulative investments	Electrification rate	fe_ electricity	fe_ hydrogen	non_bio_ res_share	total_RE_ share
Change| Final Energy	1.00	0.07	-0.28	0.69	-0.46	-0.88	-0.88
Cumulative investments	0.07	1.00	0.61	0.49	0.66	0.16	0.16
electrification _rate	-0.28	0.61	1.00	0.50	0.55	0.53	0.55
fe_electricity	0.69	0.49	0.50	1.00	-0.03	-0.36	-0.34
fe_hydrogen	-0.46	0.66	0.55	-0.03	1.00	0.59	0.59
non_bio_res_ share	-0.88	0.16	0.53	-0.36	0.59	1.00	1.00
total_RE_ share	-0.88	0.16	0.55	-0.34	0.59	1.00	1.00

Two results can be observed here. First of all, the average level of correlation between the underlying indicators is low, with average R^2 of 0.19. This highlights the continued degree of flexibility in the form of the energy transition. However, this flexibility should not be seen as a reason to defer climate action. Rather, it highlights the need for decisions to be made to guide the EU27 and member states on any particular transformation pathway. Second, despite the general lack of correlation between underlying indicators in the pathways, there are some areas where there is a clearer link between variables. Some of these correlations are unsurprising (such as between the level of investment in the power sector, and the level of electricity production), but others merit further investigation. A few relationships are highlighted here.

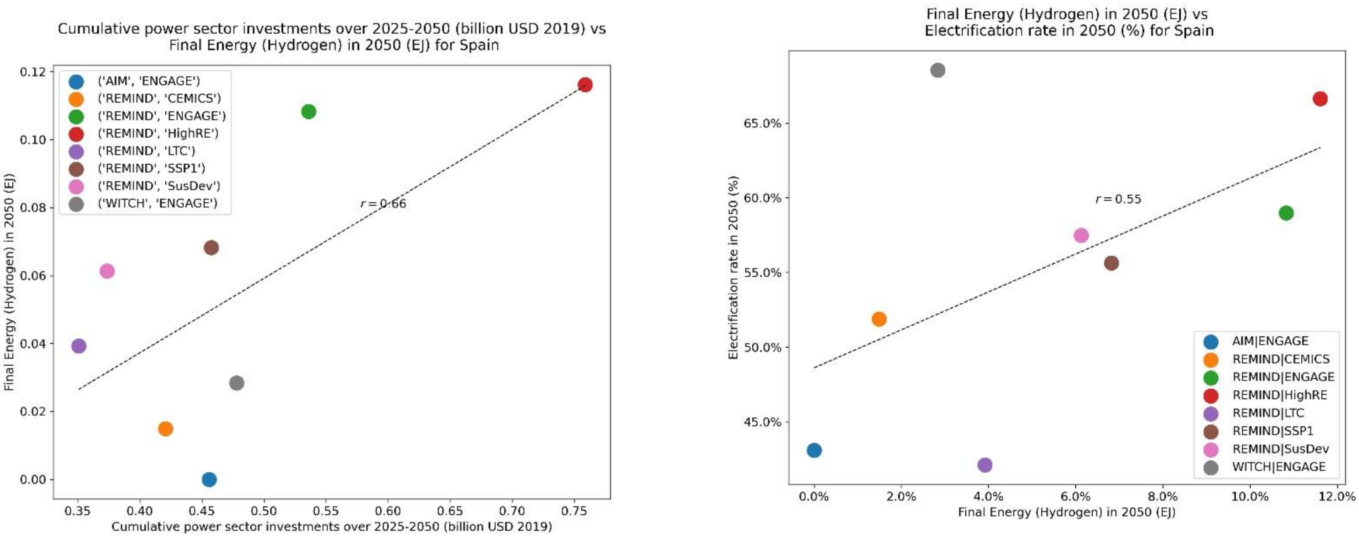


Figure A28|Spain results: Relationship between selected underlying indicators.

Shows (a) Cumulative investment vs. Final Energy|Hydrogen in 2050 and (b) Final Energy|Hydrogen in 2050 vs. electrification rate in 2050

Hydrogen integration linked to electricity system investments

Figure A28a shows the relationship between cumulative investments in the power sector for the selected pathways, and the level of hydrogen consumption in final energy in 2050. The positive correlation here indicates that to enable integration of hydrogen playing a key role in the future energy system closely relates to additional investment needs in the power sector.

Hydrogen can enable increased electrification of demand

Figure A28b shows the relationship between the level of hydrogen consumption in final energy in 2050, and the level of electrification in 2050. The positive correlation here suggests that, in the underlying pathways, hydrogen is an enabling factor in electrification. Greater deployment of hydrogen leads to greater levels of electrification of energy demand. This in turn increases the level of transformation across all three dimensions of infrastructure, integration and innovation.

Appendix B: Energy and emissions pathways used in this report

The report uses eight 1.5°C compatible pathways produced by integrated assessment models, which are downscaled to the EU and member state level using SIAMESE (Appendix C). This appendix describes the pathways, including the scenario assumptions applied and the model used to produce them, in greater detail.

Appendix B1: Integrated Assessment Models used in this report

The report uses pathways produced by three different IAMs: REMIND, WITCH and AIM. Each of these models is an example of a detailed-process integrated assessment model (Weyant 2017), which provides a detailed representation of the different technologies and strategies by which emissions could be reduced across all sectors of the economy.

All three models apply a general equilibrium framework, matching supply and demand for goods (including energy services) to find a 'cost-optimal' solution at each point in time. This means the pathways produced by these models represent a cost-effective strategy to achieve the Paris Agreement goals, which minimise the cost of decarbonisation (Clarke *et al* 2014). The assumption of general equilibrium, and the ability to identify cost-effective pathways, contrasts with non-equilibrium perspectives (Mercure *et al* 2019). Non-equilibrium based modelling can give very different results (Köberle *et al* 2021) and it would be valuable to additionally consider pathways produced using non-equilibrium perspectives.

Appendix B2: Pathways used in this report

This section provides additional information on the eight pathways used in this report.

ENGAGE pathways: AIM ENGAGE, REMIND ENGAGE and WITCH ENGAGE

These pathways are produced as part of the ENGAGE intermodelling comparison project (Riahi *et al* 2021). Each of them is generated by applying a limit to the cumulative emissions of CO_2 which can be emitted between 2020-2100 (a global carbon budget). This constraint needs to be met by 2100 – meaning that the model can overshoot the carbon budget before 2100, as long as it can reduce cumulative emissions to within the budget by 2100 using carbon dioxide removal. The size of the budget varies between pathways here, with the REMIND pathway using a 200GtCO_2 budget over 2020-2100, the AIM pathway using a 300GtCO_2 budget, and the WITCH pathway using a 400GtCO_2 budget. However, all three pathways therefore demonstrate the largest level of net negative CO_2 emissions, with CO_2 emissions falling below -10GtCO_2/y by 2100.

Each of these ENGAGE pathways uses the SSP2 socio-economic setup (Fricko *et al* 2017). This is a "middle of the road" future in which social, economic and technological developments do not shift markedly from historical trends.

CEMICS pathway

The CEMICS pathway is produced by the REMIND-MAgPIE integrated assessment model. It limits global CO_2 emissions to 600GtCO_2 from 2020 onwards. Unlike ENGAGE, this pathway explicitly limits the scale of net negative CO_2 emissions, which reduces the scale of temperature overshoot and decline that is possible in the pathways. However, it therefore is only able to achieve less stringent carbon budgets – with a budget of 600GtCO_2 being 400GtCO_2 larger than the REMIND ENGAGE pathway.

In addition, the CEMICS pathway uses the SSP1 socio-economic set up (van Vuuren *et al* 2017), which represents a shift to a more sustainable society. In the SSP1 socio-economic set-up, there is greater access to education, healthcare and modern energy, leading to improved equality within and between regions. As well as development progress, there are some shifts which help enable stronger climate action in this pathway. These include changes in consumption patterns towards low material growth, and greater progress in resource and energy efficiency. This therefore represents a pathway in which climate action occurs alongside broader progress towards sustainable development.

The CEMICS pathway is produced as part of a research project investigating the role of CDR in meeting climate targets (Strefler *et al* 2021). This particular pathway therefore includes CDR via BECCS, AR, enhanced weathering (EW) and limited Direct Air Carbon Capture and Storage (DACCS) deployment.

SSP1 pathway

The SSP1 pathway is broadly similar to the CEMICS pathway. It is also produced by the REMIND model, also uses the SSP1 underlying socio-economic setup, and also applies a global carbon budget of 500GtCO_2 from 2020 onwards, with limits to the scale of net negative CO_2 emissions that are achievable.

The key differences between the CEMICS and SSP1 pathway are that a) the SSP1 pathway is produced by the REMIND model in isolation, without coupling to the MAgPIE land-use model, and b) that in the SSP1 pathway, enhanced weathering is not available as a CDR option. As a result, the SSP1 pathway does not consider the possibility of removing CO_2 via afforestation or enhanced weathering. It relies on greater BECCS/DACCS deployment to limit total warming, as well as a stronger emphasis on emissions reductions.

LTC pathway

The LTC pathway is also produced by the REMIND energy-economy model, but this time without coupling this model to the MAgPIE land use model. Unlike the other pathways in this report, this pathway explicitly includes represents the damages from climate change on the economy. It does so by including a damage function which reduces economic output as a function of temperature increase in each region (Burke *et al* 2015). This function accounts for both instantaneous effects of climate damages, as well as long-run damages which have a persistence time of fifteen years (Schultes *et al* 2021).

The LTC pathway then finds the optimal pathway which minimises total costs (both mitigation costs and climate damages), while remaining under a given temperature threshold. This is a blended approach of cost-effectiveness analysis and cost-benefit analysis.

The LTC pathway limits total CO_2 emissions to around 700GtCO_2 from 2020 onwards, again using a formulation which explicitly limits the scale of net negative CO_2 emissions. This means it demonstrates less net negative CO_2 emissions than comparable ENGAGE pathways (although the 2020-2100 carbon budget it is therefore able to achieve is correspondingly larger). As in the CEMICS and SSP1 pathways, the LTC pathway also uses the SSP1 socio-economic setup.

SusDev pathway

The SusDev pathway is taken as an illustrative mitigation pathway in this report and used to perform an in-depth assessment of energy system transformation at the EU27 and member state level. It is produced by the REMIND-MAgPIE modelling framework.

This pathway has an explicit focus on achieving the Sustainable Development Goals alongside the Paris Agreement's long-term temperature target (Soergel *et al* 2021). It does so by combining ambitious climate policy with an additional sustainable development package, which includes international climate finance, a global transition to sufficient and healthy nutrition, and ambitious reductions in energy demand in developed countries.

The SusDev pathway focuses on achieving the SDGs while reducing emissions. In this pathway, there is a global shift to the EAT-Lancet planetary health diet (Willett *et al* 2019), which reduces pressure on land and enables zero malnutrition to be achieved by 2050. This involves substantial reductions in meat and dairy intake, and as a result there are very strong reductions in CH_4 and N_2O emissions from the agricultural sector. The pathway also envisages a transition away from energy-intensive lifestyles in the Global North, with strong reductions in demand in Europe. This enables rapid growth in energy demand in lower-income countries, that enables decent living standards to be achieved by all within planetary boundaries. As in the previous three REMIND pathways, the SusDev pathway uses the SSP1 socio-economic setup.

HighRE pathway

The HighRE pathway is taken as an illustrative mitigation pathway in this report and used to perform an in-depth assessment of energy system transformation at the EU27 and member state level. It is produced by the REMIND-MAgPIE modelling framework.

This pathway focuses on limiting warming to 1.5°C via a combination of rapid deployment of renewables and sectoral integration through electrification of end-use sectors (Luderer *et al* 2021b). There is explicit consideration of demand-side flexibility and battery storage to help integrate high shares of VRE into the power sector. Green hydrogen also plays a key role in providing long-term energy storage and driving sector coupling between industry/transport and the power sector.

The HighRE pathway uses the SSP2 underlying socio-economic set-up (Fricko *et al* 2017), in which social, economic and technological developments do not shift markedly from historical trends. As a result, there is relatively limited change in the demand for energy service demands, although energy efficiency improvements (particularly via electrification) still lead to strong reductions in final energy.

Appendix C: Downscaling methodology

Appendix C1: Energy sector downscaling: SIAMESE

The Simplified Integrated Assessment Model with Energy System Emulator (SIAMESE) is a reduced complexity IAM. SIAMESE is used to downscale the energy system transitions produced by global/regional IAMs (Sferra *et al* 2019). These models provide cost-effective energy and emissions pathways for a given *macro region*, but often do not provide results at the national or sub-national level. For example, the REMIND integrated assessment model provides data for the Europe region, which represents a set of 45 countries including the EU27 and a range of other non-EU countries such as Norway, Switzerland and the UK.

SIAMESE can be used to downscale these aggregated results to the required spatial resolution, accounting for the relationship between economic growth, energy consumption and associated emissions. SIAMESE provides downscaled energy consumption pathways for each country of interest, as well as national CO_2 emissions pathway for the energy sector. This can then be combined with non-energy CO_2 and non-CO_2 emissions pathways to give an economy-wide emissions pathway covering all relevant gases.

SIAMESE takes the energy consumption in the wider macro region and allocates it across the underlying countries that constitute this larger region. It does so by equating marginal fuel prices across all countries in the macro region. This gives a distribution of energy consumption across the underlying countries which maximises the total welfare of the macro region. By finding a cost-effective allocation of energy consumption and emissions across individual countries, SIAMESE mirrors the internal logic of IAMs and ensures consistency between the downscaled results and the initial model pathway used as an input.

SIAMESE is used to downscale final energy demand in the industry, buildings and transport sectors, as well as electricity generation in the power sector. Pathways are downscaled from the IAM macro region to the EU27 and member state level.

The downscaling process itself can be broken down into several sub-steps:

1. **The macro region containing the EU27 is defined**. This is usually a wider European region containing a range of non-EU27 countries as well as the EU27.
2. **Historical emissions and energy consumptions** are determined for all countries in the macro region for the base year (2019).
3. **Future emissions and energy consumption for the macro region** are obtained from to-be-downscaled 1.5°C compatible pathway.

4. **This data from the pathway is adapted to match historical data** in the base year. This process is called *harmonisation*. Harmonisation ensures that the pathways accurately represent the energy system in each country in 2019.
5. **The macro region's energy consumption is downscaled to the underlying countries using SIAMESE.** It is distributed to the countries in an internally consistent way, which preserves total consumption in the macro region and matches historical consumption in each country in the base year. To optimise computational performance, SIAMESE does not downscale countries which represent <1% of the macro region's GDP. In the downscaling algorithm, SIAMESE finds a fuel price equilibrium in which the marginal price of production for a given fuel is equivalent across all countries in the macro region. SIAMESE performs this downscaling routine for every time step in the model pathway.
6. **Once the consumptions are downscaled, then energy sector CO_2 emissions can be determined.** A calibration process is run which calculates emissions factors for coal, oil, gas and biomass in each sector. The calibration process aims to ensure that the sum of downscaled emissions equals the emissions pathway of the macro region as a whole. Once these emissions factors have been identified, total energy sector CO_2 emissions can be inferred.

Appendix C2: Downscaling non-energy CO_2 emissions and non-CO_2 emissions

SIAMESE is used to provide energy consumptions and energy sector CO_2 emissions pathways for the EU27 and selected member states. This then needs to be combined with data on non-energy CO_2 emissions and non-CO_2 emissions to give a complete emissions pathway. The following sections explain how this is undertaken in the analysis.

Agricultural emissions

The emissions on the macro region level for the agriculture sector are collected for each modelled pathway and harmonised to historical data using the Aneris harmonisation tool (Gidden *et al* 2019). The emissions for individual countries are determined by assuming their shares in the base year (2019) are constant over the whole scenario period, a simple downscaling methodology called *base-year pattern*.

Remaining energy system emissions

The remaining emissions for industrial processes, waste and non-CO_2 emissions in the energy sector are collected from each pathway and harmonised to historical data in 2019. To perform the downscaling from the macro region to the individual country level, a methodology based on *intensity convergence* is used; more specifically the Impact, Population, Affluence, and Technology (IPAT) method (van Vuuren *et al* 2007, Gidden *et al* 2019).

This assumes that emission intensities (the ratio of emissions to GDP) will converge from their values in the historical base year to the macro region intensity in the last year of the scenario data (here 2100). This is made possible by an exponential interpolation of emission intensities from the base-year to the convergence year. These emissions intensity trajectories in emissions/GDP are then combined with country-level GDP trajectories for the given SSP, to give country-level emissions pathways for industrial processes, waste and non-CO_2 energy sector emissions.

Global Warming Potentials

All historical and projected emissions series use global warming potentials from the IPCC's Fourth Assessment Report (AR4).

About the project

4i-TRACTION – innovation, investment, infrastructure and sector integration: TRAnsformative policies for a ClimaTe-neutral European UnION

To achieve climate neutrality by 2050, EU policy will have to be reoriented – from incremental towards structural change. As expressed in the European Green Deal, the challenge is to initiate the necessary transformation to climate neutrality in the future, while enhancing competitiveness, productivity, employment.

To mobilise the creative, financial and political resources, the EU also needs a governance framework that facilitates cross-sectoral policy integration and that allows citizens, public and private stakeholders to participate in the process and to own the results. The 4i-TRACTION project analyses how this can be done.

Project partners

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