Assessing and categorising the latest IPCC scenarios from the perspective of barriers and enablers in the context of the 4 I's

Research Report

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29/04/2022

Document information	
Project name:	4i-TRACTION
Project title:	Transformative Policies for a Climate-neutral European Union (4i-TRACTION)
Project number:	101003884
Duration	June 2021 – May 2024
Deliverable:	D 1.3 Report on assessing latest and categorizing IPCC scenarios from the perspective of barriers and enablers in the context of the 4 I's
Work Package:	WP1: Defining transformation and developing transformational scenarios
Work Package leader:	Climate Analytics
Task:	Task 1.2: Conceptual framing of transformative policies and the "four I's"
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Peer reviewed by / on	Reviewer 1: Bettina Kampman; CE Delft; 03/2022 Reviewer 2: Elina Brutschin; IIASA; 03/2022
Planned delivery date:	31/03/2022
Actual delivery date:	29/04/2022

Suggested citation

Aboumahboub, Tina, Himalaya Bir Shrestha, Andrzej Ancygier, Michiel Schaeffer, Nils Grant, Lara Welder, and Clare Waldmann (2022): Assessing latest and categorising IPCC scenarios from the perspective of barriers and enablers in the context of the 4 I's. 4i-TRACTION Deliverable D 1.3. Climate Analytics Institute; Berlin

Acknowledgements

The authors would like to thank the 4I Topic Leads (Anuschka Hilke, Bettina Kampman, Kati Kulovesi, Brendan Moore and Tomas Wyns) for the feedback they provided regarding indicator selection. The authors would also like to thank Bettina Kampman and Elina Brutschin for a thorough review of this report.

Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101003884.

Abstract

Holding global average temperature well below 2°C, while pursuing efforts to limit it to 1.5°C above pre-industrial levels, requires a substantial transformation across all economic sectors. Toward this aim, a systematic transformation needs to be implemented beyond sectoral approaches. For this purpose, a closer look at the changes needed in terms of investment, innovation, and infrastructure is essential. Also, it is essential to understand how sectoral integration – especially through smart electrification - can accelerate decarbonisation.

Related to the need for transformative change, this report focuses on four cross-cutting core challenges at the heart of the transformation effort that are critical for transformative climate action in the coming years and for the path towards net zero emissions by 2050. The "four I's" include: fostering Innovation, mobilising Investment and finance, rolling out the Infrastructure, and enabling greater Integration across sectors. In this scenario analysis exercise, we start from global 1.5°C compatible pathways from the latest available IPCC Integrated Assessment Model scenario ensemble, filter them based on temperature limit and basic sustainability criteria, and develop a new systematic framework for classifying transformation pathways and assessing their implications for those core challenges of transformation, the "four I's". We develop a set of archetypal 'landing zones', each of which describe different modes of achieving the goals of the Paris Agreement. This scenario classification allows to understand emergent enabling factors across scenarios and relate them to the "four I's".

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Abbreviations

4I	Innovation, Investment, Infrastructure, and Integration
A/R	Afforestation/Reforestation
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal

EJ/yr	Exajoule per year
EU	European Union
EVs	Electric Vehicles
FE	Final Energy
GHG	Greenhouse gas
GtCO2e	Giga tonnes of Carbon Dioxide equivalent
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPCC AR6	Sixth Assessment Report of IPCC
IPCC SR1.5	IPCC Special Report on 1.5°C
LTTG	Long Term Temperature Goal
LULUCF	Land Use, Land Use Change and Forestry
MtCO2e	Million tonnes of Carbon Dioxide equivalent
PA	Paris Agreement
RE	Renewable Energy
UNFCCC	United Nations Framework Convention on Climate Change
VRE	Variable Renewable Energy

Executive summary

Achieving the long-term temperature goal of the Paris Agreement (PA) requires a substantial transformation of all economic sectors. Related to the need for a transformational change in the context of the 4I-TRACTION project, our quantitative 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. In this report, we aim to operationalise the conceptualizations and taxonomy developed in (Görlach et al., 2022), by assessing them against the latest global Integrated Assessment Model (IAM) scenario literature.

Chapter 2 of this report first provides an overview of methodologies for comparative assessment of low-carbon scenarios. Chapter 3 describes the scenario assessment framework developed and applied throughout this report for evaluating global PA-compatible transformation pathways. Chapter 4 presents the results from the scenario assessment exercise, and finally, Chapter 5 draws conclusions.

The IPCC Special Report on 1.5°C (Intergovernmental Panel on Climate Change (IPCC), 2018) (SR1.5) provides a comprehensive assessment of transformation pathways compatible with the long-term temperature goal (LTTG) of the Paris Agreement. Those global mitigation pathways have been developed by a broad range of detailed process-based IAMs covering all sectors and regions over the 21st century.

We filter this scenario ensemble comprising 413 scenarios to include only "Below 1.5°C" and "1.5°C low overshoot" scenarios as assessed in IPCC SR1.5. This results in a set of 53 scenarios that are consistent with the temperature target of the Paris Agreement. Next, we apply sustainability filters for Carbon Dioxide Removal (CDR) via Bioenergy with Carbon Capture and Storage (BECCS) and Afforestation/Reforestation (A/R). As a result, 18 of the 53 scenarios pass the scenarios filter as shown in Table 1, which we explore further for the scenarios assessment exercise.

To assess what these scenarios mean for the 4I's, we identify the key indicators with a focus on mid-century, which reflect the scenario characteristics over time, and serve the purpose of evaluating global climate scenarios and classifying them. These include:

1. Infrastructure: Variable renewable energy (VRE) share in electricity generation mix, CCS volume, hydrogen production from biomass and electrolysis, and final electricity consumption

2. Innovation: VRE share in electricity generation mix, hydrogen production from biomass and electrolysis, electricity share in final energy use i.e. electrification rate, and change in final energy demand relative to the base year

3. Integration: Renewable energy (RE) share in electricity generation mix, electrification rate of final energy, and hydrogen production from biomass and electrolysis.

4. Investment: growth of investment in energy supply relative to the base year

Each indicator of the 4I dimensions is rated between 0 and 1 for each scenario in the ensemble. The quantification of these scenario indicators is available in Chapter 4 of the report. These scenario indicators are further classified into low, medium, and high categories based on the defined thresholds. The aggregate ratings of all corresponding indicators for each of the 4I dimensions are plotted and presented as heatmaps in Section 4.2.

As a result, we classify filtered scenarios into low, medium, and high impact categories for each of the 4I dimensions as shown in Figure 3. We then develop and cluster the scenarios into archetypal 'landing zones' concerning the 4I's, each representing a different mode of achieving the Paris Agreement's goals. In theory – colours match the number of scenarios in each category. More scenarios mean more evidence that these indicators are 'optimal' in energy-economic terms (balanced against other indicators) or necessary for achieving net zero emissions.

It is worth mentioning that even if the scenarios are clustered into the same landing zone, for instance with high infrastructure and innovation needs, the scenarios might differ in their characteristics and the various mitigation measures that they apply. For example, some might see strong electrification of demand sectors, while others might see a greater expansion of hydrogen production. This is the purpose of Chapter 4.3, which provides an in-depth assessment of the scenarios, looking into the detailed characteristics of individual scenarios.

The key findings of the scenario assessment exercise for 4I's can be summarized in the following points:

Key Findings:

- There is a diversity of pathways that could meet the PA goals. We identify scenarios with low, medium and high impact on all of the 4I's. There remains flexibility in the path towards climate neutrality, with a range of possible 'landing zones' that policymakers could aim for. It is therefore essential that a diversity of paths is explored and understood, so that decisions can be made on the relative merit of different landing zones across the 4I's.

- The assessment of 4I dimensions shows that scenarios with relatively higher energy efficiency tend to depend less on CCS, renewable hydrogen, or VRE integration to decarbonise the energy system. In addition, scenarios with higher penetration of VRE put less focus on CCS application.

- There is a strong positive correlation between VRE share in the electricity mix and electrification rate across scenarios. There exists a moderate correlation between RE share in the electricity mix and electrification rate across scenarios.

- However, there is no clear correlation between variables such as VRE share and energy efficiency improvements, and electrification rate and total CCS volume.
- There are limited scenarios (six out of 18 filtered scenarios) that report data for hydrogen production. Therefore, there are not enough data points to assess the correlation between hydrogen production and other variables.
- No clear correlation can be concluded between the energy system investments and the share of renewables in electricity generation. A high renewables future does not inherently require mobilising greater investment. This is partially due to the declining cost of renewable electricity, and because increases in RE investments are partially off-set by decreased investments in fossil fuels.

The framework we developed throughout this report provides a systematic approach to assess and classify the scenarios across the 4I dimensions. Some of the indicators used for assessing 4I's are reported directly by the scenarios; otherwise, we performed additional calculations where necessary. Not all scenarios provide the required data and indicators that we need for assessing 4I's across scenarios, which limits the analysis.

The scenario analysis we conducted allows identifying indicators that show strong correlations for the different "I's. For instance, in some scenarios high final electricity consumption coincides with a high VRE share in electricity to achieve complete decarbonisation of the energy system. This would lead to high infrastructure needs. On the other hand, other scenarios see a strong interlinkage and electrification of end-use sectors but may achieve complete decarbonization through demand reduction. High electrification rate of end-use sectors, as well as a high level of hydrogen production is seen across other scenarios, increasing the need for sectoral integration.

The scenario assessment tool we develop and apply in this report provides a flexible framework for quantification, comparison, and classification of scenarios while new scenarios, different thresholds, further dimensions, and indicators can be added in the future depending on the availability of model variables in the scenario ensemble.

The report indicates that there are different pathways to reach full decarbonization of the economy. While moving from incremental to transformative change requires increased investment in infrastructure and innovation, different sectors also need to interlink to take advantage of the potential to balance the electricity grid powered up to 81% by wind and solar energy. Renewables itself could provide up to 91% of electricity generation. At the same time, some trade-offs can be made on the path to a fully decarbonized economy.

These trade-offs will have an important impact on the economy before 2050 but even more afterward: relying on much higher shares of negative emissions but postponing transformative action will result in higher costs for future generations. Conversely, higher investments in innovation and the development of low carbon infrastructure will create a basis for the welfare of future generations.

The global long-term transformation pathways assessed in this report are based on the published IAM scenario literature in SR1.5. Those scenarios were mainly developed in 2017 or before that; thus, they do not keep track of recent technological developments and policy frameworks. Also, sustainability constraints and plausibility assessment of large-scale deployment of CDR technologies such as BECCS as well as nuclear, fossil fuel with CCS, and land-use options are not taken into account in those pathways.

Additional 1.5°C compatible pathways have been developed by the modelling community as a contribution to the upcoming IPCC 6th Assessment Report (AR6), taking into account both the IPCC assessments and the recent data on policies and technology markets, and costs. An addendum to this report is planned to incorporate those more up-to-date pathways that will be complementing the scenario ensemble analysed in this version of the report.

1. Introduction

In December 2015, parties adopted the Paris Agreement to combat climate change, enhance actions, and intensify investments towards a sustainable low-carbon future. The Paris Agreement's central aim is 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 it to 1.5°C (UNFCCC, 2021).

Achieving the long-term temperature goal (LTTG) of the Paris Agreement requires a substantial transformation of all economic sectors, including mobility, industry and buildings, along with the power sector. Toward this aim, a systematic transformation needs to evolve beyond sectoral approaches. Related to the need for a transformational change in the context of the 4I-TRACTION project, our quantitative 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. In this report, we aim to operationalise the conceptualizations and taxonomy developed in (Görlach et al., 2022), by assessing them against the latest global Integrated Assessment Model (IAM) scenario literature.

This report will first provide a literature background on the methodologies for comparative assessment of long-term decarbonisation scenarios in Chapter 2. Chapter 3 describes the new scenario assessment framework developed and applied throughout this report for evaluating global PA-compatible transformation pathways of global and regional emissions and energy mix. It presents the scenario benchmarking ensemble and elaborates on the selection of key indicators. Chapter 4 presents the results from scenario assessment and classification. Finally, Chapter 5 summarises the report and draws conclusions.

2. Background

The IPCC Special Report on 1.5°C (Intergovernmental Panel on Climate Change (IPCC), 2018) (SR1.5) provides a comprehensive assessment of transformation pathways compatible with the LTTG of the Paris Agreement. Those global mitigation pathways have been developed by a broad range of detailed process-based IAMs covering all sectors and regions over the 21st century.

The IAMs and energy-economy models applied in the development of such long-term climate stabilisation scenarios as assessed by IPCC SR1.5 are based on a diverse set of methodologies, functional structures, and assumptions about future growth of socio-economic drivers and technological development, for instance, with respect to the use of bioenergy and availability of carbon dioxide removal (CDR) technologies. Therefore, a strand of literature has focused on developing a diagnostic scheme and proposing key indicators to uncover divergent patterns of model behaviours. This would facilitate explaining why results differ among those models for a similar set of scenario boundary conditions (Harmsen et al., 2021; Kriegler et al., 2015). For instance, the paper by (Kriegler et al., 2015) proposes a set of indicators to characterize model responses to carbon price signals and test these in a study, including 11 global models. The recent follow-up study by (Harmsen et al., 2021) presents a set of indicators for the systematic assessment of the IAM models' behaviour and to identify their key differences.

Furthermore, evaluation and comparative analysis of low-carbon scenarios have been the focus of a few recent studies (Brutschin et al., 2021; German Environment Agency (UBA), 2021). For instance, the study by (German Environment Agency (UBA), 2021) outlines a set of criteria for the comparative and normative evaluation of long-term climate protection scenarios. An exemplary application of the catalogue of criteria to a German and French long-term scenario study is then performed to compare and assess the validity of climate protection scenarios. The study conducted in (Brutschin et al., 2021) applies a multi-dimensional assessment framework to evaluate and compare decarbonisation pathways from the IPCC Special Report on 1.5°C (Intergovernmental Panel on Climate Change (IPCC), 2018) and quantifies feasibility concerns across geophysical, technological, economic, socio-cultural, and institutional dimensions. Their framework allows identifying scenarios that might cross feasibility boundaries. The framework also allows highlighting, for instance, which scenarios are feasible from a technological perspective but assume rapid decarbonisation in regions with low institutional capacity, or which scenarios assume a conservative perspective with respect to demand-side transformation. The study by (Brutschin et al., 2021) identifies indicators and classifies scenarios across each of the feasibility dimensions of geophysical, economic, technological, sociocultural, and institutional feasibility. They apply strict thresholds for the categorisation of scenarios with respect to each feasibility dimension.

The study by (Warszawski et al., 2021) categorises the IPCC SR1.5 scenario ensemble for five key individual mitigation levers, including reduction of global energy demand, decarbonisation of energy production, development of land-management systems, and the pace and scale of deploying CDR technologies. For each of these levers, the scenarios are categorised between `reasonable`, `challenging` and `speculative` use by mid-century based on the `medium` and `high` upper bounds defined by various literature. The study finds that none of the SR 1.5◦C scenarios offer a fair chance of staying below 1.5◦C by the end of the century with reasonable use of the potential of mitigation levers. Achieving the 1.5◦C temperature target with no or low overshoot is feasible only if mitigation levers are utilised at levels that will be challenging to realise. Alternatively, 1.5◦C might be attainable with lower use of mitigation levers than implied in the scenarios on the condition that there are substantial mitigation levers that are not considered in the scenarios.

In the present study, we first apply sustainability filters (such as level of emissions from BECCS and LULUCF) to derive a subset of scenarios which are feasible with respect to sustainable global NET potentials. This subset of scenarios constitutes our benchmarking ensemble for further in-depth assessment of implications of different pathways for the 4I's. We then identify key indicators, assess, and classify scenarios across four dimensions of cross-cutting core challenges of transformation, the four I's.

In this report, we develop a new framework for assessing and classifying long-term transformation pathways with a focus on four core challenges of the transformation, the 4I's. We operationalise the conceptualizations and taxonomy developed in (Görlach et al., 2022) by assessing them against the latest global IAM scenario literature. Through mapping this taxonomy on the global scenario benchmarking ensemble, we will develop a set of archetypal 'landing zones', each of which describes a different mode of achieving the Paris Agreement's goals. The scenario assessment methodology applied in this report allows us to understand emergent enabling factors across those scenarios and relate them to the 4I's.

3. Systematic framework for scenario evaluation

The 1.5°C scenario ensemble we apply in this report incorporates scenarios assessed in the IPCC SR1.5 as a starting point[1]. The scenario ensemble data from IPCC SR1.5 utilised for filtering and clustering is obtained from (Huppmann et al., 2019). Figure 1 shows the methodology flowchart, summarising the major steps of our scenario assessment framework.

(i) We filter the scenario ensemble concerning the climate target and sustainability criteria

(ii) For each of the 4I dimensions, we select a set of relevant indicators, measuring scenario changes over time in relation to the corresponding "I"

(iii) We quantify the identified indicators across different pathways of the given scenario ensemble

(iv) We specify thresholds to define low, medium, and high classes for each indicator, and classify the scenarios into the so-called "landing zones", each representing a different mode of achieving the Paris Agreement's goals in relation to the 4I's.

[1] An addendum to this report is planned to also incorporate recent scenarios developed by the IPCC 6th Assessment Report that will be complementing this scenario assessment.

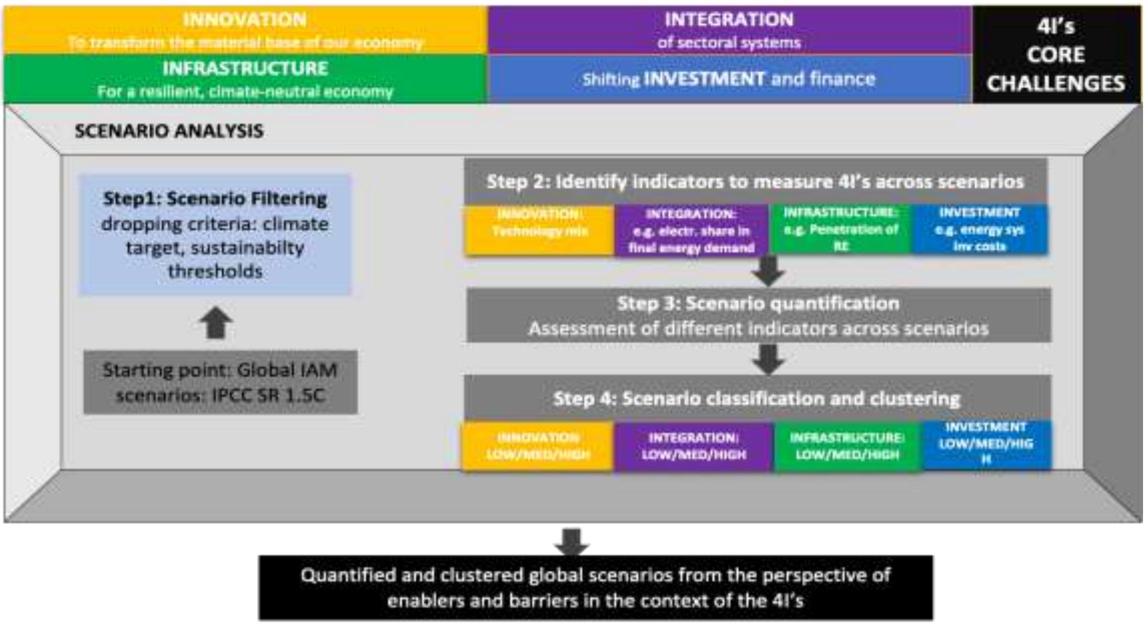


Figure 1 Methodology for scenario assessment as part of 4I-TRACTION project

The outcome of this assessment provides a quantified and clustered set of global 1.5°C transformation pathways from the perspective of 4I's. Later on, this will serve as the starting point for Project Task 1.3, where we aim to translate findings from global scenarios to the EU level and selected Member States.

Furthermore, the scenario assessment tool we develop and apply in this report provides a flexible framework for quantification, comparison, and classification of scenarios while new scenarios, different thresholds, further dimensions, and indicators can be added in the future depending on the availability of model variables in the scenario ensemble.

The following subsections further elaborate on the methodology applied at individual steps of our scenario evaluation framework.

3.1 Filtering scenarios

In the employed scenario ensemble, some scenarios do not incorporate the Paris Agreement LTTG or apply high (unsustainable) levels of CDR, either through biomass energy with carbon capture and storage (BECCS), afforestation/reforestation (A/R), or both. Therefore, as a first step, we apply the following criteria to filter and select a subset of scenarios that meet the primary objectives of sustainable transformative pathways in line with the Paris Agreement LTTG.

a. We filter this scenario ensemble to include only "Below 1.5°C" and "1.5°C low overshoot" scenarios as assessed in IPCC SR1.5. The only emission pathways from the IPCC SR1.5 that are in line with the Paris Agreement LTTG are those categorised as "no or low overshoot", i.e., scenarios that provide at least a 33% chance to keep warming to below 1.5°C over the course of the century and to limit warming to below 1.5°C in 2100 with at least 50% chance (Schleussner et al., 2016; Wachsmuth et al., 2018). This results in a set of 53 scenarios that are consistent with the temperature target of the Paris Agreement.

b. Within the employed scenario ensemble, many scenarios rely heavily on CDR, raising concern about the sustainability of these scenarios. Therefore, we apply sustainability thresholds for CDR via Bioenergy with Carbon Capture and Storage (BECCS) and Afforestation/Reforestation (A/R) as presented in (Fuss et al., 2018). Based on estimates in (Fuss et al., 2018), we apply a maximum global potential of 3.6 $GtCO_2$ yr−1 for A/R, and 5$GtCO_2$ yr−1 for BECCS.

In summary, only 18 of the 53 scenarios pass all the criteria presented above and are applied as a benchmarking ensemble for further scenario assessment in the following sections. The selected subset of scenarios is listed in **Table 1** below. Each scenario is given an abbreviation for ease of future reference. These scenarios provide a variety of different paths that can meet the Paris Agreement goals. This diversity is valuable as it allows a range of Paris-compatible energy system configurations to be identified, which may differ across the 4 I's. Some key characteristics by which scenarios can be identified are provided in the scenario characteristics column. In addition, the 4 scenarios for which all 4 I's can be quantified are given descriptive names which are used in Sections 4.2 and 4.3.

Table 1 Filtered scenario subset

Model	Scenario Name	Abbreviation: Descriptive name	Scenario characteristics*
AIM/CGE 2.0	SSP2-19	A1	Medium demand | High bioenergy | Medium CCS
AIM/CGE 2.1	TERL_15D_ LowCarbon TransportPolicy	A2	Medium demand | High bioenergy | High CCS
IMAGE 3.0.1	SSP1-19	I1: "Sustainable society"	Medium demand | High bioenergy | Medium CCS Uses the SSP1 set-up which has lower population growth & faster technological progress
IMAGE 3.0.1	IMA15-LiStCh	I2: "Lifestyle Change"	Medium demand | Medium bioenergy | High CCS Significant lifestyle changes assumed, including dietary change, modal shifts in transport and reduced energy demand in buildings
MESSAGE-GLOBIOM 1.0	SSP1-19	M1	Medium demand | High bioenergy | High CCS

MESSAGE-GLOBIOM 1.0	SSP2-19	M2	High demand | High bioenergy | Medium CCS | High nuclear
MESSAGEix-GLOBIOM 1.0	LowEnergy Demand	M3: "Low Demand"	Low demand | Low bioenergy | No CCS | Specific focus on demand reduction and efficiency improvements to reduce final energy demand
REMIND 1.7	CEMICS-1.5-CDR8	R1: "Rapid Action"	High demand | Medium bioenergy | Low CCS *Smaller carbon budget drives faster action*
WITCH-GLOBIOM 4.4	CD-LINKS_ NPi2020_400	W1	Medium demand | High bioenergy | Medium CCS | Strong non-CO2 mitigation
POLES EMF33	WB2C_nobeccs	P1	Medium demand | High bioenergy | Low CCS | No BECCS
POLES EMF33	WB2C_none	P2	Medium demand | High bioenergy | Low CCS | No advanced bioenergy technologies
POLES EMF33	WB2C_limbio	P3	Medium demand | Medium bioenergy | Low CCS | Reduced bioenergy availability
POLES EMF33	WB2C_cost100	P4	Medium demand | High bioenergy | Medium CCS | More expensive bioenergy technologies
POLES EMF33	WB2C_nofuel	P5	Medium demand | High bioenergy | Medium CCS | No modern biofuels
POLES EMF33	1.5C_cost100	P6	Medium demand | High bioenergy | Medium CCS | More expensive bioenergy technologies
POLES EMF33	1.5C_full	P7	Medium demand | High bioenergy | Medium CCS
POLES EMF33	1.5C_nofuel	P8	Medium demand | High bioenergy | Medium CCS | No modern biofuels
POLES EMF33	1.5C_limbio	P9	Low demand | Medium bioenergy | Low CCS | Limited bioenergy potential

* The scenario characteristics column provides a brief description of some key metrics by which scenarios differ. The classification of scenarios into high/medium/low levels of demand, bioenergy use and CCS deployment is performed as follows. Demand is quantified by Final Energy in 2100, with >500EJ: High demand, 300-500EJ: Medium demand, <300EJ: Low demand. Bioenergy is quantified by Primary Energy | Biomass in 2100, with >200EJ: High bioenergy, 100-200EJ: Medium bioenergy, <100EJ: Low bioenergy. CCS is quantified by CCS deployment in 2100, using the thresholds of >20GtCO_2/y: High CCS, 10-20GtCO_2/y: Medium CCS, <10GtCO_2/y: Low CCS

There are four scenarios, providing full data availability for our scenario analysis exercise, for which all 4I's can be quantified: I1, I2, M3 and R1. While all 18 scenarios are used in the rest of the analysis, these four scenarios feature particularly prominently. They are therefore given further descriptive names. Scenario I1 uses the SSP1 socio-economic set-up, and therefore envisages mitigation taking place in a sustainable society where there is rapid progress on low-carbon technologies, and an affluent low-population world works together to reduce emissions. It is therefore termed the 'sustainable society' scenario. Scenarios I2, M3 and R1 have a more conventional socio-economic setup that extrapolates past trends in GDP, population and urbanisation. The scenario I2 focuses on the role of lifestyle change in limiting warming to 1.5 °C, with dietary and modal shifts in transport a particular focus. This is termed the 'lifestyle change' scenario. M3 focuses on reducing final energy demand through accelerated progress on efficiency and dematerialisation and is thus termed 'low demand'. Finally, scenario R1 has the highest final energy demand of all scenarios. However, it also has the smallest carbon budget and therefore displays very rapid reductions in CO_2 emissions. It is called the 'rapid action' scenario. The rapid action scenario has faster mitigation of CO_2 emissions, but this is compensated for by reduced action on non-CO_2 emissions, particularly N_2O. As a result, it has a similar temperature outcome to the other scenarios, despite faster action to reduce CO_2 emissions.

3.2 Selection of indicators

In this section, we aim to identify key indicators which serve the purpose of evaluating global climate scenarios and classify them with respect to the 4I's. The selected indicators allow the measuring of scenario characteristics over time, identifying similarities and differences among scenarios, and enabling a transparent, comparative analysis. These indicators are either reported by the scenarios directly or we perform additional calculations where necessary.

For this purpose, we first propose a set of key guiding questions that serve as a starting point to identify the major groups of criteria for evaluating and classifying the global climate stabilisation scenarios.

- **How much** mitigation is achieved across scenarios?
- **How** will mitigation be achieved?
- At **which costs** will mitigation be achieved?

The first question assesses the scope and ambition of mitigation. This relates to the extent of emission reduction achieved by different mitigation pathways (ambition) as well as the time horizon, economic sectors, and greenhouse gases (GHG) covered in those scenarios (scope of mitigation). Scenarios also differ regarding mitigation options applied to decarbonise and transform the economy, which are addressed by the second question. The various mitigation options include, for instance, renewable technologies, Carbon Capture and Storage (CCS) applied to fossil fuels, nuclear energy, emerging technologies such as green hydrogen, CDR, sector coupling and electrification of demand sectors, energy efficiency, as well as behavioural and structural transitions. Finally, the third question assesses the costs associated with the decarbonisation of the economy towards net zero emissions. The following subsections provide the list of selected indicators for each 4I dimension.

3.2.1 Selection of indicators for 4I's - Infrastructure

Here, we identify indicators that reflect the level of infrastructure needs across the selected scenarios. Transition to energy systems powered mostly by variable renewable energy sources (VRES) such as solar and wind require a transformation of the current energy infrastructure, especially in storage and transmission infrastructure, to deal with the variable character of VRES. Furthermore, large-scale applications of CCS applied to fossil fuels for GHG emission reduction and to bioenergy to generate negative emissions can imply further infrastructure challenges. The production of hydrogen from renewable electricity to replace fossil fuels in the mobility and industry demand sectors imposes further infrastructure needs to the system. In addition, sector coupling and electrification of industry, transport, and building sectors leads to the growth of electricity demand, raising further challenges to satisfy the scaled-up infrastructure requirements. Below, we provide a list of indicators identified here, matched with public data availability of scenario data, to reflect the level of infrastructure needs across scenarios.

- VRE share: % share of electricity generation by variable renewable energies (solar, wind) in total generated electricity at a given year
- CCS volume: total sequestered carbon in $MtCO_2e$ via fossil CCS and BECCS at a given year
- Hydrogen production: Total hydrogen production from biomass and electrolysis in EJ at a given year
- Final energy (FE) – electricity: Final electricity consumption in EJ at a given year

3.2.2 Selection of indicators for 4I's – Innovation

In this section, we identify main indicators which capture the level of innovation needed across scenarios. A transformative change towards an emission-free energy system requires development of new technologies on both the supply and demand sides. The need for continued innovation in wind, solar PV, and energy storage is a key aspect to realise a fully renewables-based future energy system that achieves global net zero, or even negative GHG emissions. Emerging materials and new technologies might allow the generation of solar electricity with higher conversion efficiency and at lower costs. Substantial research and innovation are still needed to demonstrate the reliability and large-scale manufacturing capabilities of such new technologies. Similarly, novel wind turbines such as vertical-axis, floating offshore turbines, or other alternative wind energy technologies will enhance long-term wind energy's perspectives and support accelerating the deployment of wind energy. Advanced technologies allow the combination of bioenergy with CCS for power to generate negative emissions. Furthermore, the integration of hydrogen into future energy systems brings up further innovation needs. For instance, advancements in cell component material may enhance the performance and reduce the costs of electrolysers and fuel cells. Similar to the supply side, technological innovation is needed on the demand side, too. Electrification of demand sectors, for example via use of electric vehicles (EVs) in the mobility sector or heat pumps in buildings, scales up the innovation needs in future scenarios. Also, advancements in the energy efficiency of appliances and further measures to reduce the final energy demand require innovation. Below, we summarise the indicators identified to reflect the level of innovation needs across scenarios, again matched with public data availability of scenario data.

- VRE share: % share of electricity generation by variable renewable energies (solar, wind) in total generated electricity at a given year
- Hydrogen production: Total hydrogen production from biomass and electrolysis in EJ at a given year
- Electrification rate: % share of electricity in final energy consumption at a given year
- Final energy demand: Change in final energy consumption at a given year relative to base year

3.2.3 Selection of indicators for 4I's – Integration

In this section, we identify the main indicators reflecting a need for integration across sectors or for driving sectoral integration. Increasing the share of renewable energy sources across the scenarios is a key indicator, reflecting the growing need for integration of energy sectors. 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 demand sectors (end-use sector coupling) is one of the key strategies applied across scenarios to decarbonise the energy system. This can be achieved via direct electrification of demand via the use of electric vehicles (mobility sector), heat pumps (space heating), industrial heat, etc., as well as indirect electrification (e.g., via green hydrogen, synthetic fuels, etc.). This enables higher shares of renewables across the entire energy system beyond the power sector only, while increasing the flexibility of energy demand and providing further storage and balancing measures to the power system to deal with the intermittency of variable renewables. Below, we summarise the indicators identified to reflect the need for integration across sectors or for driving sectoral integration, again matched with public data availability of scenario data.

- RE share: % share of electricity generation by renewables (solar, wind, hydro, biomass, geothermal) in total generated electricity at a given year
- Electrification rate: % share of electricity in final energy consumption at a given year

- Hydrogen production: Total hydrogen production from biomass and electrolysis in EJ at a given year

3.2.4 Selection of indicators for 4I's – Investment

Scenarios also differ concerning the costs associated with the energy system transformation. To assess and classify the scenarios with respect to arising investment needs, we take the total energy system investment costs as reported directly by the scenarios over time. We quantify the growth of the total investments into energy supply in 2050 relative to the base year as a proxy to reflect the energy system investment needs across scenarios.

The list of key indicators that relate to each of the 4 I's allows to evaluate and compare the ambition level of the scenarios based on the 4I challenges of the transformation needed to achieve net zero emissions. These indicators for each scenario are matched with publicly available scenario ensemble data obtained from (Huppmann et al., 2019). It is worth mentioning that those indicators overlap across different 4I dimensions as elaborated in sections 3.2.1-3.2.4.

4. Scenario analysis

IAM scenarios assess the feasibility of achieving the proposed climate targets under given boundary conditions. The IPCC Special Report on 1.5°C (Intergovernmental Panel on Climate Change (IPCC), 2018) 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 scenario analysis we conduct in this report is mainly designed to quantify, compare, and classify those scenarios concerning the four cross-cutting core challenges of the transformation, the "four I's": 1) fostering breakthrough Innovation, 2) shifting Investment and finance, 3) rolling out the Infrastructure for a claimed neutral economy, and 4) Integration of solutions across sectors.

4.1 Quantification of indicators across scenarios

In this section, various indicators identified in Section 3.2 for each of the 4I's are quantified at global scale across the benchmarking scenario ensemble.

- VRE share in electricity generation: The share of wind and solar energy, as well as total VRE share in 2050, is depicted in Figure A 1 across various scenarios. The total VRE share varies between 41% and 81% with a median of 46% as assessed across the scenario ensemble's 18 pathways. For comparison, the 2019 level reached 9% (IEA, 2021) which needs to be extensively scaled up before 2050 according to the global PA-compatible pathways.

The study by (Jaxa-Rozen & Trutnevyte, 2020) depicted that the deployment of solar PV as a VRE technology has consistently outpaced expectations of various scenarios over the past decade owing to its growing cost-competitiveness. The study highlights that the long-term prospects of the solar PV remain deeply uncertain indicating the energy models employed, modelling institutions and policy assumptions as the chief reasons associated with the uncertainty (Jaxa-Rozen & Trutnevyte, 2020).

- RE share in electricity generation: The renewable share in electricity generation in 2050 is depicted in Figure A 2 across various scenarios. Total RE share varies between 62% and 91% with a median of 75% across 18 pathways of the scenario ensemble. For comparison, the 2019 level reached 28% (IEA, 2021), which needs to be extensively scaled up until 2050 according to the global PA-compatible pathways.

- CCS volume: Total sequestered carbon via fossil CCS and BECCS by 2050 is depicted in Figure A 3 across various scenarios. Total CCS volume varies between 0 and 15 $GtCO_2$/yr with a median of 5 $GtCO_2$/yr across 18 pathways of the scenario ensemble.

- Hydrogen: Hydrogen production from biomass and electricity as well as total hydrogen production in 2050 is visualised in Figure A 4 across various scenarios. Hydrogen production via biomass and electricity varies between 0 and 13 EJ/yr with a median of 10 EJ/yr. Total hydrogen production from all sources varies between 15 and 55 EJ/yr with a 31 EJ/yr median.

- Final electricity consumption: Final electricity consumption in 2050 is visualised in Figure A 5 across various scenarios. Final electricity consumption varies between 110 and 318 EJ/yr with a median of 132 EJ/yr across 18 pathways of the scenario ensemble. For comparison, the 2019 level reached 82 EJ (IEA, 2021). Thus, the scenario range varies between 1.3 to 4 times of 2019 level mainly driven by the electrification of demand sectors as one major mitigation strategy applied in the scenarios to decarbonise the energy system.

- Electrification rate: electrification rate in terms of % share of electricity in final energy consumption by 2050 is visualised in Figure A 6 across various scenarios. The electrification rate varies between 34% and 68% with a median of 40%. For comparison, the 2019 level reached 20% (IEA, 2021), far below the level achieved in global PA-compatible pathways.

The rapid decline in the cost of VRE technologies and battery storage in the recent years combined with the carbon pricing has contributed to make electricity more cost-competitive against carbon-based fuels (Luderer et al., 2021). In combination with demand-side innovation such as e-mobility and heat pumps, this is likely to induce a fundamental transformation of the energy systems towards a dominance of end uses. The study by (Luderer et al., 2021) shows that electricity could account for 66% of total final energy consumption by mid-century in a 1.5°C scenario with limited availability of BECCS.

- Final energy demand: Change in final energy consumption by 2050 relative to base year (2019) is shown in Figure A 7 across various scenarios. This indicator varies between 0.54 and 1.14 across scenarios with a median of 0.81.

- Energy investment growth: the growth of energy supply investments in 2050 relative to base year is visualised in Figure A 8 across various scenarios. This indicator varies between 0.9 and 3.7 with a median of 2.1 as assessed across 18 pathways of the scenario ensemble.

Scenario data statistics for various indicators identified for our scenario comparison exercise with respect to 4I's is summarised in Table 2. Historic data is also shown for comparison.

Table 2 scenario data statistics for 2050, for indicators identified for a scenario analysis with respect to 4I's

Indicator	Min	Max	Median	33rd percentile	67th percentile	Historic data 2019
VRE share	41%	81%	46%	43%	47%	9%
RE share	62%	91%	75%	69%	77%	28%
CCS volume	0	15 $GtCO_2e$/yr	4.7 $GtCO_2e$/yr	4.1 $GtCO_2e$/yr	7.5 $GtCO_2e$/yr	0
Hydrogen production from biomass and electrolysis	0.0044 EJ/yr	13.28 EJ/yr	8.71 EJ/yr	6.18 EJ/yr	9.66 EJ/yr	0
Final electricity consumption	110 EJ/yr	318 EJ/yr	132 EJ/yr	131 EJ/yr	141 EJ/yr	82 EJ/yr
Electrification rate of final energy	34%	68%	40%	40%	43%	20%
Final energy demand rel. to 2019	0.54	1.14	0.81	0.78	0.98	1
Energy Investment growth rel. to base year	0.90	3.70	2.1	1.95	2.31	1

Next, we define thresholds for each indicator based on the scenario data range obtained from indicator quantification across the scenario ensemble. We apply these thresholds to specify each indicator's low, medium, and high scenario classes and classify the scenarios accordingly for each indicator (cf. and Figure A 9).

Table 3 Thresholds for Low/Medium/High classification of scenarios

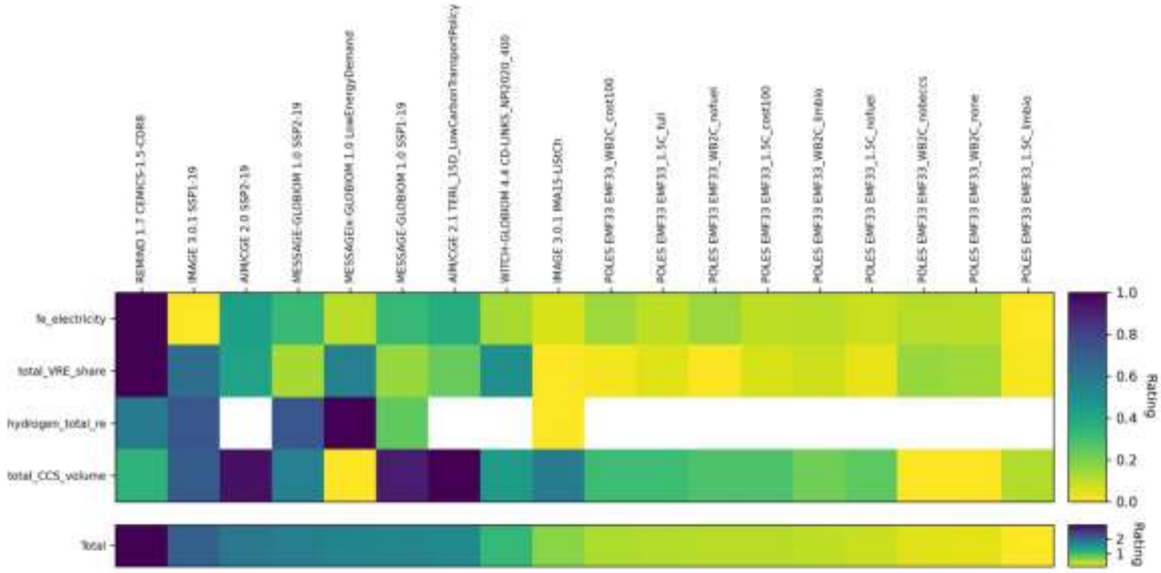
Indicator	Unit	Low	Medium	High	Historic data 2019
VRE share	%	41%≤x≤54%	54%<x≤68%	68%<x≤81%	9%
RE share	%	62%≤x≤72%	72%<x≤82%	82%<x≤91%	28%
CCS volume	GtCO$_2$e/yr	0≤x≤5	0.5<x≤10	10<x≤15	0
Hydrogen production from biomass and electrolysis	EJ/yr	0.0044≤x≤6.18	6.18<x9.66	9.66<x≤13.28	0
Final electricity consumption	EJ/yr	110≤x≤180	180<x≤249	249<x≤318	82 EJ/yr
Electrification rate of final energy	%	34%≤x≤45%	45%<x≤56%	56%<x≤68%	20%
Final energy demand rel. to 2019	-	0.54≤x≤0.74	0.74<x≤0.94	0.94<x≤1.14	1
Energy Investment growth rel. to base year	-	0.90≤x≤1.83	1.83x≤2.76	2.76<x≤3.70	1

4.2 Scenario classification

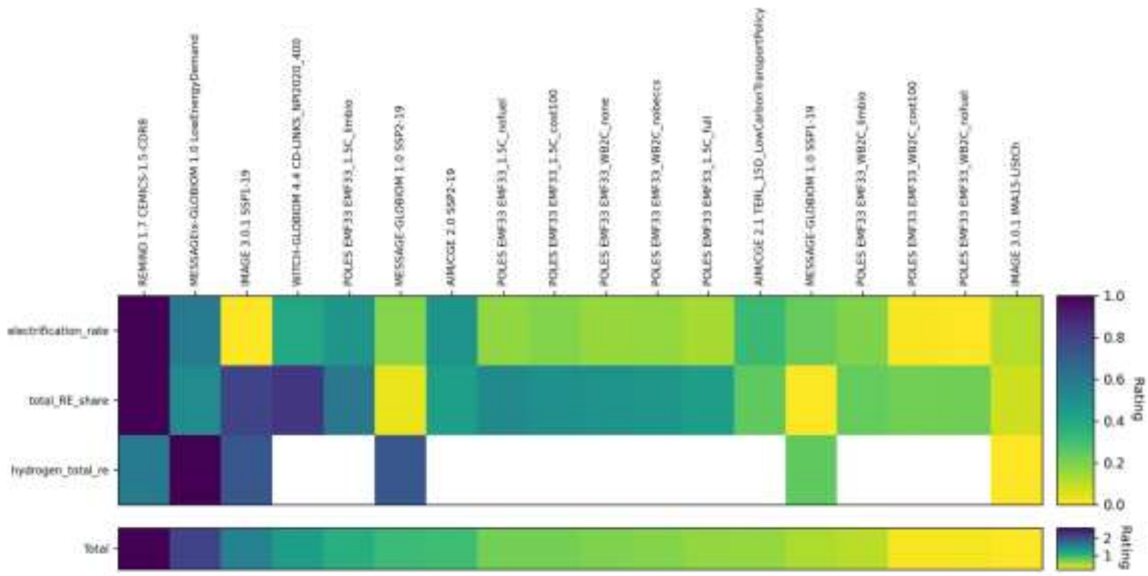
In this section, we cluster the global scenarios across the four major dimensions of the cross-cutting core challenges of transformation, the 4I's. For this purpose, we first rate all the identified indicators between 0 and 1 across the benchmarking ensemble's scenarios. For dimensionless indicators such as VRE share, RE share, and electrification rate, the rating is equivalent to the level as quantified from the scenario data (cf. Section 4.1). For other indicators such as final electricity consumption, hydrogen production from biomass and electrolysis measured in EJ/yr, and final energy demand, we rate the highest scenario as 1 and the lowest as 0; scenarios in between are rated between 0 and 1 accordingly. The energy system investment growth is calculated by taking the relative value of annual investment in 2050 to the base year (2020) from the scenario data.

For each of the 4I dimensions, we calculate a total rating by aggregating over all corresponding indicators. Figure 2 shows the indicator-specific and aggregated rating across the scenario benchmarking ensemble for each of the 4I's. For instance, the scenarios R1: "Rapid Action" and I1: "Sustainable society" are identified as most transformational scenarios with highest infrastructure needs within the benchmarking scenario ensemble. On the other hand, scenarios R1: "Rapid Action" and M3: "Low Demand" imply highest level of sectoral integration and innovation needs within the benchmarking scenario ensemble. Finally, scenarios I1: "Sustainable society" and I2: "Lifestyle Change" represent the highest growth in energy system investments within the benchmarking scenario ensemble.

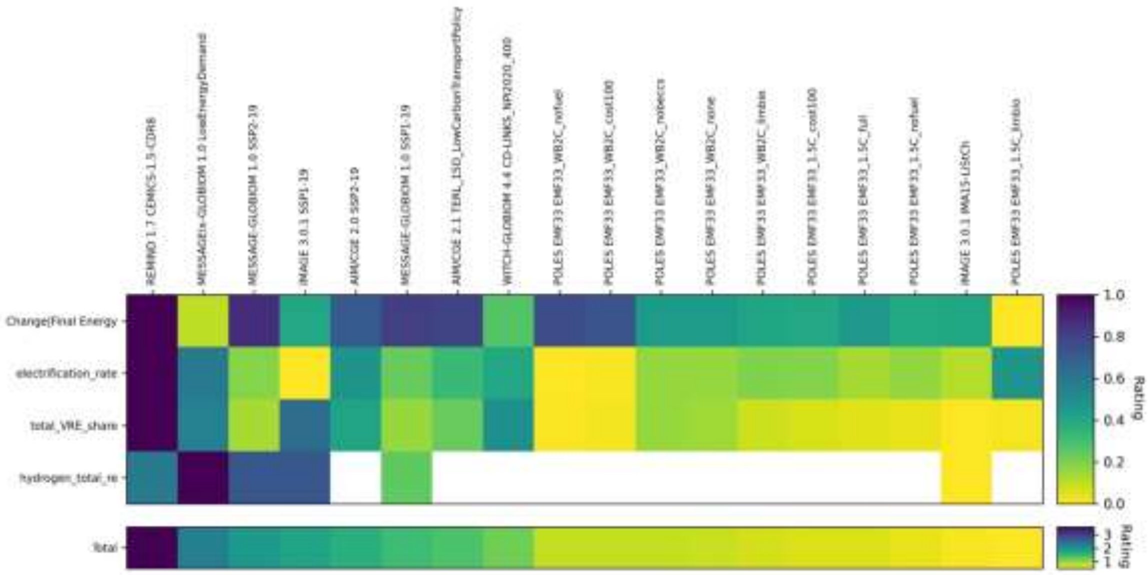
(a)



(b)



(c)



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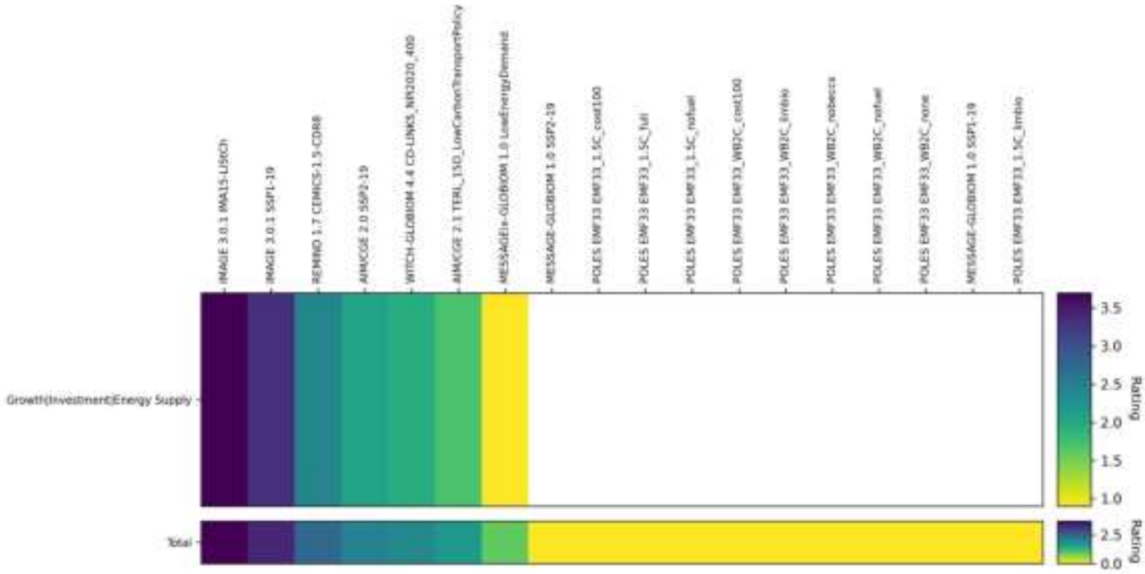


Figure 2 Scenario rating for indicators of 4I dimension: (A) Infrastructure (B) Integration (C) Innovation (D) Investment

After quantifying the aggregated rating over all corresponding indicators for each 4I dimension, we define the low, medium and high scenario classes based on the scenario percentile ranges (Low category: up to 33rd percentile, Medium category: 33rd to 67th percentile, High category: above 67th percentile). **Table 4** shows each 4I's specified ranges for low, medium, and high classification.

Table 4 Thresholds for Low/Medium/High scenario classification across 4I dimensions

4I's	33rd percentile	67th percentile	Low	Medium	High
Infrastructure	1.66	1.74	0.63≤x<1.66	1.66≤x<1.74	1.74≤x≤2.93
Innovation	0.05	0.99	-0.29≤x<0.05	0.05≤x<0.99	0.99≤x≤2.05
Integration	0.77	1.53	0.18≤x<0.77	0.77≤x<1.53	1.12≤x≤2.58
Investment	1.95	2.3	0.9≤x<1.95	1.95≤x<2.3	2.3≤x≤3.7

This assessment enables us to cluster all the scenarios of the given benchmarking ensemble into low, medium and high classes given the transformation's four core challenges. Figure 3 shows, for instance, which scenarios are assessed as low/medium/high regarding infrastructure, innovation, integration, and investment needs. It is worth mentioning transformation needs towards net zero emissions for each of these pathways is a challenging process. The classification into low/medium/high categories is presented only in relative terms based on comparing the scenarios from the benchmarking ensemble against each other with respect to indicators we assessed at global level.

While for some scenarios (e.g. I2: "Lifestyle Change"), we see slight acceleration of several indicators over next decades compared to their present-day value, other scenarios (e.g. R1: "Rapid Action", M3: "Low Demand" and I1: "Sustainable society") are classified as more transformational with significant acceleration of several key indicators such as renewable share, electrification rate, etc. over next decades (cf. Table A1). According to the ranges derived from those transformational scenarios, the share of renewables in global electricity generation mix rises from 28% today (9% VRE share) up to 91% by 2050 (81% VRE share). In scenario R1: "Rapid Action", the share of renewables reaches to 70% by 2030 already. Similarly, those transformational scenarios imply an acceleration of end-use sectors' electrification as the electrification rate of final energy rises from 20% today to 68% by 2050. Thus, scenarios R1: "Rapid Action", M3: "Low Demand", and I1: "Sustainable society" may be classified as more transformational pathways within the benchmarking scenario ensemble, in particular, as they score high/medium in several I's (cf. Figure 3).

model	scenario	scenario abbreviation	Infrastructure	Integration	Innovation	Investment
AIM/CGE 2.0	SSP2-19	A1				medium
AIM/CGE 2.1	TERL_15D_LowCarbonTransportPolicy	A2				low
IMAGE 3.0.1	IMA15-LiStCh	1: "Sustainable society"	low	low	low	high
	SSP1-19	I2: "Lifestyle Change"	high	medium	medium	high
MESSAGE-GLOBIOM 1.0	SSP1-19	M1	low	low	low	
	SSP2-19	M2	medium	medium	medium	
MESSAGEix-GLOBIOM 1.0	LowEnergyDemand	M3: "Low Demand"	medium	high	high	low
POLES EMF33	EMF33_1.5C_cost100					
	EMF33_1.5C_full					
	EMF33_1.5C_limbio					
	EMF33_1.5C_nofuel					
	EMF33_WB2C_cost100					
	EMF33_WB2C_limbio					
	EMF33_WB2C_nobeccs					
	EMF33_WB2C_nofuel					
	EMF33_WB2C_none					
REMIND 1.7	CEMICS-1.5-CDR8	R1: "Rapid Action"	high	high	high	medium
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_400					medium

Figure 3 Scenario classification into low/medium/high category with respect to Infrastructure/Innovation/Integration/Investment needs.
The dark orange, orange, and light orange colours represent high, medium, and low classes of the scenarios for the corresponding 4 I's, respectively. (Note: The scenarios which do not provide the required indicators for assessment are marked in grey.)

We then develop and cluster the scenarios into archetypal 'landing zones' concerning the 4I's, each representing a different mode of achieving the Paris Agreement's goals. Figure 4 visualises the subset of scenarios clustered into each landing zone regarding the 4I's. In our visualisation colours match the number of scenarios in each category. For instance, the scenario "R1: "Rapid Action" is classified under high infrastructure and innovation needs, while M3: "Low Demand" characterises high innovation and medium infrastructure needs. On the other hand, Scenarios I2: "Lifestyle Change" and "M1" represent low infrastructure and innovation needs in relative terms. Finally, scenario I1: "Sustainable society" is classified under the medium category with respect to both infrastructure and innovation again represented in relative terms (cf. Figure 4.a and Figure 4.b).

It is worth mentioning that even if the scenarios are clustered into the same landing zone, for instance with high infrastructure and innovation needs, the scenarios might differ with respect to their individual characteristics and the various mitigation measures that they apply. For example, some might see strong electrification of end-use sectors, while others might move towards high penetration of renewables or high application of CCS to decarbonise the energy system. This is the purpose of the following section, which provides an in-depth assessment of the scenarios, looking into the detailed characteristics of individual scenarios.

(a)

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

(b)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	R	I1	[]
Medium	M3	M2	[]
Low	[]	[]	I2, M1

(c)

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

(d)

Innovation(X) Infrastructure (Y)	High	Medium	Low
High	R	I1	[]
Medium	M3	M2	[]
Low	[]	[]	I2, M1

(e)

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

(f)

Investment(X) Infrastructure (Y)	High	Medium	Low
High	I1	R	[]
Medium	[]	[]	M3
Low	I2	[]	[]

(g)

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

(h)

Innovation(X) Integration (Y)	High	Medium	Low
High	R, M3	[]	[]
Medium	[]	I1, M2	[]
Low	[]	[]	I2, M1

(i)

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

(j)

Innovation(X) Investment (Y)	High	Medium	Low
High	[]	I1	I2
Medium	R	[]	[]
Low	M3	[]	[]

(k)

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

(l)

Integration(X) Investment (Y)	High	Medium	Low
High	[]	I1	I2
Medium	R	[]	[]
Low	M3	[]	[]

Figure 4 Scenario clustering into landing zones with respect to 4I's.
(a) Infrastructure Innovation: number of scenarios (b) Infrastructure Innovation: scenario abbreviations (c) Integration Infrastructure: number of scenarios (d) Integration Infrastructure: scenario abbreviations (e) Investment Infrastructure: number of scenarios (f) Investment Infrastructure: scenario abbreviations (g) Integration Innovation: number of scenarios (h) Integration Innovation: scenario abbreviations (i) Investment Innovation: number of scenarios (j) Investment Integration: scenario abbreviations (k) Investment Integration: number of scenarios (l) Investment Innovation: scenario abbreviations Note: (grey = no evidences, light orange = less evidences, orange = moderate evidences, dark orange = more evidences)

4.3 In-depth scenario assessment

Table A1 provides a summary of key characteristics of global 1.5°C compatible pathways and includes the level of indicators in 2030 and 2050 across all scenarios of benchmarking ensemble with partial or full data availability as required for our scenario analysis exercise. The full set of indicators required for the assessment and classification of global scenarios is made available only for four scenarios, including scenarios I1: "Sustainable society" and I2: "Lifestyle Change" from the IMAGE model, The scenario M3: "Low Demand" by the MESSAGEix-GLOBIOM model and the R1: "Rapid Action" scenario from the REMIND model. Thus, we particularly focus on this subset of scenarios with full data availability for a more in-depth assessment of scenario characteristics and comparative analysis[2].

In these scenarios, ongoing efficiency improvements hold the total energy demand from rising, with the exception of Scenario R1: "Rapid Action". The total energy demand declines by about 40% in scenario M3: "Low Demand" which by design has a particular focus on reduction of demand as a mitigation strategy (cf. Figure A 10). According to Figure A 10, coal use is nearly phased out by 2035 in the R1: "Rapid Action" scenario, followed by the decline in oil and gas, and they constitute a negligible share of total energy use by 2050. The fossil generation is replaced by scaled-up contribution from renewables, reaching 77% (Scenario M3: "Low Demand") to 91% (Scenario R1: "Rapid Action") by 2050 – with the high share in the latter mirroring its relatively higher energy demand by necessity, to still reach low PA-compatible emissions. However, fossil gas still represents a non-negligible share of 2050 energy demand in scenarios I1: "Sustainable society" and I2: "Lifestyle Change", applying CCS to fossil fuels as a mitigation strategy. The scenarios achieve 80-92% reduction of GHG excluding LULUCF by 2050 relative to 2019 levels, with Scenario R1: "Rapid Action" reaching the lowest emissions in comparison.

Electricity generation mix over time is visualised in Figure A 11 for selected 1.5°C compatible pathways. In 2019, the renewable energy share reached 28% of global produced electricity (IEA, 2021). However, according to the most ambitious range of PA compatible pathways, the share of renewables must be drastically scaled up to 72% by 2030 and 91% in 2050 to meet the 1.5°C temperature target. Coal needs to phase out by 2035 at the latest from the global power system with a complete phase-out of all fossil fuels before mid-century.

The scenarios apply various measures to decarbonise the economy and achieve zero emissions. For example, some PA-compatible scenarios will likely see a strong interlinkage and electrification of sectors, but may achieve complete decarbonization by means of demand reduction or extensive use of novel fuels, e.g., hydrogen or through the use of CDR. Such scenario characteristics may have different implications for the 4I's core challenges of the transformation. Therefore, in the following sub-sections, we assess how the scenarios differ regarding applied mitigation measures. Or if any correlation occurs, that the scenarios with a focus on high integration of VRES coincide with the scenarios with a high electrification rate,

[2] Other scenarios are also included in the graphs and analysis depending on data availability.

etc. The following subsections, outlined with respect to 4I's core challenges of the transformation, provide an in-depth comparative analysis of scenarios by looking into their individual characteristics based on identified indicators assessed in Sections 4.1 and 4.2.

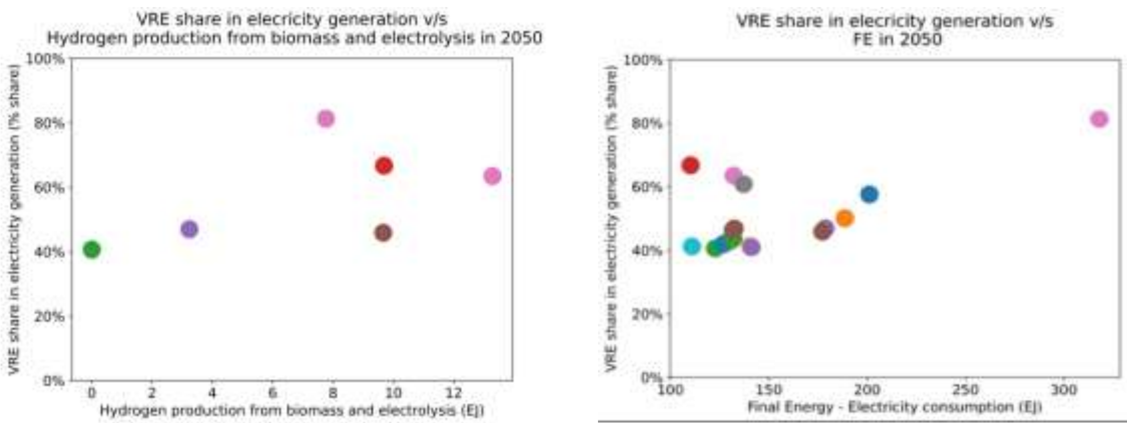
4.3.1 Infrastructure

VRE share in electricity generation vs. hydrogen production from biomass and electrolysis is depicted in Figure 5. Some scenarios characterise a high level of hydrogen production from biomass and electrolysis and high generation from VRE (I1: "Sustainable society" and M3: "Low Demand"), while other scenarios characterise a low class in both VRE generation and hydrogen production from biomass and electrolysis (I2: "Lifestyle Change" and M1).

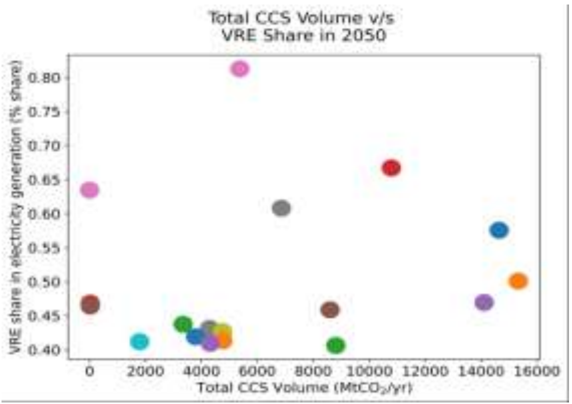
VRE share in electricity generation vs. final electricity consumption is depicted in Figure 5 (b). Scenario R1: "Rapid Action" is characterised with a high final electricity consumption coinciding with high penetration of VRE. Correspondingly, this scenario is classified under high infrastructure needs (cf. Figure A 9 and Figure 3). On the other hand, scenarios I2: "Lifestyle Change" characterises both low final electricity demand as well as a low VRE share. In Scenario I1: "Sustainable society" and M3: "Low Demand", final electricity demand belongs to the low class among the scenarios with high class of VRE share.

VRE share is shown in Figure 5 (c) against total CCS volume. The scenarios A1, A2, M1, M2, and I1: "Sustainable society" and I2: "Lifestyle Change" characterise a high application of CCS. The scenario M3: "Low Demand" has a particular focus on applying energy efficiency measures to reduce the energy demand, while a low CCS contribution is noticed in this scenario. Also scenario R1: "Rapid Action", with a focus on high penetration of VRE as major option to decarbonise the energy system has less application of CCS compared to scenarios A1, A2, M1, M2, and I1: "Sustainable society" and I2: "Lifestyle Change".

(a) (b)



(c)



(d)

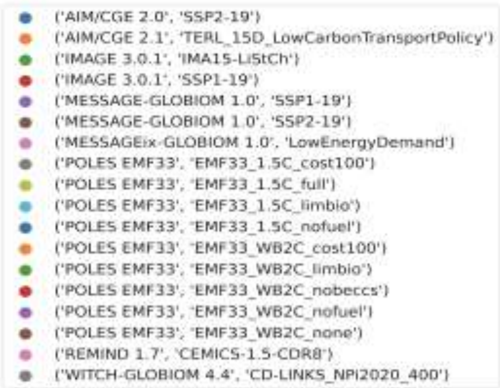


Figure 5 (a) VRE share in electricity generation vs. hydrogen production from biomass and electrolysis in 2050. (b) VRE share in electricity generation vs. final electricity consumption in 2050(c) VRE share in electricity generation vs. CCS volume in 2050 (d) Marker colors and scenario names as legends

Below, we summarise the list of scenarios classified as Low/Medium/High in regard to infrastructure needs, indicating their key characteristics.

- Scenarios with high infrastructure needs
  - Scenario R1: "Rapid Action": high final electricity consumption coincides with high VRE share in electricity, medium hydrogen production from biomass and electrolysis level and medium CCS application
  - Scenario I1: "Sustainable society": low final electricity consumption, high VRE share, high hydrogen production from biomass and electrolysis and high CCS application
- Scenarios with medium infrastructure needs
  - Scenario M2: high final energy electricity consumption, medium VRE share, medium hydrogen production level from biomass and electrolysis, high CCS application
  - Scenario M3: "Low Demand": medium final electricity consumption, high VRE share, high hydrogen production from biomass and electrolysis, low CCS application
- Scenarios with low infrastructure needs
  - Scenario I2: "Lifestyle Change": low final electricity consumption, low VRE share, low hydrogen production from biomass and electrolysis, high CCS application

- Scenario M1: high final electricity consumption, medium VRE share, low hydrogen production from biomass and electrolysis, high CCS application

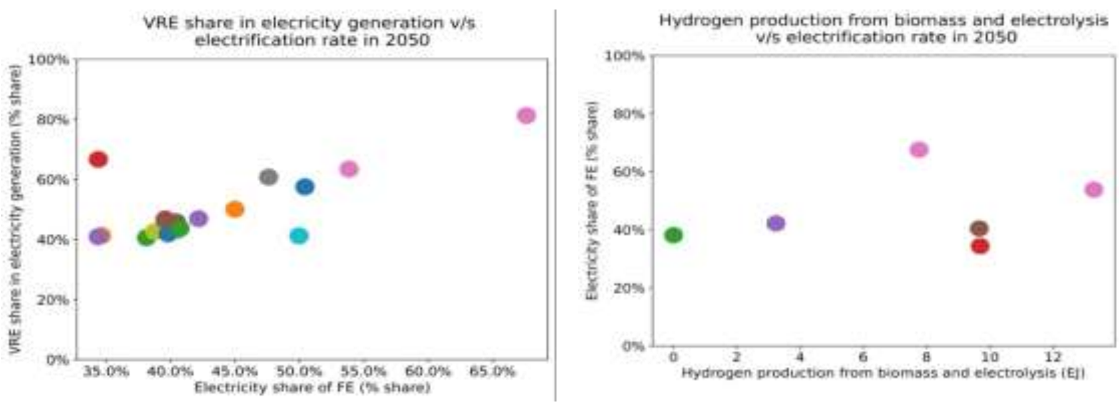
4.3.2 Innovation

VRE share vs. electrification rate is depicted in Figure 6(a). In R1: "Rapid Action" and M3: "Low Demand" also A1 and A2 and W, high VRE share coincides with high electrification rate. On the other hand, scenario: I2: "Lifestyle Change" is classified as low with respect to both VRE share and electrification rate.

The relation between hydrogen production from biomass and electrolysis v/s electrification rate in 2050 is depicted in Figure 6(b). Scenario M3: "Low Demand" has both high levels of hydrogen production from biomass and electricity as well as a high level of electrification rate. Scenario I1: "Sustainable society" is characterised by high level of hydrogen production from biomass and electrolysis with a low level of electrification rate. On the other hand, scenario I2: "Lifestyle Change" is characterised with low levels of both hydrogen production and electrification rate.

VRE share is depicted in Figure 6(c) against the change in final energy demand over 2019-2050. For instance, scenario R1: "Rapid Action" shows a high growth of final energy demand and applies a high VRE share to decarbonise the energy system. Other scenarios are characterised by low growth of final energy demand and a high share of VRE (Scenario I1: "Sustainable society" and M3: "Low Demand"). Scenarios I2: "Lifestyle Change" is distinguished by medium growth of final energy demand and low integration of VRE. This can be explained as this scenario has a high contribution of CCS to decarbonise the energy system.

(a) (b)



(c) (d)

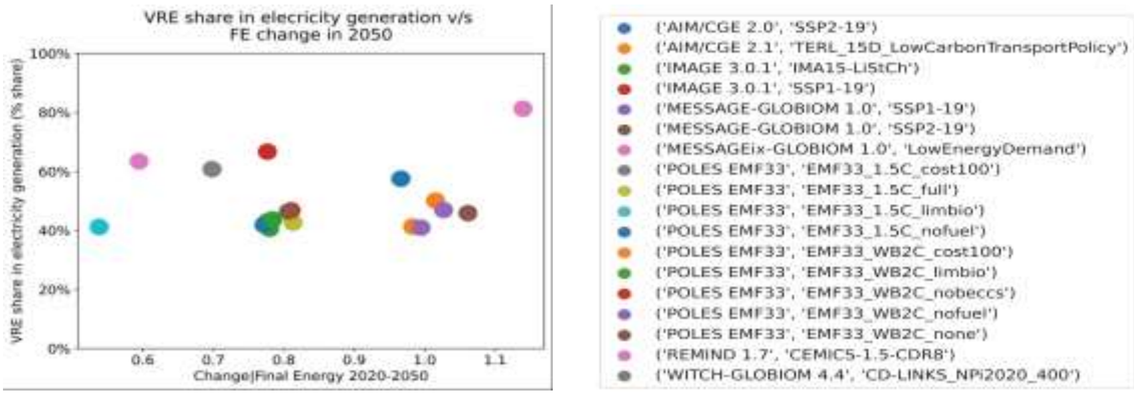


Figure 6 (a) VRE share in electricity generation vs. electricity share in 2050. (b) Electricity share in final energy vs. Total CCS Volume in 2050. (c) VRE share in electricity generation in 2050 vs. change in final energy demand between 2020 and 2050. (D) Marker colors and scenario names as legends

Below, we summarise the list of scenarios classified as Low/Medium/High concerning innovation needs, indicating their major characteristics.

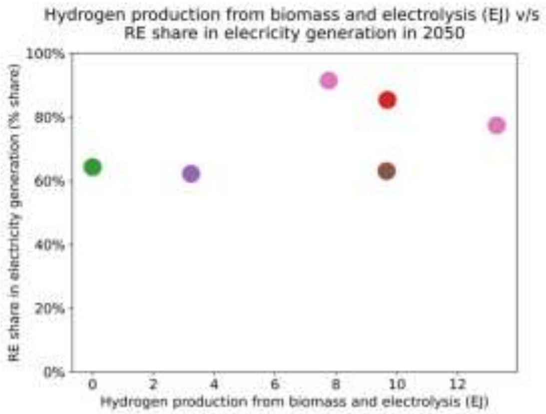
- Scenarios with high innovation needs
  - Scenario R1: "Rapid Action": high VRE share coincides with high electrification rate, medium hydrogen production from biomass and electrolysis, high final energy growth
  - Scenario M3: "Low Demand": high VRE share, high electrification rate, high hydrogen production from biomass and electrolysis, low growth of final energy demand
- Scenarios with medium innovation needs
  - Scenario I1: "Sustainable society": high VRE share, low electrification rate, high hydrogen production from biomass and electrolysis, low final energy growth
  - Scenario M2: medium VRE share, medium electrification rate, medium hydrogen production from biomass and electrolysis, high final energy growth
- Scenarios with low innovation needs
  - Scenario M1: low VRE share, medium electrification rate, low hydrogen production from biomass and electrolysis, high growth of final energy demand
  - Scenario I2: "Lifestyle Change": low VRE share, low electrification rate, low hydrogen production from biomass and electrolysis, medium growth of final energy demand

4.3.3 Integration

RE share vs. hydrogen production from biomass and electrolysis is portrayed in Figure 7(a). In some scenarios, high RE share coincides with a high level of hydrogen production from biomass and electrolysis (scenario I1: "Sustainable society" and M3: "Low Demand"). On the contrary, scenarios I2: "Lifestyle Change" and M1 both characterise a low level of hydrogen production from biomass and electrolysis, as well as a low share of renewables. Scenario R1: "Rapid Action" has a medium level of hydrogen production from biomass and electrolysis while having high level of RE share.

RE share vs. electrification rate is depicted in Figure 7(b). In some scenarios, a high share of renewables coincides with a high electrification rate (scenario R1: "Rapid Action"). Some scenarios characterise a high renewable share but a low electrification rate (scenario I1: "Sustainable society"). In contrast, some scenarios characterise both low renewable share and low electrification rate (I2: "Lifestyle Change") and mainly apply CCS and nuclear power as low carbon energy sources to decarbonise the energy system.

(a)



(b)

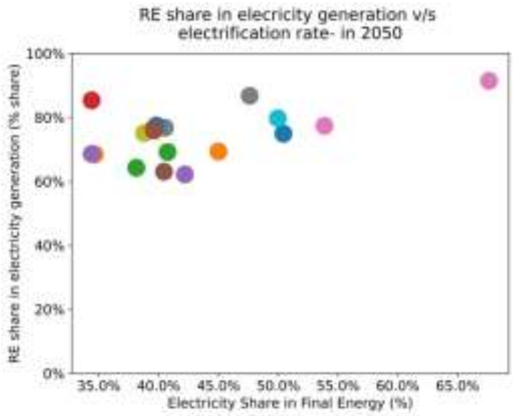


Figure 7 (a) RE share in electricity generation vs. hydrogen production from biomass and electrolysis in 2050. (b) RE share in electricity generation vs. electrification rate in 2050.

Below, we summarise the list of scenarios classified as Low/Medium/High regarding integration and indicate their major characteristics.

- Scenarios with high integration level
  - Scenario R1: "Rapid Action": high RE share, high electrification rate and medium hydrogen production from biomass and electrolysis
  - Scenario M3: "Low Demand": high RE share, high electrification rate, high hydrogen production from biomass and electrolysis

- Scenarios with medium integration level
  - Scenario I1: "Sustainable society": high RE share, low electrification rate, high hydrogen production from biomass and electrolysis
  - Scenario M2: low RE share, medium electrification rate, medium hydrogen production from biomass and electrolysis
- Scenarios with low integration level
  - Scenario I2: "Lifestyle Change": low RE share, low electrification rate, low hydrogen production from biomass and electrolysis
  - Scenario M1: Low RE share, medium electrification rate, low hydrogen production from biomass and electrolysis

4.3.4 Investment

Limiting end of the century warming to 1.5°C requires a substantial shift in energy system investments in the coming decade, with decisive changes compared to current investment patterns and different from patterns implied by current policies or the NDCs submitted by the countries to the UNFCCC (Bertram et al., 2021). The study by (Bertram et al., 2021) provides a detailed perspective on the near-term energy system changes and associated investments that are consistent with the Paris Climate targets. The study shows fundamental reduction in fossil fuel investments, especially coal, along with increasingly tightened investments in oil and gas in the 1.5°C compatible scenarios. At the same time, enhanced investments are shown for efficiency measures, low carbon fuels, and low carbon power generation.

As part of our study, we assess the investment needs across scenarios based on the indicator of growth in energy supply investment in 2050 relative to the base year calculated from the model variable directly reported by the scenarios (cf. Figure A 8).

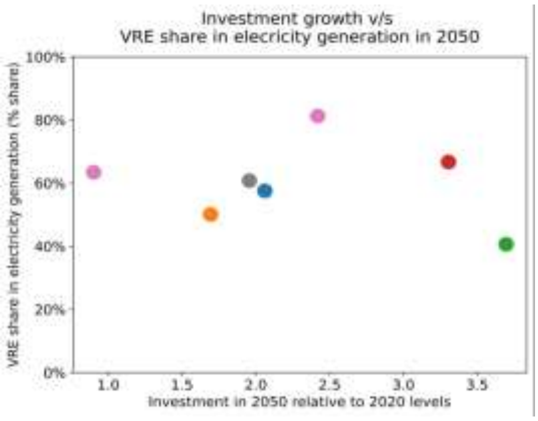
The energy system investment growth is shown against VRE and total renewable share in Figure 8(a) and Figure 8(b), respectively. No direct correlation can be concluded between the energy system investments and the share of renewables in electricity generation. This can be explained as the investment variable covers the investment needs for the entire energy system's decarbonisation, and it can only be partially related to the integration of renewables and the power sector's decarbonisation while, in addition, increases in RE investments are partially off-set by decreased investments in fossil fuels. For instance, scenario M3: "Low Demand" characterises a high share of renewables while it is classified as low class concerning energy system investments. Scenario R1: "Rapid Action" integrates a high share of renewables in the power sector and stays in the medium range with respect to the energy system investment needs.

The energy system investment growth is rendered against the electrification rate in Figure 8.c. Both scenarios R1: "Rapid Action" includes a high electrification rate of final energy consumption in 2050 with medium growth of energy system investment needs. Scenario M3: "Low Demand" with a particular focus on reduction of energy demand includes a high electrification rate of final energy consumption in 2050; the growth of energy system investment needs represents the scenario range's lower end.

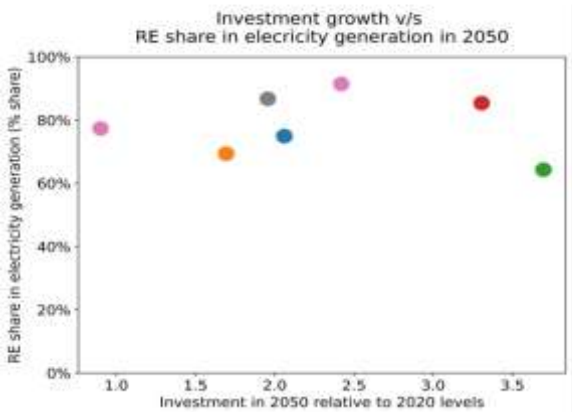
Figure 8.d shows the energy system investment growth vs. hydrogen production from biomass and electrolysis across different scenarios. Scenario I1: "Sustainable society" characterises high hydrogen production from biomass and electrolysis and at the same time, it characterises a high growth of energy system investments. Scenario R1: "Rapid Action" represents a medium level in regard to indicators. On the other hand, scenario M3: "Low Demand" is classified as high with respect to hydrogen production from biomass and electrolysis and low class for energy system investment needs.

The energy system investment growth is depicted against total CCS volume in Figure 8(e). CCS application in scenarios I1: "Sustainable society" and I2: "Lifestyle Change" is classified as high, while representing a high growth of energy system investment needs. Scenario R1: "Rapid Action" on the other hand represents the lowest range across scenarios concerning CCS application, with a medium growth of energy system investments.

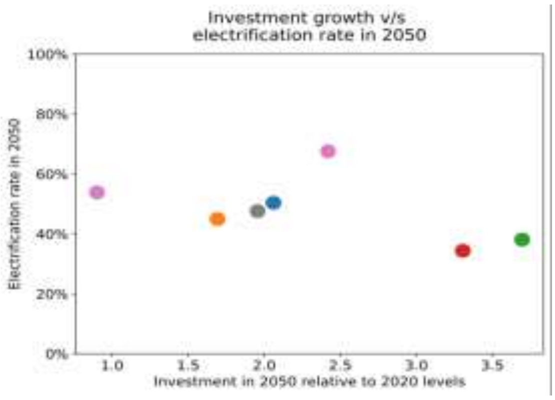
(a)



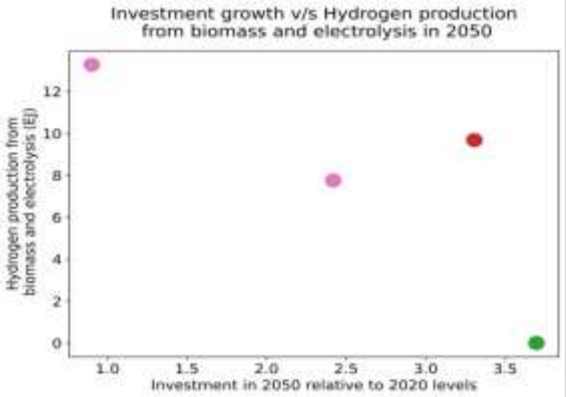
(b)



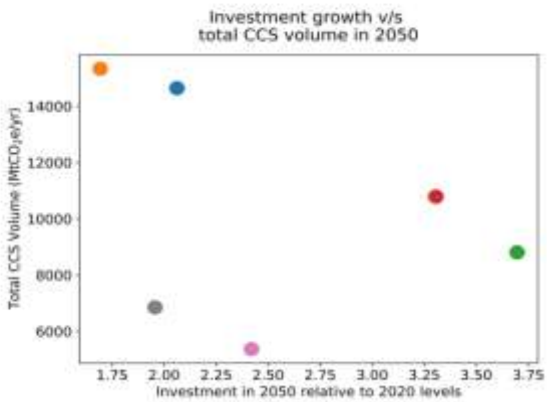
(c)



(d)



(e)



(f)

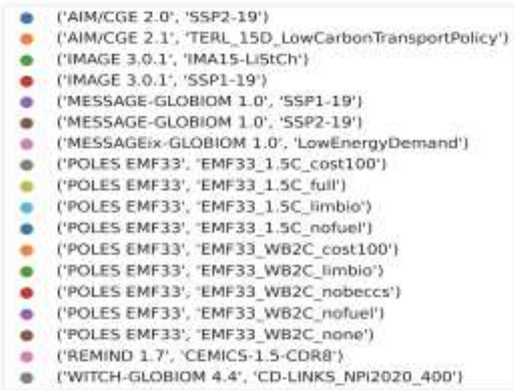


Figure 8 (a) VRE share in electricity generation vs. investment growth over 2020-2050. (b) RE share in electricity generation vs. investment growth over 2020-2050. (c) Electrification rate vs. investment growth over 2020-2050. (d) hydrogen production from biomass and electrolysis vs. investment growth over 2020-2050. (e) Total CCS volume vs. investment growth over 2020-2050. (F) Marker colour and scenario names as legends.

Below, we summarise the list of scenarios classified as Low/Medium/High concerning investment needs.

- Scenarios with high investment needs
  - Scenario I1: "Sustainable society"
  - Scenario I2: "Lifestyle Change"
- Scenarios with medium investment needs
  - Scenario R1: "Rapid Action"

  - Scenario W1
  - Scenario A1
- Scenarios with low investment needs
  - Scenario M3: "Low Demand"
  - Scenario A2

Scenario I1: "Sustainable society" is characterised by high infrastructure and medium innovation needs with a high growth of energy system investments. Scenario R1: "Rapid Action" is designated by high infrastructure and high innovation needs as well as high level of sectoral integration; this scenario is assessed as medium with respect to energy system investment needs. This may be explained according to renewable cost declines which allows a highly renewable energy system at medium costs. Scenario M3: "Low Demand" is distinguished by medium infrastructure needs and high innovation as well as high integration, while it represents a low range with respect to investment needs. Scenario I2: "Lifestyle Change" is characterised by low infrastructure and innovation needs as well as low integration. High investments in this scenario is mainly affected by high fossil CCS generation and nuclear power as major mitigation measures applied in this scenario to decarbonise the energy system (cf. Table A1).

5. Conclusions and outlook

The framework we developed throughout this report provides a systematic approach to evaluate scenarios with respect to the 4I's: Infrastructure, Innovation, Integration and Investments. We applied several criteria while filtering out the scenarios and limiting the assessment to a subset of scenarios that meet the primary objectives of sustainable transformative pathways in line with the Paris Agreement LTTG. We identified key indicators at global level which serve the purpose of evaluating global climate scenarios, and classified them according to the 4I's. Some of those indicators are reported directly by the scenarios; otherwise, we performed additional calculations where necessary. Not all scenarios provide the required indicators that we need for assessing 4I's across scenarios, which limits the analysis. Then, we rated all the identified indicators across the benchmarking scenario ensemble. This enabled us to cluster all the scenarios into low, medium and high classes with respect to the four core challenges of the transformation. We then develop and cluster the scenarios into archetypal 'landing zones' regarding the 4I's, each representing a different mode of achieving the Paris Agreement's goals.

The scenario analysis we conducted allows identifying indicators that show strong correlations for the different "I's. For instance, in some scenarios high final electricity consumption coincides with high VRE share in electricity to achieve complete decarbonisation of the energy system. This would lead to high infrastructure and innovation needs. However, other scenarios see a strong interlinkage and electrification of sectors, but may achieve complete decarbonisation by means of demand reduction. High electrification rates of end-use sectors as well as high level of hydrogen production is seen across other scenarios, increasing the need for sectoral integration

The scenario assessment tool we develop and apply in this report provides a flexible framework for quantification, comparison, and classification of scenarios while new scenarios, different thresholds, further dimensions, and indicators can be added in the future depending on the availability of model variables in the scenario ensemble.

The report indicates that there are different pathways to reach a full decarbonisation of the economy. While moving from incremental to transformative change requires increased investment in infrastructure and innovation, different sectors also need to interlink to take advantage of the potential to balance the electricity grid powered up to 81% by wind and solar energy. Renewables itself could provide up to 91% of electricity generation.

At the same time, there are some trade-offs that can be made on the path to fully decarbonised economy. These trade-offs will have an important impact on the economy before 2050 but even more afterwards: relying on much higher shares of negative emissions but postponing transformative action will result in higher costs for future generations. At the same time, higher investments in innovation and development of low carbon infrastructure will create a basis for welfare of future generations.

The global long-term transformation pathways assessed in this report are based on the published IAM scenario literature in SR1.5. Those scenarios were mainly developed in 2017 or prior to that; thus, they do not keep track of recent technological developments and policy frameworks. Also, sustainability constraints and plausibility assessment of large-scale deployment of CDR technologies such as BECCS as well as nuclear, fossil fuel with CCS, and land-use options are not taken into account in those pathways.

Additional 1.5°C compatible pathways have been developed by the modelling community as a contribution to the upcoming IPCC 6th Assessment Report (AR6), taking into account both the IPCC assessments and the recent data on policies and technology markets and costs. An addendum to this report is planned to incorporate those more up to date pathways that will be complementing the scenario ensemble analysed in this version of the report.

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Appendix Figures

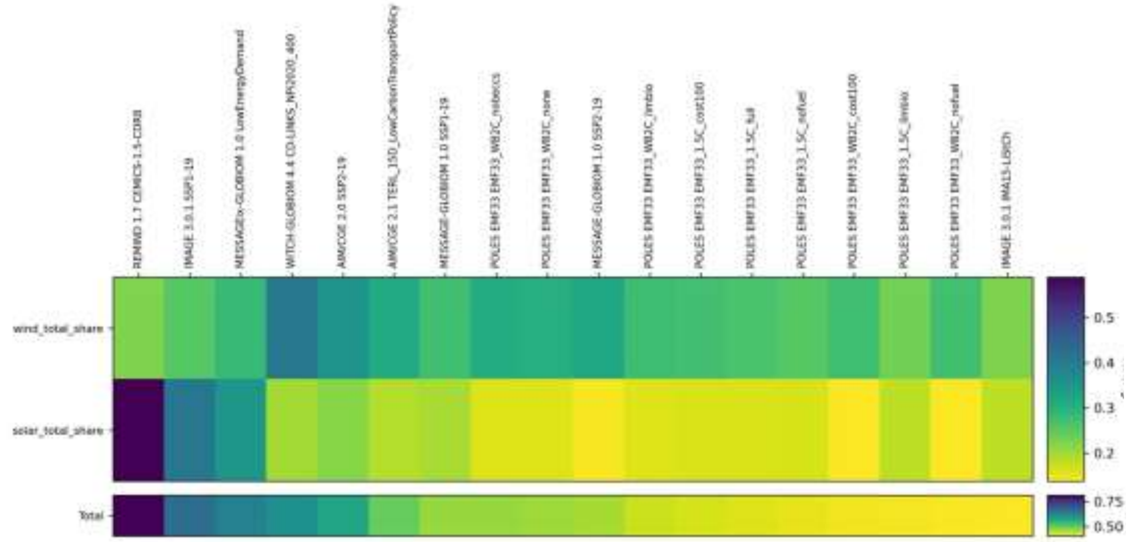

Figure A 1 VRE share in electricity generation represented as a fraction of total electricity generation in 2050.

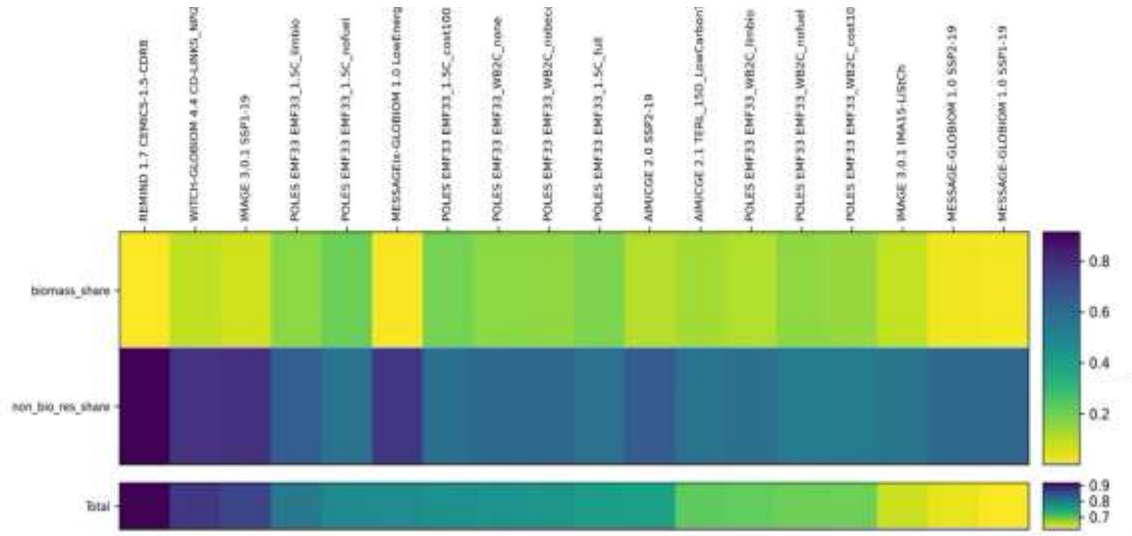

Figure A 2 Share of biomass, non-biomass, and total renewable generation represented as a fraction of total electricity generation in 2050

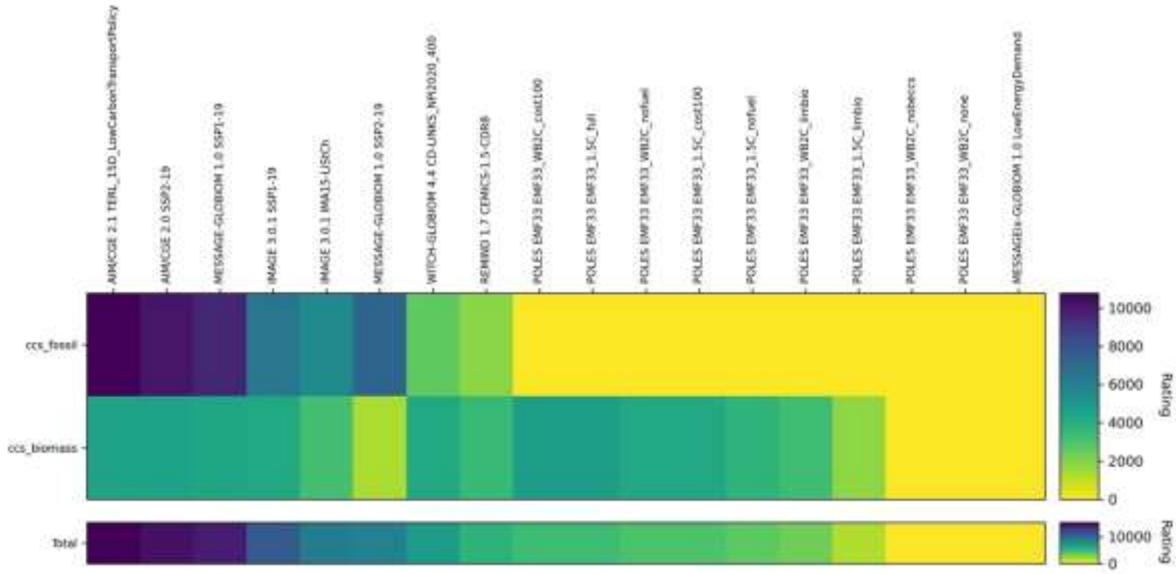

Figure A 3 Sequestered carbon via fossil CCS and BECCS by 2050 in $MtCO_2e/yr$

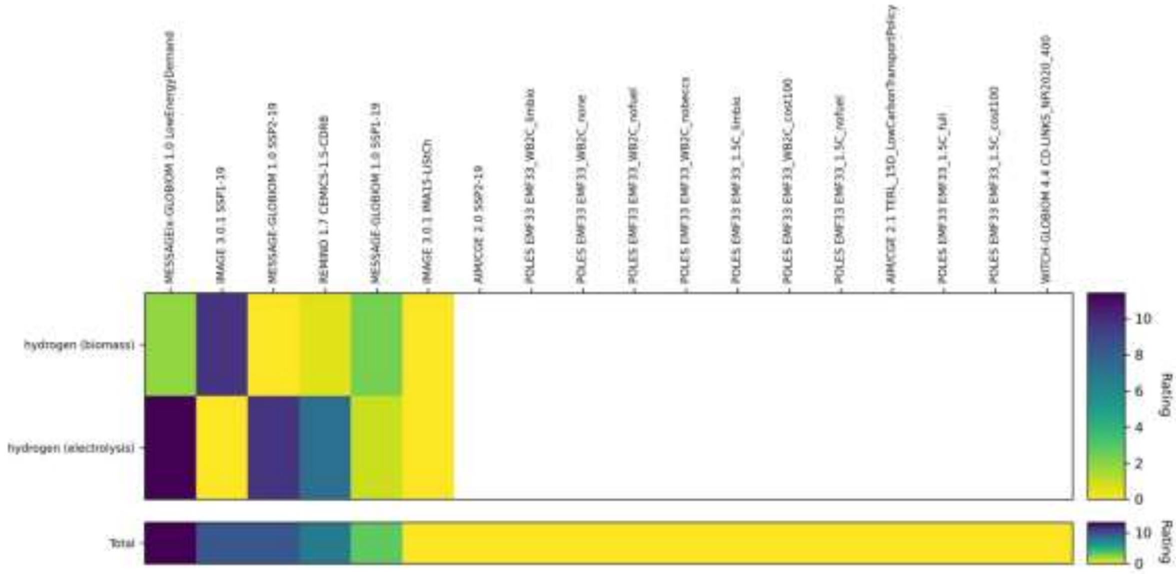

Figure A 4 Hydrogen production from biomass and electrolysis and their sum in 2050 in EJ/yr. Note: data only available for 6 scenarios among 18

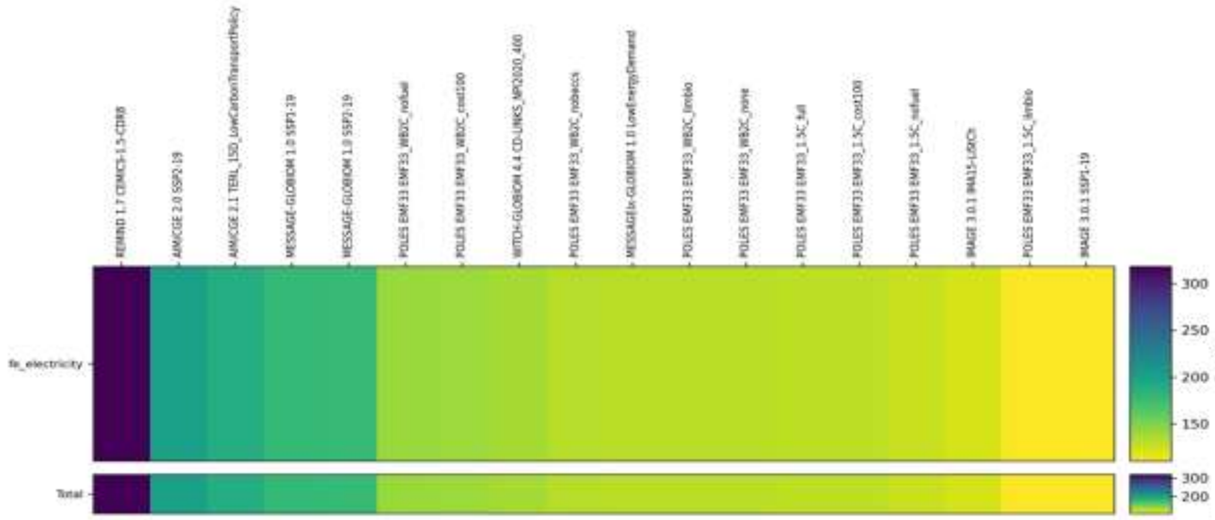

Figure A 5 Final electricity consumption in 2050 in EJ/yr

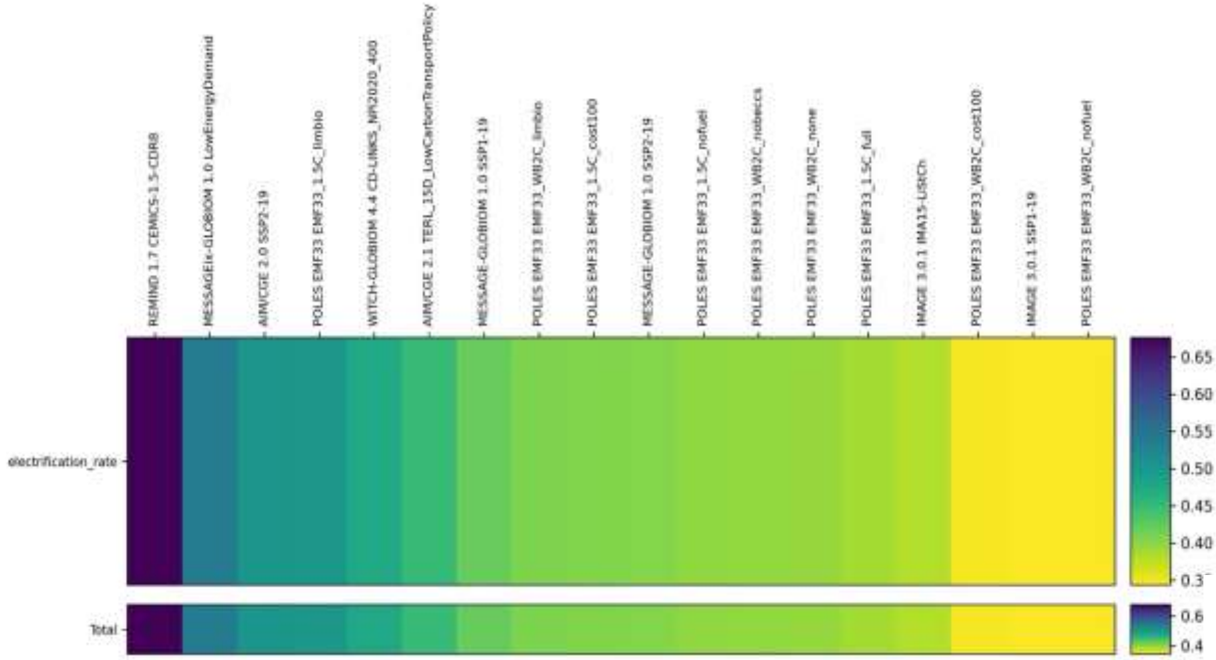

Figure A 6 Electrification rate in terms of fraction of electricity in final energy consumption by 2050

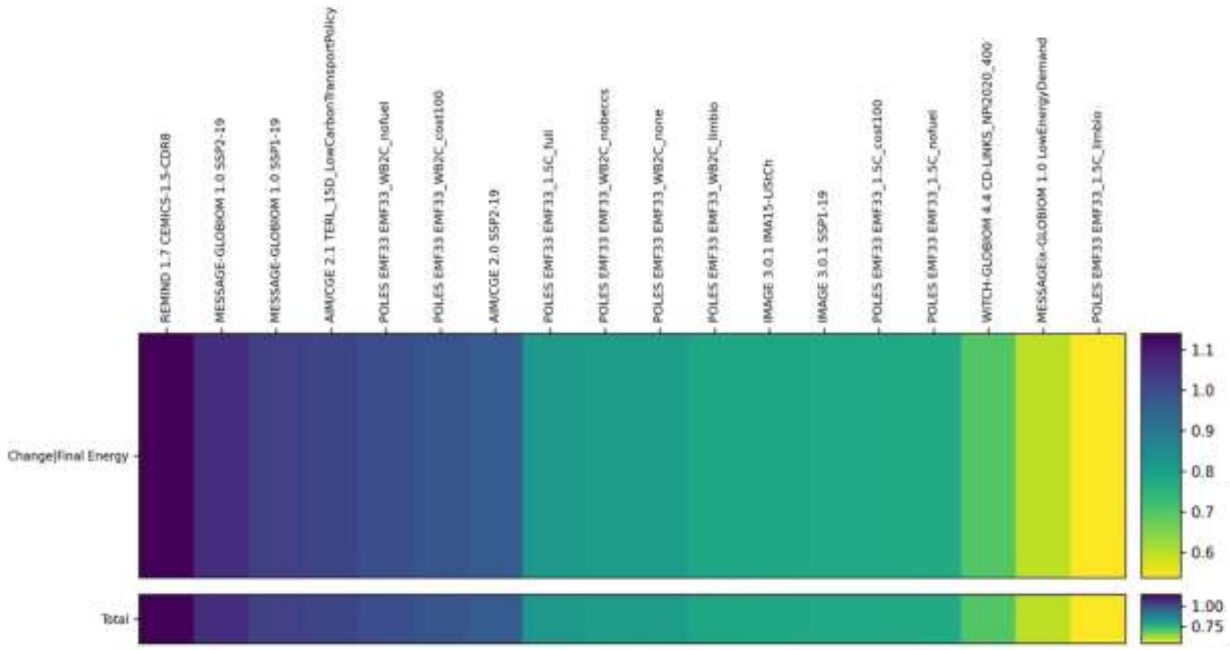

Figure A 7 Change in final energy consumption by 2050 rel. to base year (2019)

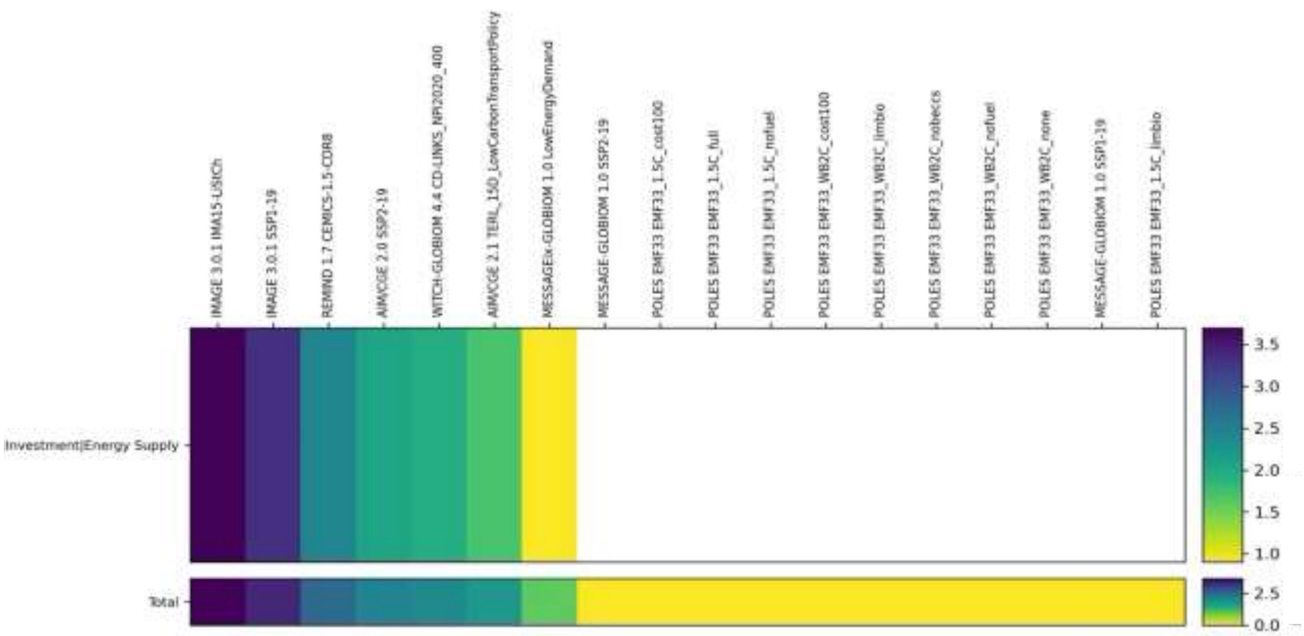

Figure A 8 Energy supply investments in 2050 rel. to 2020. Note: data available only for 7 scenarios among 18

model	scenario	Change|Final Energy|Electricit	ccs_biomass	ccs_fossil	fe_electricity	re-hydrogen (biomass)	re-hydrogen (electrolysis)	solar_total_share	wind_total_share	total_VRE_share	hydrogen_total_re	total_CCS_volume	Growth|Investment|Energy
AIM/CGE 2.0	SSP2-19	high	high	high	high			high	high	high		high	medium
AIM/CGE 2.1	TERI_15D_LowCarbonTra	high	high	high	high			medium	high	high		high	low
IMAGE 3.0.1	IMA15-LiStCh	low	low	high	low	low	low	medium	low	low	low	high	high
	SSP1-19	low	medium	high	low	high	low	high	low	high	high	high	high
MESSAGE-GLOBIOM 1.0	SSP1-19	high	high	high	high	high	medium	high	medium	medium	low	high	
	SSP2-19	high	low	high	high	low	high	low	high	medium	medium	high	
MESSAGEix-	LowEnergyDemand	medium	low	low	medium	medium	high	high	medium	high	high	low	low
POLES EMF33	EMF33_1.5C_cost100	low	medium	low	low			medium	medium	medium		medium	
	EMF33_1.5C_full	low	high	low	low			medium	low	low		medium	
	EMF33_1.5C_limbio	low	low	low	low			medium	low	low		low	
	EMF33_1.5C_nofuel	low	medium	low	low			medium	low	low		low	
	EMF33_WB2C_cost100	medium	high	medium	medium			low	medium	low		medium	
	EMF33_WB2C_limbio	medium	medium	medium	medium			low	medium	medium		low	
	EMF33_WB2C_nobeccs	medium	low	medium	medium			low	high	medium		low	
	EMF33_WB2C_nofuel	high	high	medium	high			low	medium	low		medium	
	EMF33_WB2C_none	medium	low	low	medium			low	high	medium		low	
REMIND 1.7	CEMICS-1.5-CDR8	high	medium	medium	high	medium	medium	high	low	high	medium	medium	medium
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_400	medium	medium	medium	medium			high	high	high		medium	medium

Figure A 9 Scenario classification to Low, Medium, High feasibility ranges for each indicator

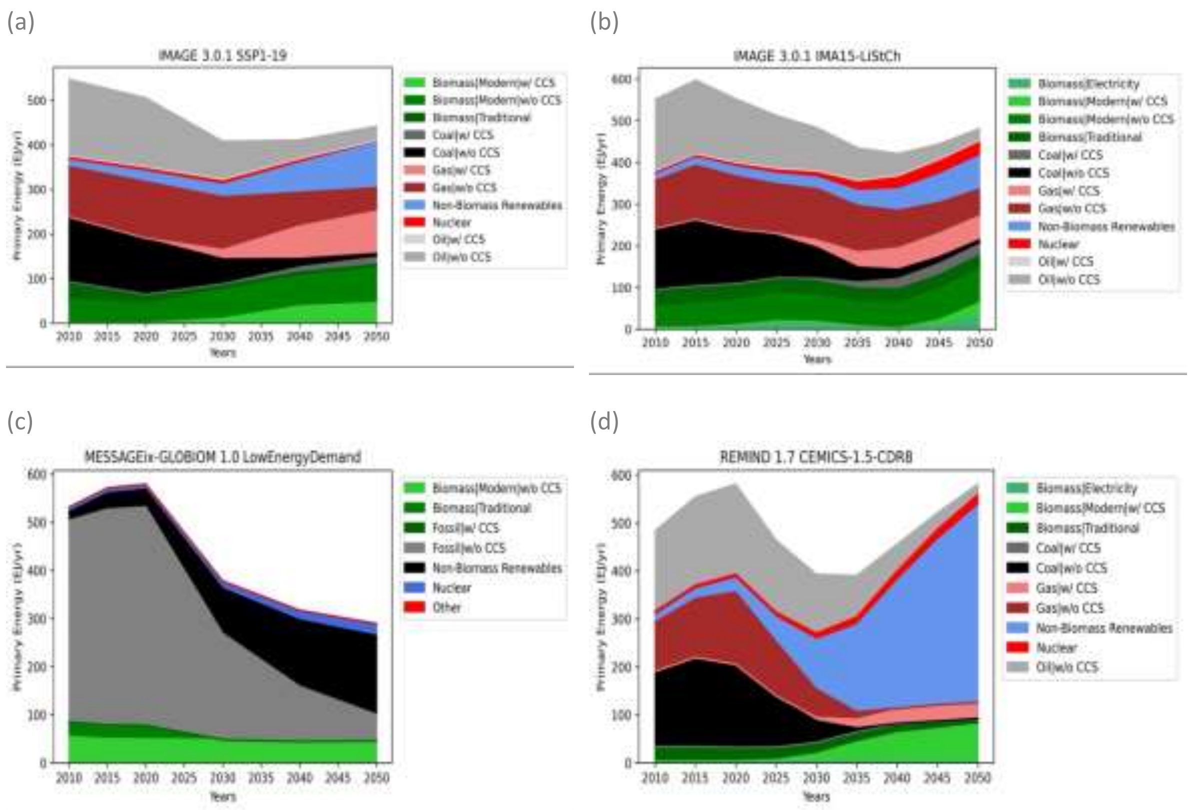

Figure A 10 Primary energy supply pathways for selected 1.5°C compatible scenarios: (a) Scenario I1 (b) Scenario I2 (c) Scenario M3 (d) Scenario R

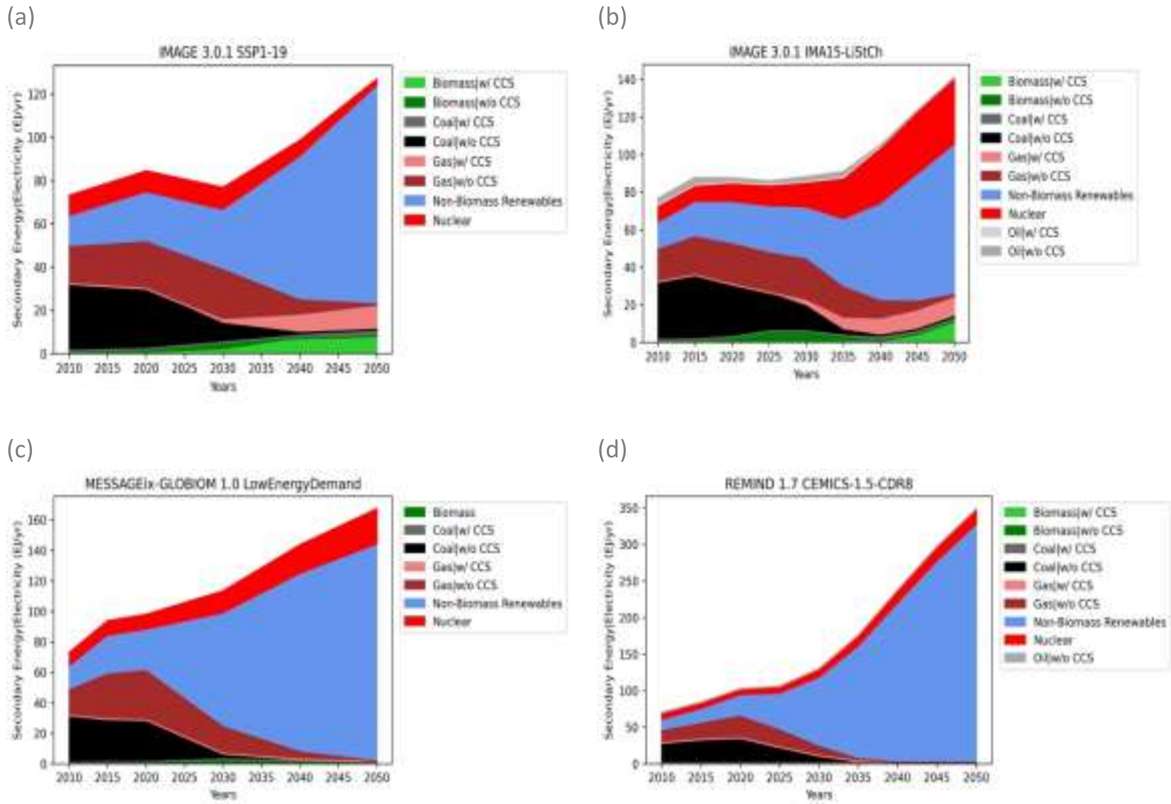

Figure A 11 Power generation mix over time for selected 1.5°C compatible scenarios: (a) Scenario I1 (b) Scenario I2 (c) Scenario M3 (d) Scenario R (Scenario abbreviations are listed in Table1).

Appendix Table

Table A1 Key characteristics of selected global 1.5°C compatible pathways.

	Scenario																		
	Historic	A1		A2		I2: Lifestyle Change		I1: Sustainable Society		M1		M2		M3: Low Energy Demand		R1: Rapid Action		W1	
Scenario	2019	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Total GHG excluding LULUCF (AR5-GWP100)	48.3 GtCO2e /yr	24.9	7.9	27.2	11.1	30.1	8.6	25.9	8.2	34.4	33.9	33.9	14.6	25.7	11.4	26.8	8.5	22.9	8.9
Renewables share in electricity	28%	57%	75%	49%	69%	37%	64%	40%	85%	45%	48%	48%	63%	60%	77%	72%	91%	55%	87%
VRE share in electricity	9%	53%	65%	47%	57%	31%	56%	34%	79%	44%	47%	47%	61%	57%	77%	71%	81%	49%	78%
Nuclear share in electricity	10%	16%	8%	15%	6%	16%	26%	13%	3%	13%	16%	16%	25%	12%	13%	10%	7%	30%	9%
Fossil CCS share in electricity	0%	5%	14%	3%	22%	3%	9%	2%	11%	5%	6%	6%	10%	0%	0%	0%	0%	4%	3%
Fossil CCS based generation (EJ/yr)	~ 0	6.6	35.6	3.8	50.3	3.0	12.0	1.7	13.5	5.1	6.3	6.3	22.7	0.0	0.0	0.3	0.9	3.9	5.9
Final energy demand rel. to 2019	1	0.80	0.92	0.83	0.97	0.72	0.74	0.63	0.74	0.94	0.98	0.98	1.01	0.71	0.57	0.81	1.09	0.59	0.67
Final electricity consumption	82 EJ/yr	107	201	109	189	75	123	70	110	94	98	98	177	99	132	120	318	77	137
Electrification rate	20%	31%	50%	30%	45%	24%	38%	26%	34%	23%	23%	23%	40%	32%	54%	34%	68%	30%	48%

Hydrogen production (total)	~ 0	N/A	N/A	N/A	N/A	1.1	17.6	7.0	54.7	3.6	4.9	4.9	40.9	2.6	15.5	5.4	30.5	N/A	N/A
Hydrogen production (electrolysis & biomass)	~ 0	N/A	N/A	N/A	N/A	0.0	0.0	2.6	9.7	0.8	0.5	0.5	9.7	2.5	13.3	0.5	7.8	N/A	N/A
Total CCS volume (GtCO2/yr)	~ 0	2.0	14.6	0.8	15.9	2.1	10.3	2.5	10.8	1.8	1.8	1.8	8.6	0.0	0.0	1.1	5.4	2.3	6.9
Growth in energy supply investment (relative to 2020 model data)	~ 1	1.8	2.1	2.2	1.7	0.8	3.7	1.1	3.3	N/A	N/A	N/A	N/A	1.1	0.9	2.7	2.4	1.0	2.0

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 coming years, 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

ecologic · VUB Brussels School of Governance · Climate Analytics · CE Delft · I4CE Institute for Climate Economics · University of Eastern Finland · Wageningen University & Research · WiseEuropa · rede research group in energy, innovation and environment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement **No. 101003884**.