European Commission
Joint Research Centre

IRENA
International Renewable Energy Agency

BENCHMARKING SCENARIO COMPARISONS

KEY INDICATORS FOR THE CLEAN ENERGY TRANSITION

2021

ISBN 978-92-9260-359-5

Citation: IRENA and JRC (2021), Benchmarking Scenario Comparisons: Key indicators for the clean energy transition, International Renewable Energy Agency, European Commission's Joint Research Centre, Abu Dhabi, Brussels.

Acknowledgements

This report was prepared by Pablo Carvajal, Nadeem Goussous and Chidubem Onah from the International Renewable Energy Agency (IRENA), and Wouter Nijs from the European Commission's Joint Research Centre (JRC). The report was supervised by Asami Miketa and Dolf Gielen from IRENA, and Jose Moya, Vangelis Tzimas and Stathis Peteves from the JRC. The report was edited by Justin French-Brooks.

This report benefited from the reviews and comments of numerous experts, including William Zimmern (bp), Christoph Jugel (German Energy Agency [dena]), Mathias Kimmel (BloombergNEF [BNEF]), Sheila Samsatli (University of Bath [UoB]), Trieu Mai (National Renewable Energy Laboratory [NREL]), Anahi Molar-Cruz (Technical University Munich [TUM]), Christof van Agt (International Energy Forum [IEF]), Edward Byers (Institute for International Applied System Analysis [IIASA]), Jürgen Kropp (Potsdam Institute for Climate Impact Research [PIK]), Andries Hof (Netherlands Environmental Assessment Agency [PBL]), James Newcomb (Rocky Mountain Institute [RMI]), Anastasia Belostotskaya (World Energy Council [WEC]) and Daniel Raimi (Resources for the Future [RFF]). We also would like to thank Ioannis Tsiropoulos, who helped to shape the workshop at the very start.

Workshop participants

IRENA and the JRC would like to express their gratitude to the participants of the Expert Workshop, "Benchmarking long-term scenario comparison studies for the clean energy transition", which took place as a virtual event on 10 and 11 September 2020.

About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

About the European Commission's Joint Research Centre

As the European Commission's science and knowledge service, the Joint Research Centre (JRC) supports EU policies with independent scientific evidence throughout the whole policy cycle. We create, manage and make sense of knowledge and develop innovative tools and make them available to policy makers. We anticipate emerging issues that need to be addressed at the EU level and understand policy environments. We collaborate with over a thousand organisations worldwide whose scientists have access to many JRC facilities through various collaboration agreements. Our work has a direct impact on the lives of citizens by contributing with its research outcomes to a healthy and safe environment, secure energy supplies, sustainable mobility and consumer health and safety.

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Abbreviations

BDI	Federation of German Industries
BECCS	Bioenergy with carbon capture and storage
BEIS	UK Department for Business, Energy & Industrial Strategy
bp	British Petroleum
CCS	Carbon capture and storage
DAC	Direct air capture
dena	German Energy Agency
EC	European Commission
EMF	Energy Modelling Forum
ESYS	Energy Systems for the Future
ETS	Economic Transition Scenario
EU	European Union
EUCALC	European Calculator
GDP	Gross domestic product
GHG	Greenhouse gas
IAMC	Integrated Assessment Modeling Consortium
IEA	International Energy Agency
IEF	International Energy Forum
IIASA	Institute for International Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LTES	Long-term Energy Scenarios
NCS	NEO Climate Scenario
NEO	New Energy Outlook
NREL	National Renewable Energy Laboratory
OPEC	Organization of the Petroleum Exporting Countries
PBL	Netherlands Environmental Assessment Agency
PIK	Potsdam Institute for Climate Impact Research

PV	Photovoltaic
RFF	Resources for the Future
RMI	Rocky Mountain Institute
SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
SEI	Stockholm Environment Institute
TUM	Technical University of Munich
TWH	Terawatt hour
UN	United Nations
UOB	University of Bath
US EIA	US Energy Information Administration
WEC	World Energy Council
WES	World Energy Scenarios

THIS REPORT AND ITS FOCUS

THE INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA) under its Long-term Energy Scenario Network, in collaboration with the Knowledge for the Energy Union Unit of the Joint Research Centre (JRC) of the European Commission, organised a two-day virtual workshop on "Benchmarking long-term scenario comparison studies for the clean energy transition" on 10 and 11 September 2020.

Over 20 experts from technical institutions, international organisations, academia and the private sector joined the event to exchange experience on long-term energy scenario comparison studies, in a bid to map the motivation, focus and methods of such studies. They discussed how scenario comparison results and insights could be used for policymaking in the context of the clean energy transition.

This report synthesises the workshop discussions among experts from institutions that have recently developed long-term energy scenario comparison studies to benchmark scenario assumptions and results, increase the reliability of scenario outputs, and improve the robustness of insights for policy makers planning the energy transition (see Table 1). Clean energy transition scenarios are defined as pathways toward transforming the energy system from fossil-based to climate neutral by the second half of this century. The workshop provided a platform to discuss a systematic and formalised approach to scenario comparison, and to identify areas for improvement in the context of the clean energy transition and climate neutrality.

Chapter 1 presents a summary of the expert interventions at the workshop. Chapter 2 describes the benchmarking of 24 scenario comparison indicators critical for the energy transition and for achieving net-zero greenhouse gas (GHG) emissions, derived from 14 scenario comparison studies presented at the workshop. Finally, Chapter 3 presents an overview of recent long-term energy scenario comparison studies, highlighting the aims, scopes and main findings in line with the clean energy transition.

More information on the workshop can be found on IRENA's website.

Which comparison studies were benchmarked?

Table 1 shows a list of the 14 institutions that showcased their scenario comparison studies at the workshop, which have been benchmarked in this report. The studies assessed are either dedicated scenario comparison studies or scenario studies that include a specific comparison section. Further details on each of these scenario comparison studies can be found in Chapter 3.

TABLE 1 List of recent scenario comparison studies assessed

Name of study	Institution	Scope	Region	Year
Towards net-zero emissions in the EU energy system by 2050	JRC	Energy system	European Union	2020
Energy Outlook 2020	bp	Energy system	Global	2020
Comparison of three fundamental "2050" studies on the feasibility of the energy transition in Germany	Energy Systems for the Future (ESYS), the Federation of German Industries (BDI) and the German Energy Agency (dena)	Energy system	Germany	2018

Comparing Long-Term Energy Outlooks 2020	BloombergNEF (BNEF)	Energy System	Global	2021
The curious case of the conflicting roles of hydrogen in global energy scenarios	University of Bath (UoB)	Hydrogen	Global	2020
Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective	National Renewable Energy Laboratory (NREL)	Power	United States	2017
Intermodel comparison: North American Energy Trade and Integration (EMF 34)	Energy Modelling Forum (EMF)	Energy system	North Americas	2020
IAMC 1.5°C Scenario Explorer	Institute for International Applied System Analysis (IIASA)	Energy system	Global	2018
Pathways towards a fair and just net-zero emissions Europe by 2050: Insights from the EUCalc for carbon mitigation strategies	Potsdam Institute for Climate Impact Research (PIK)	Energy system	European Union	2020
A comparison of key transition indicators of 2°C scenarios	Netherlands Environmental Assessment Agency (PBL)	Energy system	Global	2019
The Map Is Not the Territory: New Routes to a 1.5°C Future	Rocky Mountain Institute (RMI)	Energy system	Global	2019
Global Energy Scenarios Comparison Review	World Energy Council (WEC)	Energy system	Global	2019
IEA-IEF-OPEC Outlook Comparisons Update	International Energy Forum (IEF) in partnership with RFF	Energy system	Global	2020
The Global Energy Outlook	Resources for the Future (RFF)	Energy system	Global	2020

KEY FINDINGS

1. How scenario comparison studies are conducted

The variety of long-term energy scenarios produced by various institutions results in an abundance of insights and technology combinations to guide the clean energy transition.

Scenario comparisons can be used to:

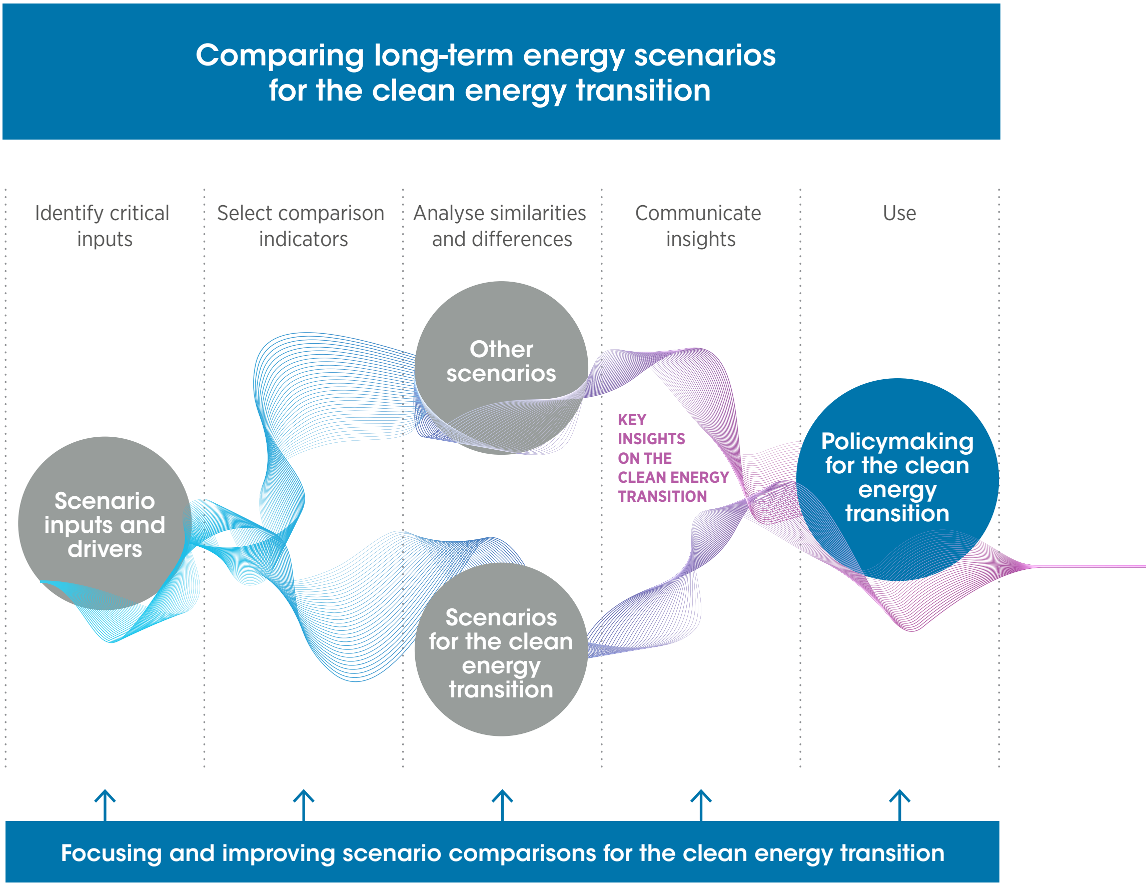
- Understand why scenarios are consistent or divergent.
- Improve comparability of scenario indicators, narratives and values.
- Identify commonalities and trade-offs for decision makers.
- Explore a range of scenario results from different frameworks.

Comparison exercises dedicated to the clean energy transition are rather new. Specific challenges arise in relation to identifying key insights for policymaking and communication and improving different steps within the process. Figure 1 presents a conceptualisation of the process for comparing long-term energy scenarios for the clean energy transition.

There are consistent or *similar* elements in what the clean energy transition requires. Similarities in scenarios can be the basis for greater convergence among stakeholders on technology development and investment.

There are also divergences or *differences* in energy transition scenario results, which indicate the need for further study and discussion, such as critical assumptions. Differences can provide insight for policy makers on uncertainties, trade-offs and choices to be made, especially considering the high inertia of the energy system.

FIGURE 1 Scenario comparison process



2. How to focus and improve scenario comparisons to better address the clean energy transition?

Energy transition assumptions and indicators that need more focus

The benchmarking of scenario indicators identified significant gaps between what scenario comparison studies look at and what policy advice requires. Important supply, demand and other indicators are often missing in the comparison of energy transition scenarios. Another key takeaway is that scenario comparisons should focus on critical assumptions related to the limits of energy transitions and technology trade-offs (Table 2). This will improve our understanding of what changes are possible and what trade-offs are already important for today's decision-making.

TABLE 2 Assumptions and indicators that need more focus in scenario comparisons

Indicators	Supply	• Biofuel feedstock • Power-to-X capacity • Material flow needs
	Demand	• Zero-emission vehicles • Electrification of final energy • Heating systems in buildings • Consumer behaviour
	Cost and emissions	• CO_2 reuse or sequestration • Afforestation or other natural carbon sinks • Investment cost and finance gaps

Assumptions	Limits of what is possible	• How fast sectors can grow • How much can be electrified • How easily climate-neutral fuels can be supplied • What role consumers can play in technology uptake • How much natural carbon sinks can contribute and what impact carbon budgets may have • What are the limits of financing
	Technology trade-offs	• Electrification versus the use of green hydrogen or derived fuels • Natural gas with carbon capture and storage (CCS) versus upscaling renewables and electricity storage • Public transport versus private electric vehicles

Improving communication to make comparison insights clearer for policy makers

Scenario comparisons with understandable and interpretable results will be more useful to policy makers in guiding the energy transition. Table 3 presents two approaches that can improve the communication of results to policy makers.

TABLE 3 Improving communication when comparing energy scenarios

Grouping scenarios by policy relevance	Using visualisation tools
Policy choices can explain most of the differences between scenarios. Grouping scenarios with similar policy approaches helps provide clear insights.	Online visual platforms designed to communicate complex results improve accessibility and transparency for distilling policy messages.

3. What do scenario comparisons say about the clean energy transition?

Our exercise to benchmark scenario comparison studies led us to identify similarities and differences between what the scenarios stated as being required for the energy transition (Table 4).

TABLE 4 Scenario comparison studies – similarities and differences for the energy transition

Similarities	Differences
• Renewable energy as the backbone of the energy transition, led by solar photovoltaic (PV) and wind capacity • Massive electrification of end uses • The increasing complexity of the energy system • A rapid phase-out of fossil fuels requiring a speedy regulatory response • An unprecedented scale-up of disruptive technologies, of which some need support today, namely: › New technology mix in transport, led by electric vehicles › Hydrogen becoming a main energy commodity, strongly impacting the growth of wind and solar › Low-carbon heating systems in buildings • The need to enable investment and deep structural transformation through an integrated planning approach with room for continuous social dialogue • The need for long-term scenarios and policies also to focus on the near future up to 2030	• The extent of energy efficiency improvements and the reduction of final energy demand • The roles of CCUS and natural gas • The degree to which carbon-neutral fuels, derived from electricity, replace fossil fuels • The level of emission offsets from carbon dioxide removal, linked to the speed of emission mitigation • The speed at which disruptive technologies are scaled up • The role of small modular nuclear reactors

CHAPTER 1

EXPERT INSIGHTS ON SCENARIO COMPARISON

THIS CHAPTER SUMMARISES the expert interventions during the workshop's panel discussions, namely the scene-setting segment by the JRC and IRENA and two break-out groups. The first break-out group discussed "Focusing the scenario comparison" and the second "How to improve scenario comparison for policymaking".

Setting the scene

IRENA and the JRC joined forces to assess 14 recently published energy scenario comparison studies. Two work streams at the respective organisations motivated this work:

First, the Knowledge for the Energy Union Unit at the JRC published the study, Towards net-zero emissions in the EU energy system — Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal (JRC, 2020). The study compared a total of 16 decarbonisation scenarios for the European Union, looking into the similarities and differences among them. Further details of this study are shown in p.23-24.

Second, IRENA published the report Scenarios for the Energy Transition: Global experience and best practices (IRENA, 2020). The study collected experience and good practice from government and technical institutions worldwide dedicated to improving the use and development of long-term energy scenarios to guide the clean energy transition. The report was part of the activities of IRENA's Long-term Energy Scenarios Network (LTES Network). Further details on the report and the LTES Network can be found in p.25-26.

Wouter Nijs
Joint Research Centre (JRC)

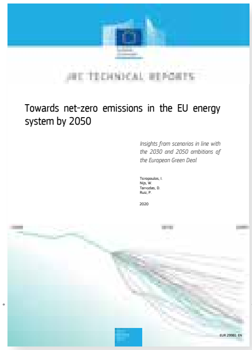
TOWARDS NET-ZERO EMISSIONS IN THE EU ENERGY SYSTEM BY 2050

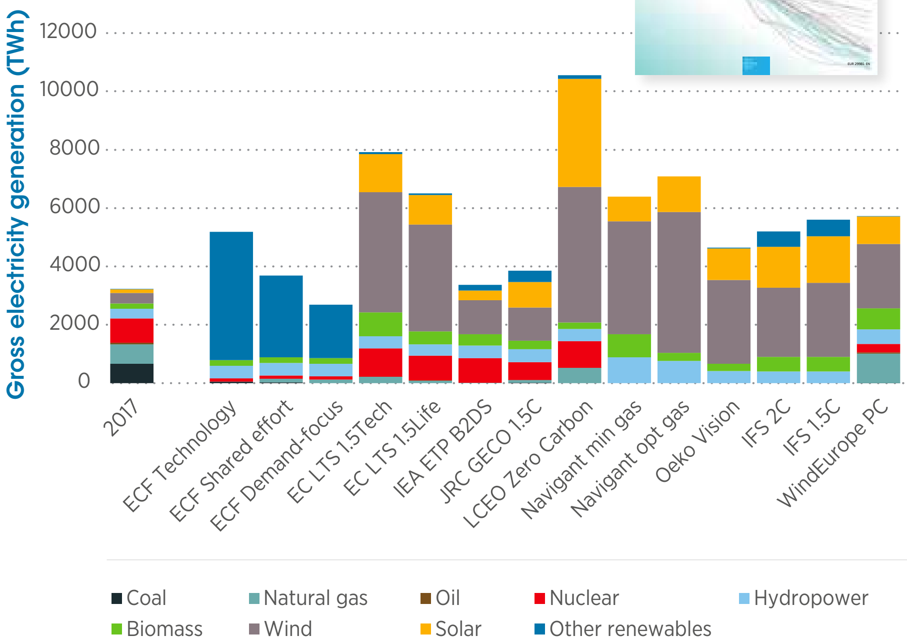
"Similarities in scenarios can create a predictable environment for investors, showing what needs to be done and at what speed. Differences can identify key drivers and can underpin choices for transformations with long lead times."

The JRC report, Towards net-zero emissions in the EU energy system by 2050, compares scenarios produced by several important organisations in Europe and around the world that achieve a reduction of around 55% in GHG emissions by 2030, and aim for climate neutrality by 2050, similar to the ambitions of the European Green Deal. It summarises their insights into how the energy system may change by 2030 and by 2050, compared to today.

When aiming for climate neutrality, some robust transition similarities need to happen rapidly, requiring large investments such as in electrification or zero-emission vehicles. The results also confirmed that we should refocus from "integration of renewables" to "new ways of using renewables". Scenarios mostly differ regarding energy efficiency and the size of the energy system, suggesting that we have to increase our efforts to provide key insights on the limiting factors for the rapid growth of new markets, for example the extent to which building renovation can penetrate the existing building stock. More research is needed to analyse the extent to which enabling technologies such as electrolysers, CCUS and solutions for aviation will be deployed.

FIGURE 2 Cover and example output on electricity generation from the JRC report Towards net-zero emissions in the EU energy system by 2050





Note: Data behind the graphs are available from the JRC data catalogue.
Source: JRC, 2020.

__Asami Miketa__

International Renewable Energy Agency (IRENA)

IRENA'S LONG-TERM ENERGY SCENARIOS (LTES) NETWORK

"Long-term energy scenarios have been used for policymaking for several decades, but what are the key features that define clean energy transition scenarios?"

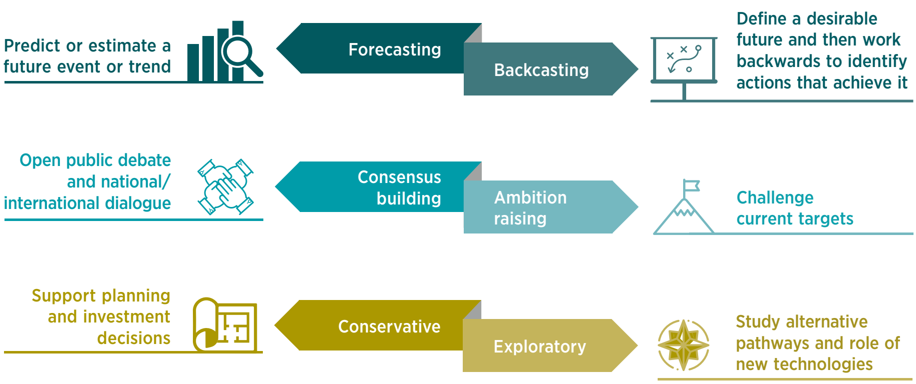
IRENA's LTES Network provides a global platform where government practitioners and other experts can share their experience in developing and using long-term energy scenarios to guide the clean energy transition. The LTES Network is open for membership to national energy planning offices in ministries, agencies and technical institutions supporting governments in scenario development.

The LTES Network has focused on exploring the key features that define clean energy transition scenarios, addressing three interrelated topics: **1)** how to improve scenario use for better strategic decision-making, **2)** how to strengthen scenario development to better account for potentially transformational changes, and **3)** what approaches can enhance institutional capacity for scenario planning.

Numerous discussions held during LTES Network activities have identified that scenarios for planning the clean energy transition have different types of uses. Figure 3 shows three polar pairings of uses. We have found that conservative scenarios tend to be used for infrastructure planning (such as that undertaken by public utilities), while more exploratory scenarios tend to remain as academic exercises to explore more radical or even extreme transformations. Such distinctions are useful in better understanding scenario features and comparing them.

Additional findings of the LTES Network have been collected in the report, Scenarios for the Energy Transition: Global experience and best practices (IRENA, 2020).

FIGURE 3 Types of uses of energy scenarios for planning the clean energy transition



Source: IRENA, 2020

EXPERT INSIGHTS

Focusing scenario comparisons for carbon neutrality

This section summarises expert interventions during the panel discussion on **focusing scenario comparisons in pursuit of a low-carbon energy system.** Critical questions addressed were:

- What similarities seen in the results can guide policy makers on the way forward in the transition to a clean energy system?
- What main assumptions, in factors that can be influenced by policymaking, create differences in the results from critical indicators?
- With different pathways to decarbonisation, what are the trade-offs policy makers face and how quickly do they need to make choices?

Expert panel: Focusing the scenario comparison

WATCH ONLINE

PANELLISTS

- William Zimmern, Head of Energy Transition and Systems Analysis, bp
- Christoph Jugel, Director Energy Systems, dena
- Seb Henbest, Chief Economist, BNEF
- Sheila Samsatli, Assistant Professor, UoB
- Trieu Mai, Senior Energy Analyst, NREL
- Anahi Molar-Cruz, Research Associate, Technical University Munich (TUM) (EMF study)

OTHER EXPERTS

- Pablo Ruiz, Scientific Officer, JRC
- Jose Moya, Scientific Officer, JRC
- Uwe Remme, Energy Analyst, International Energy Agency (IEA)
- Kaare Sandholt, Chief Expert, China National Renewable Energy Centre (CNREC)
- Niels Pedersen, Advisor, Danish Energy Agency (DEA)

MODERATOR

Wouter Nijs, Project Officer, JRC

William Zimmern

bp

CONSISTENT BREAKTHROUGH TECHNOLOGIES IN TRANSITION SCENARIOS

"Electrification is something you see consistently across scenarios, even in business-as-usual scenarios."

"In climate scenarios, fossil oil is significantly reduced because you can't capture CO_2 from mobile sources."

Some trends are apparent in all scenarios: electrification, increased use of renewable resources and increased energy system complexity. Across the climate scenarios, there is also a significant reduction in oil consumption. Electrification occurs in almost all sectors, but is more advanced in passenger cars and heating of buildings. We also see a move towards systems with more complexity. Historically, systems have been dominated by a single fuel, say coal or oil, with little competition between fuels for many applications. In the future, competition will increase significantly; for example, electricity can compete against oil in the transport sector. Another element of complexity is the increasing requirement for equipment to manage intermittent power and balance the energy system. Spare generation capacity, batteries and build-out of transmission and distribution networks are all required alongside the build-out of wind and solar capacity itself. In climate scenarios, oil use is reduced. Oil is a dense and portable energy source, but this unique value can be difficult to exploit in a net-zero climate scenario because it is difficult to capture the CO_2 at the point of consumption in its primary use for transport. This is in contrast to natural gas, where emissions can be more cost-effectively captured when used in the power sector, for hydrogen production or in larger industrial processes.

Policy makers have the power to prioritise investments and can already select from a wide range of technologies to support, such as CCS and hydrogen. Should we invest only in the low-hanging fruit such as replacing coal-based power production, or should we also invest in more complex solutions? By encouraging technology learning, policy intervention can lead to very positive feedback loops. The key is to select technologies that will need to be built out at scale, but still need support today to yield benefits in the 2030s, 40s and 50s. Cost optimisation models provide advice on the selection of technologies and often include a mix of technologies.

Policy also influences drivers that significantly affect the results of scenarios, such as nuclear energy, natural climate solutions and consumer behaviour. Differences in acceptance create large differences in scenario results and create a challenge for determining long-term transitions. With reforestation and afforestation, you can, for example, offset the emissions from jet fuel. Also, policy makers and education can affect consumer choices on the demand side. Consumer behaviour such as meat consumption or travelling preferences for leisure can have a huge impact on emissions or on energy demand.

Christoph Jugel
German Energy Agency (dena)

SETTING INTERMEDIATE GOALS FOR AN INTEGRATED ENERGY TRANSITION

"Building renovation rates are around 1%, but more interestingly they have been around 1% for three decades now while during the same period, studies have been saying that they have to go up to 2%."

Focusing only on scenario similarities comes with the risk that promising new ideas are not picked up, that the time horizon is too far away and that the similarities are too vague. Many scenarios take for granted average political ambitions, while other scenarios are pushing those goals. When drawing conclusions from scenario similarities, one has to be careful not to miss out innovative insights that appear in few scenarios. After all, studies were discussing the overall goal of climate neutrality before politicians were. Only comparing scenario results for 2050 poses another danger. Transition paths should, for that reason, bridge the gap between the long run and the present. Also, conclusions should not be too vague. A discussion on, for example, reducing the use of fossil oil cannot happen without a discussion about the demand side. What will oil demand look like? What oil uses are included? Do studies realise that they project very low use of fossil fuels and at the same time ignore a much higher use of fossil products for non-energy uses (feedstock)?

Scenarios show large differences in their emission reduction paths and in the supply of climate-neutral fuels. When drastic changes are projected, comparison studies should make clear the additional effort that will be needed. We have to bring the message to politicians that the choice of emission reduction pathway has significant impacts on total emissions as well as innovation structures. To ensure the best use of innovation effects on the economy, there has to be a clear action plan throughout the entire period and we should not put all our hopes on the target year. Emission reductions are not standalone numbers and have to be realised in real time by real technologies, by real people with real business models.

Studies agree on electrification rates reaching 40-60%, but disagree on the remaining 40-60% of energy needs not covered by electricity. Studies differ on how we are going to supply those renewable, climate-neutral molecules or power fuels, and to what extent there will be imports and global trade. In comparing scenarios, we have to be alert and verify whether the assumptions on drastic changes in consumption patterns are realistic. How realistic is it to assume we will cut our mobility demand by a factor of two or three or four? Sometimes drastic changes are needed, but the message does not come across even if it is based on a large ensemble of scenarios. It is not helpful to repeat over and over that, for example, renovation rates have to go up to 2%. The reality is that investment in the efficiency of the buildings must go hand in hand with a move away from fossil energy carriers.

Seb Henbest

BloombergNEF (BNEF)

TRADE-OFFS, SECTOR GROWTH AND THE ROLE OF CONSUMERS

"Scenarios differ in their assumption of what is impossible. Trading off renewable energy production against other land uses will have to become mainstream."

Concentrating on similarities in scenario results is useful. It can increase our confidence in the future trajectory of some technologies such as PV and wind or electric vehicles. Yet, we still should be aware that the consensus can change over time. It is also useful to focus on variation in emissions between policy and non-policy-driven scenarios. This is particularly important for industry, heavy transport and buildings.

There is still an underlying sense that so-called "new energy technologies" are too different and disruptive, and will break existing systems. However, we should be more confident that barriers to deployment and integration will be overcome. For example, the barriers to increased wind and PV deployment are about engineering and social acceptance, rather than deficiencies in the technology itself. Market design and price formation are a challenge in a zero marginal cost environment, but are important to get right if we are to leverage private-sector capital in innovation. Wind and PV at high penetration also take up a lot more physical space than conventional thermal power stations. This may become particularly acute if renewables are used to power electrolysers in a possible future hydrogen economy. Looking for consensus in modelling results is certainly useful, but it can also lead us astray. Fifteen years ago, nuclear energy, biomass and CCS dominated most climate scenarios, whereas today we are likely to see hydrogen play a larger role.

Scenarios differ in their assumption of what is impossible, or "off limits". I recommend focusing on the trade-offs, how fast sectors can grow and the role of consumers in the dynamic of technology uptake. There are significant differences between scenarios when it comes to the trade-offs of high renewable energy production, particularly as they relate to land use. Similarly, scenarios differ in assumptions about how rapidly supply chains can be scaled up and mobilised to build renewable capacity. The past 15 years in the power sector have shown that many things people thought were impossible were not.

Studies also differ in the assumptions they make regarding fossil fuel plant operations, such as minimum load factors, ramp rates and capacity factors. Certain power plants are converted from baseload plants into providers of flexibility. Other efficiency improvements in vehicles or white goods, for example, are driven by policy decisions and assumptions there could have a significant impact. Another important difference in modelling is the role of consumers. Consumer choice is something policy makers can affect and has the potential to very quickly ramp up deployment of low-carbon products. In general, public acceptance of low-carbon alternatives is critical to moving fast and achieving net-zero emissions in 2050. What is required to convince people to install rooftop PV and a heat pump, or buy an electric car?

Sheila Samsatli

University of Bath (UoB)

SIMILARITIES AND DIFFERENCES ACROSS SCENARIOS PROVIDE A RANGE FOR TECHNOLOGICAL DEPLOYMENT

"Studies agree on the desire to move away from coal and other fossil fuels. We have to use more renewables regardless of how we can get there."

Studies agree on the desire to move away from coal and other fossil fuels. We have to use more renewables regardless of how we can get to higher penetration of renewables in the system. Another similarity has to do with policy intervention. Many scenarios have established that policy intervention in the form of incentives helped to achieve higher decarbonisation levels, as happened with solar and wind. We will need more policy intervention if other technologies are going to be required. Emission trajectories differ across studies: some only decarbonise towards the end, while others decarbonise much earlier. One crucial underlying factor is the assumptions on the discount rate and the time value of money. Nevertheless, studies conclude that it is cheaper if we set our ambitions higher in the early stages.

Differences across scenarios are useful for policy makers because they provide a range, showing how low or high a particular indicator can be. For example, generating a large number of scenarios enables us to see what the energy system would look like if we incrementally increase the level of ambition, and calculate essential metrics such as the marginal cost of mitigating an additional unit of CO_2, which is helpful for decision-making. One of the critical questions is what we will do to mitigate the last tonnes of CO_2, because these can be very expensive. What technology solution is going to provide this final reduction? In general, scenarios should also try to show the impact on the consumer's energy bill because that is a very useful metric for policy makers. Where scenarios disagree, it is on what sector should be decarbonised first, whether it is mobility first or heating first and what technologies to use. Many scenarios focus on minimising costs, but it is also essential to consider environmental and social objectives, and a particular challenge is how to quantify soft metrics such as consumer behaviour and include them in the models. It is vital to model the trade-offs between economic, environmental and social objectives.

The role hydrogen plays in different scenarios is inconsistent. Energy systems are becoming increasingly complex, and it is within these complexities that new technologies such as hydrogen emerge. As energy systems transition from fossil-based to low carbon, they face many challenges, particularly energy security and flexibility. Hydrogen can help overcome these challenges. Hydrogen has historically had a limited role in influential global energy scenarios, while more recent studies are beginning to include hydrogen.

Trieu Mai
National Renewable Energy Laboratory (NREL)

UNCERTAINTY ON BREAKTHROUGHS CAUSES DIFFERENCES ACROSS SCENARIOS

"There is an underestimate of change in the business-as-usual scenarios and perhaps an over-optimism of technology success in the policy-driven scenarios."

The similarities between the long-term 1.5°C or 2°C scenarios are that some herculean successes are needed. Yet, we do not know which breakthroughs are needed and that creates differences across scenarios. For the long term, there needs to be some breakthrough. It would be helpful to compare which breakthrough technologies are chosen across scenarios. It would be even better to do that over a broader timespan to see whether the selected technologies change over time. A moving consensus would imply that there is still uncertainty in the 2050 timeframe. There is an underestimation of forthcoming change in the business-as-usual scenarios, especially in the power sector, and perhaps over-optimism for technological success in the long-term policy-driven scenarios. In reality, we will probably land somewhere between those bounds.

It is essential to recognise that there has been a narrowing of the pathway for a long-term perspective. This also allows us to start to think about the long-term breakthrough technologies that policy makers might today want to investigate, abandoning ship if some of those do not come to fruition.

If the question is whether we need electrification to reach 1.5°C-type scenarios, the obvious answer is yes. What is different between the scenarios is the level of electrification. Should electrification encompass all light-duty vehicles, or will it be joined by hydrogen or other fuels? I do not think we know the answer to that yet. Examining the assumptions about service demand across all sectors is also essential. Are we underestimating potential changes? Are we overestimating people's willingness to change behaviours and lifestyles to accommodate those service demand changes that we need to reduce emissions? Finally, a helpful exercise would be to look at each study and examine the scenario's most unrealistic assumption or outcome. Some of what we currently believe to be unrealistic may be realistic in the future.

Anahi Molar-Cruz
Technical University of Munich (TUM)

THE BENEFITS OF INTEGRATED MODELLING OF SECTORS AND REGIONS THAT TRADE ELECTRICITY AND OTHER ENERGY RESOURCES

"Understanding major modelling differences is crucial for interpreting the results. One example is the level of electrification of different sectors."

When doing comparison studies, it is important to have transparency regarding the data, the baseline assumptions and the modelling approaches, because we all use different models. If we do not understand the modelling approaches and the assumptions behind them, we cannot draw significant conclusions. This is different from seeking to align every assumption behind the models; each model needs to use its own base assumptions. We found that allowing disagreement on these baseline assumptions makes the derived policies more resilient to a broader set of outcomes. Sometimes key similarities are found in the long-term trend. We concluded, for example, that the impact of a carbon tax favoured renewables at the expense of coal and some natural gas, but had almost no effect on overall oil consumption.

One of the main differences between scenarios is how much electrification is allowed in the different sectors. If we start analysing the power sector alone, we lose some essential information. Electrification of the transport sector and the heating sector need to be taken into account in the models. With the same share of renewables for power generation, the outcome of a high electrification scenario will be significantly different from a medium electrification scenario. This might mean that we would need to increase the models' complexity and create genuinely integrated assessment models. Ideally, these would integrate the different sectors and the various regions trading other energy resources, not only electricity. For sure, we would be able to understand the possible pathways a little more. Also, we need to move away from the assumption that energy demand will always be increasing. We usually start with the belief that our consumption behaviour is going to continue as it is. However, we might need to start thinking about what happens if we reduce our demand and then see how that works in the overall energy system.

Other experts' insights

PABLO RUIZ, JRC

"The best similarities to bring to the attention of policy makers are the ones related to the targets in 2030."

"Consumer choice can work in two ways and we have to learn lessons from the past. People do not like to switch, especially if they are told to."

JOSE MOYA, JRC

" Decarbonisation of industry is a real challenge. Policy makers cannot force industry to make specific investments to become carbon-neutral. There has to be a sufficiently wide choice of technologies to let the market work. To make a difference by 2050, breakthrough technologies should soon be deployed extensively."

" Importing hydrogen from outside the EU is also a market decision and a societal decision on whether we want public taxes to be invested abroad."

" We need new communication methods or tools that allow us to inform policy makers based on the outcomes of models that are becoming more and more complex."

UWE REMME, IEA

" Everybody agrees that the power sector needs to be decarbonised. Differences occur in industry, transport and buildings because these sectors are inherently more difficult to analyse and because of differences in the methodology and scope of the models. Also, models treat hydrogen differently and have different assumptions on what constitutes sustainable biomass."

"Consumer behaviour is often linked to transport and buildings; it is also indirectly linked to the industry if you consider the material needs for vehicles and buildings."

KAARE SANDHOLT, CNREC

"The three main similarities mentioned by the panellists are aggressive energy efficiency, aggressive electrification of the whole system and, of course, greening the power system. But we should also have more explorative scenarios. What would be the impact if we have a breakthrough in CCUS or in small advanced nuclear power stations?"

"The focus should not only be on technological solutions. Illustrating the choices that policy makers have is key. What policy measures are needed to implement the scenarios?"

"The increased complexity of the energy system should also be reflected in the models. Power system simulation on a detailed level and cross-sector dependencies are a must."

EXPERT INSIGHTS

Improving scenario comparison for effective policymaking

This section summarises expert interventions during the panel discussion on ***improving scenario comparisons to make results more readily available to scenario practitioners and policy makers planning the energy transition***. Key questions addressed were:

- What new methods or systematic approaches can be used to address the most common challenges for comparing clean energy transition scenarios?
- How can the communication of comparison results and insights be improved for policy makers?
- How can scenario comparison results be effectively used for policymaking and bring clear insights in a profusion of – sometimes contradicting – views for the future?

Expert panel: Improving scenario comparison

WATCH ONLINE

PANELLISTS

- Christof van Agt, Director of Energy Dialogue, IEF
- Edward Byers, Research Scholar, IIASA
- Jürgen Kropp, Department Head for Climate Resilience, PIK
- Andries Hof, Senior Researcher, PBL
- James Newcomb, Managing Director, RMI
- Anastasia Belostotskaya, Associate Director of Scenarios and Special Projects, WEC
- Daniel Raimi, Senior Research Associate, RFF

OTHER EXPERTS

- Alec Waterhouse, UK Department for Business, Energy & Industrial Strategy (BEIS)
- Charlie Heaps, Stockholm Environment Institute (SEI)
- Sebastian Bush, JRC
- Egle Ferrari, JRC

MODERATOR

Pablo Carvajal, Programme Officer, IRENA

Christof van Agt
International Energy Forum (IEF)

CONFIRMING THE AIM OF SCENARIO COMPARISON STUDIES AND IMPROVING COMPARABILITY

"Comparing scenarios is not about creating consensus, but making sure there is a valid and good intercomparison of different viewpoints."

When framing the scenario comparison study, it may be helpful to clarify that the comparison aims not to predict the energy system's future, but to understand the different ways in which investments, policies and decisions could affect its evolution in the coming years. The wider public often sees scenarios as predictions of what the future has in store, so there is an element of expectation management that can be addressed via the peer review of various scenarios. If comparison studies give the impression of being predictive and fail to manage expectations adequately, they could affect scenario credibility.

We are witnessing huge diversity in scenarios, which cast uncertainties over the energy system's long-term trajectory. For instance, what is the likelihood that the US government or China or India will impose a carbon tax? Scenario comparison should not focus on creating a consensus of what the energy future should be. It should instead focus on making sure we have a valid and reasonable intercomparison of different viewpoints. We can have a more intelligent and informed debate that creates greater clarity and makes scenarios more useful to stakeholders. Therefore, clarifying the descriptive and non-predictive qualities of scenario comparison studies can increase the utility of their results in the hands of investors, policy makers and the public.

Ensuring greater comparability of various elements across scenarios can be crucial to offering stakeholders a methodologically rigorous comparison study. However, not all variation can necessarily be considered as a hindrance to policymaking. The difference in methodologies, results or definitions can also offer insight to policy makers in and of itself. Over the past decade, the IEA, the IEF and the Organization of the Petroleum Exporting Countries (OPEC) have strengthened their commitment to achieving greater data consistency and improving the comparability of energy outlooks, specifically to inform oil and gas market stakeholders. An ongoing challenge in comparing energy outlooks concerns each organisation's different use of historical data, definitions and geographical classification, reflecting the different ways in which institutions are set up or energy sources are categorised in statistical offices in various jurisdictions. For instance, are biofuels classified as renewables? What should be the standard metric to express primary energy demand? The IEF has been comparing various scenarios from the IEA and OPEC to harmonise these variables and ensure that comparison is more on an "apples-to-apples" basis for more informed and valid debate on future projections of the energy system.

James Newcomb
Rocky Mountain Institute (RMI)

SHIFTING ATTENTION TO THE DEMAND SIDE, CONSUMER BEHAVIOUR AND THE ECOSYSTEM

"The big models that we rely on have a stronger supply-side legacy than they do capabilities to look at potentially disruptive changes on the demand side. They fail most severely in the areas that are the most critical to our future."

Achieving a workable 1.5°C future means that the next decade needs to see a quite extraordinary and unprecedented scale-up of new and fundamentally disruptive technologies. The domains of social tipping points and network effects in consumer behaviour are at the edge of our understanding, but these factors are real and significant. Scenarios also need to fully integrate the impact of technology learning to analyse futures that anticipate what is possible as we rapidly scale up production of new technologies. These are some of the most critical areas for the future, yet also among the weakest areas in scenario comparison. Existing models are, in general, built on backward-looking rather than forward-looking approaches. Over the years, we have focused on incumbent dominant pathways, but the reality is that we must disrupt such pathways if we are going to deliver a workable future for the planet. For instance, hydrogen-based steel production is a fundamentally disruptive technology in decarbonising steel manufacturing. It has the potential to scale up at an extraordinary rate not witnessed in industrial history. Future scenarios should focus on integrating the impact of technological learning and exploring learning curves that anticipate changes due to rapid scale-up of disruptive new technologies.

When comparing scenarios, the outlier scenario helps us think about a set of things that conventional scenarios have not so intensely focused on; stretching the envelope with very different approaches is healthy. Effective climate action comes from different directions. Communication and engagement need to expand to include new audiences, including corporates, the financial sector and subnational actors, who are moving in remarkable ways. The scenario community has done a poor job of putting the scope around scenarios, leading to scenarios that may be incompatible with the future ecosystem and conservative in renewable energy share and reduced primary energy. However, this is changing. For instance, the RMI, in collaboration with leaders and financiers of the shipping industry, created a document to support future investment that aligns with global climate goals in that sector (The Poseidon Principles). We expect to see a lot more of such interaction. In each case, the effort will require the creation of climate-aligned sectoral pathways on which industry leaders, the finance sector and, in some cases, the customers of that sector can unite to create ambitious goals that will be applied to future investments.

Jürgen Kropp
Potsdam Institute for Climate Impact Research (PIK)

ASSESSING TRADE-OFFS RATHER THAN ABSOLUTE VALUES IN SCENARIO COMPARISON

"When it comes to energy scenarios, we can make a lot of choices in various sectors, but it is important to focus on the co-benefits and trade-offs involved."

Scenario comparison should focus more on the trade-offs in different scenarios and their implications for policymaking rather than on the numeric differences. Energy scenario comparison indicates that climate change discussions have shifted from a scientific to a more policy-based problem. The scenarios we are creating are only valid under certain circumstances, whether physically determined or intentionally determined by policymaking. Energy scenarios can present alternative routes to achieving the same transition target. However, choosing the best options is not straightforward, and scenario comparison must shed light on the potential co-benefits and trade-offs in policymaking and show evidence of no-regret decisions. Fostering intercomparison requires a shift from focusing on the pure results of scenarios to the trade-offs and co-benefits involved in pathway choices. For example, the decarbonisation of industry through electrification or the use of green hydrogen; deployment of either more private electric vehicles or zero-emission public transport systems; and the deployment of either more natural gas with CCS or a more accelerated scale-up of renewables.

Visualisation tools aid comparison of complex scenario results to improve transparency and distil policy messages. The numerous assumptions and constraints involved in scenario development can complicate the readability and interpretability of results by stakeholders and policy makers. One important question when formulating scenarios is to find out who is using energy scenarios and under what circumstances the scenarios are being used. Posing this question to stakeholders, we identified that we are running models and we have a set of scenarios that nobody can interpret except the experts. The stakeholders, especially the politicians, become puzzled at the complexity of the results and want a simple approach to communicating the results from scenarios. This has an overarching impact on the usefulness of energy scenarios. There is a need for effective and straightforward means of communicating to non-modelling experts the assumptions and the consequences of one sector's policy choices for others. In this sense, scenario comparison study results are greatly aided by the use of visualisation tools. This required us to develop the "EUCalc Transition Pathways Explorer" (EUCalc, 2020b), an online visualisation platform that explores 16 scenarios with a multi-sectoral approach that includes scientific and societal actors in the European Union's pursuit of a net-zero economy.

Edward Byers

Institute for International Applied Systems Analysis (IIASA)

STATISTICAL CONSIDERATIONS AND REVIEWING THE BASELINE ASSUMPTIONS

"When comparing scenarios, take time to understand how different baseline assumptions differ, and be careful not to conflate agreement between scenarios with their likelihood."

Ensembles of scenarios likely under- and over-represent a number of scenario viewpoints, so should not be used to infer likelihood. We must avoid the temptation of treating them as a statistical sample of what is likely to occur; rather, they are better considered as "an ensemble of opportunity" of what could happen (Huppmann, Rogelj et al., 2018). That said, if many scenarios have similar drivers that point to the same outcome, that is a strong indicator of certainty and agreement ("if this, then that will happen"). For instance, at the IIASA, the Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenario

Explorer[1] was developed for the IPCC Special Report on 1.5°C to compare over 400 emissions scenarios consistent with reaching 1.5°C by 2100. An even more extensive effort is now underway for the forthcoming IPCC Sixth Assessment Report. Our focus is on exploring a wide range of scenarios to understand the space for mitigation options, which are the most robust policy levers, and what are their expected climate outcomes using the latest climate models. Ancillary characteristics also allow comparison across many criteria, for instance comparison of water use, material requirements, air quality impacts and land-use implications. So one of the key benefits of scenario ensembles is helping identify which trends and outcomes are robust when considering multiple scenarios and models.

It is crucial to consider the historical and baseline assumptions and context when comparing scenarios. Scenarios depend on the underlying baseline year assumptions using the best available knowledge at the time, and these must be considered when exploring the similarities and differences between scenarios. For instance, some long-term scenarios developed in the early 2010s projected lower near-term values for solar PV deployment which, with hindsight, have been greatly exceeded, and levels of CCS which industry sources assured were credible at the time, but in reality have failed to materialise. Many other aspects of old scenarios remain valid and relevant. So whilst even if some aspects now appear out of date, in certain circumstances the scenarios can still be used with caution. Nonetheless, deviations from recent observations open the door to criticism and threaten to harm the credibility of whole scenario sets and a much wider community. There are also uncertainties on historical values, particularly for emissions, but also for energy. So sometimes it can make sense to harmonise (or normalise) scenarios from different models so that they have a consistent starting point – this facilitates direct comparison of the rate and scale of changes between scenarios, which can be more insightful than focusing on specific numbers.

1 More information available at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.

Daniel Raimi
Resources for the Future (RFF)

CLEAR COMMUNICATION WITH SCENARIO USERS, NOT ONLY WITH SCENARIO DEVELOPERS

"We present policy makers with a wide range of scenarios, and then layer on uncertainties surrounding disruptions to showcase plausible pathways, identify gaps, and understand technological and policy needs."

To ensure that policy makers make full use of scenario comparisons, scenario fundamentals should be made clear to them, including the modelling process and the assumptions. It is crucial for the scenario community to continuously communicate with policy makers to maximise the potential use of scenarios in the policymaking process. We have discovered over the years that when we reach out to policy makers to inform them about the range of possible energy futures and the essential assumptions that underline different scenarios, we do a lot of basic education. Understanding the fundamentals of energy modelling and the inherent uncertainties in the process could help policy makers and their staff utilise insights from scenarios more efficiently and in the proper context.

Showcasing different scenarios (ranging from business-as-usual cases to ambitious climate scenarios) and the data behind them can help policy makers visualise plausible energy pathways and their alignment with historical trends, and show them the technological and policy gaps that exist. For instance, most scenarios do not account for disruptive events in the economy and technology or social changes. And most also have a narrow band of assumptions on GDP, population growth and learning curves for solar and wind. Policy makers also need to understand why there might be a need for rapid deployment of hydrogen in the steelmaking sector, or why there might be a real need to invest in the research and development of frontier technologies to get us to where we need to be. At the same time, looking at the scenarios shows us why we are not getting there yet.

Interactive tools such as calculators and visualisation tools can help distil policy messages from scenario comparison studies. Making underlying data transparent and available can help ensure the influential and trustworthy transmission of policy messages. In that context, we produced the Global Energy Outlook, which includes a publication and a visualisation tool[1] that provides a unique and easily understandable "apples-to-apples" comparison of global energy projections by leading international organisations and corporations. It provides insight into the range of potential scenarios developed for the global level and different regions and countries, with projections varying due to different assumptions on energy technologies and public policies.

1 More information available at www.rff.org/publications/data-tools/global-energy-outlook/.

Andries Hof
Netherlands Environmental Assessment Agency (PBL)

POLITICAL CHOICES ARE THE LARGEST DRIVERS FOR UNCERTAINTY IN ENERGY SCENARIOS

"Most of the differences identified when comparing scenarios are explained by political choices, not model uncertainties."

While input data and assumptions can be sources of uncertainty, policy decisions and inherent policy beliefs have been identified as the most significant drivers of uncertainty when comparing scenarios. Many differences in scenarios are not due to techno-economic uncertainties, but due to political choices of decision makers. These choices relate, for instance, to the extent to which society is willing to be strongly dependent on nuclear energy, biomass, carbon capture, or any other technology or source. These kinds of questions are crucial and should be discussed before developing scenarios to increase the relevance of them. When using existing scenarios, a preselection can be made linked to the research questions of what we want to compare and the pathway choice of interest.

Policy makers are focusing more on scenarios in which both the objectives of the Paris Agreement and other sustainable development goals (SDGs), such as energy access, are achieved. Simultaneously achieving climate goals and SDGs narrows the set of scenarios available to choose from, but provides a more diverse solution since it incorporates the changes on both the demand side and the supply side necessary to achieve the Paris objectives. The weight of policy choices in scenario results must be communicated clearly to policy makers who hold those beliefs; this helps them utilise scenario comparison better by judging the outcomes on the basis of the preconceived ideas that drive the results. This can also help the scenario development process to become more iterative, consisting of a feedback loop that can challenge the policy maker's biases and the assumptions and narratives used in the scenarios themselves.

Grouping scenarios according to their most policy-relevant features helps clarify the uncertainties and differences between them. At the PBL, we have studied the similarities and differences between the 2°C scenarios developed by Shell, bp, the IEA, IRENA, the WEC and the European Commission. An interesting finding from the analysis is that grouping scenarios according to the most relevant policy features helps showcase the choices that policy makers have to make and improve the comparability of scenarios by highlighting their similarities and differences. For instance, we grouped scenarios into those that avoid large-scale use of negative emissions and others that do not. We discovered that those that avoid a heavy reliance on negative emissions technologies achieve faster emission reductions and do not show an increase in natural gas in the short term. Similarly, splitting the scenarios in the IPCC 1.5°C report showed that scenarios that avoid negative emissions would achieve a reduction in GHG emissions in a range of 65-70% by 2050 relative to 2010 levels against the reduction range of 40-70% that the report earlier identified without grouping the scenarios for the same time horizon.

Anastasia Belostotskaya
World Energy Council (WEC)

MOVING BEYOND SCENARIO REPORTS TO ACTIVE USE AND IMPACT

"Building actionable global energy scenarios and putting them to effective use is far from straightforward."

The energy transition is one part of a much wider "grand transition" that is not only about energy. To promote "whole-system" thinking, scenario comparison needs to assess not only numbers, but also, most importantly, the underlying assumptions and narratives. Expanding the scope of comparisons beyond the quantitative results helps to avoid the trap of increasing bias and wishful thinking.

At the WEC, we compared 24 global energy system scenarios, including plausible scenarios (alternative future pathways that might happen whether we want them to or not), outlooks (expected/assumed futures on a business-as-usual projection of current trends) and normative visions (futures that are technically possible and focused on achieving specific goals). Our aim was to provide the worldwide energy community and our members with a clearer understanding of and new insights into the energy transition. The work also prepared them to better engage with, and learn from, new energy futures. The WEC scenario comparison looked at the energy transition's numbers, narratives and underlying assumptions, including the traditional "three Ds" of digitalisation, decentralisation and decarbonisation. And also added a "fourth D" for demand-side disruptions and the move towards a consumer-centric energy system. The key findings highlight the blind spot that energy futures have in digital productivity gains, whole system economics and innovations beyond the energy system. There is also a wide range of uncertainty in demand-side assumptions and future energy uses, and limited attention paid to new energy behaviours among consumers.

There are different ways to make effective use of energy scenarios, depending on aims and users. The proliferation of net-zero goals has triggered a new wealth of energy projections, government-led visions and top-down roadmaps. In most cases they fail to translate into tangible action. The global scenarios comparison provided an opportunity to reflect on the challenges of actually using energy scenarios to drive impact. The WEC is investing in scenario application tools and interactive learning experiences. Different scenarios can have diverse purposes and methods of application. For example, plausibility-based scenarios provide a platform to open up a safe space for disagreement. This facilitates strategic knowledge exchange that can be used as a decision support tool to stress-test an existing strategy and/or design new options for action. Using national visions and plausibility scenarios in a policy gaming exercise allows a discussion around new policy options that could close the gap between the projected and desired future in different scenarios.

Other experts' insights

ALEC WATERHOUSE, BEIS

"There are a whole series of layers when discussing deep uncertainty. There is the layer about climate uncertainty and the layer about technological uncertainty. There is the uncertainty on the input parameters and there is the uncertainty on the policies that one is going to bring forward in order to meet the decarbonisation challenge of the future."

"Sometimes what we think are genuinely new insights are usually just an artefact of the difference between models or the data being used, especially in large integrated assessment models with millions of parameters considered."

"In visualising scenarios, it is necessary to move away from presenting pathways as a series of layered or stacked bar charts, as there is a good evidence to suggest that humans are really poor at interpreting such data."

CHARLIE HEAPS, SEI

"In global modelling of scenarios, there is still the gap of developing very good methods for working with stakeholders to think not just about options on the demand side, but also on wider societal adaptations that might be needed to achieve long-term climate goals."

"It is important to think of how to get global models to reflect the realities on the ground in developing countries and how to communicate what is going on in global models to planners in developing countries struggling to perform national-scale modelling."

SEBASTIAN BUSH, JRC

"Scenarios should be wholistic, covering both technological and demand-side solutions to help policy makers justify their selections among scenarios to different interest groups."

“The open-source community could be a step forward in pooling resources together to address gaps in scenario formulation.”

“Shared socioeconomic pathways are good examples of a balanced approach to keeping scenarios flexible enough to showcase different possibilities and aligning them to be more coherent on assumptions to improve their comparison.”

EGLE FERRARI, JRC

“Scenario comparison presents important opportunities for advancing transparency of scientific studies based on modelling.”

“It is important while communicating messages to policy makers to think about the fact that in policymaking, different audiences and levels of expertise must be considered.”

“It is important to explore the role of narratives in communication, as not all scientists are good at using narratives as effective tools of communicating scenario results.”

CHAPTER 2

BENCHMARKING OF SCENARIO COMPARISON STUDIES

THIS CHAPTER PRESENTS the results of benchmarking 14 recent long-term energy scenario comparison studies. The benchmarking is carried out in two steps. First, an overview of the scope of the scenario comparisons assessed is provided, including their purpose and focus. Second, a qualitative benchmarking of the scenario comparison indicators that the studies used was conducted, with a focus on indicators relevant to the clean energy transition.

Purpose of the scenario comparison studies

Generally, scenarios from different institutions cannot be compared side by side directly. The 14 institutions that produced the studies are heterogeneous and comprise research, private, governmental and international organisations. Figure 4 presents an overview of the types of organisation behind the comparison studies, their primary purpose for comparison and their communication approaches. The comparison of purpose shows that most comparison studies are carried out to improve scenario comparability. However, other studies focus on evaluating trade-offs stemming from the disparity of scenarios that reach the same goal but via different pathways. A few studies also were designed in the context of supporting specific policies. For example, the JRC's study for the European Union is driven by the EU target of achieving net-zero emissions by 2050.

We also assessed the studies' communication approach, highlighting how insights from scenario comparison are conveyed to policy makers and other audiences. This includes studies that used online visualisation tools and those that approach the comparison by grouping scenarios according to their policy relevance.

Analysed scenario comparison studies

The 14 institutions that produced the scenario comparison studies are heterogeneous and mainly comprise research organisations; however, some private, governmental and international platforms are present. We reviewed studies published between 2017 and 2021 that were dedicated comparison studies or had a dedicated section on scenario comparison. Table 5 provides a list of the scenario comparison studies we analysed. Note that after this table we use the abbreviations of the studies to identify them.

TABLE 5 List of scenario comparison studies assessed, with abbreviations

Name of study	Institution	Abbr.
Towards net-zero emissions in the EU energy system by 2050	Joint Research Centre	JRC
Energy Outlook 2020	bp	bp
Comparison of three fundamental "2050" studies on the feasibility of the energy transition in Germany	Energy Systems for the Future (ESYS), the Federation of German Industries (BDI) and the German Energy Agency (dena)	dena
Comparing Long-Term Energy Outlooks 2020	BloombergNEF	BNEF
The curious case of the conflicting roles of hydrogen in global energy scenarios	University of Bath	UoB
Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective	National Renewable Energy Laboratory	NREL
Intermodel comparison: North American Energy Trade and Integration (EMF 34)	Energy Modelling Forum	EMF
1.5°C Scenario Explorer	Institute for International Applied System Analysis	IIASA
Pathways towards a fair and just net-zero emissions Europe by 2050: Insights from the EUCalc for carbon mitigation strategies	Potsdam Institute for Climate Impact Research	PIK
A comparison of key transition indicators of 2°C scenarios	Netherlands Environmental Assessment Agency	PBL
The Map Is Not the Territory: New Routes to a 1.5°C Future	Rocky Mountain Institute	RMI
Global Energy Scenarios Comparison Review	World Energy Council	WEC
IEA-IEF-OPEC Outlook Comparisons Update	International Energy Forum in partnership with RFF	IEF
The Global Energy Outlook	Resources for the Future	RFF

Scope of the scenario comparison studies

We benchmarked the scope of the comparison studies along four dimensions: scenarios compared, system coverage, geographical level and time horizon (Figure 5). Most of the studies include a comparison to gain insights into the clean energy transition for 2°C scenarios (or > 90% reduction of GHG) and 1.5°C scenarios (net-zero emissions). The comparison of 1.5°C scenarios is less common; however, as with 2°C scenario comparisons, they are not only from academia, but also from government research centres and private companies.

Regarding system scope, most studies cover the whole energy system. Some comparison studies focus specifically on the power system or on a technology (i.e. hydrogen). Most studies compare scenarios with a time horizon that stretches from today to 2050, with intermediate milestones focusing on shorter-term insights required for achieving longer-term goals. Only two studies have an outlook extending to 2100.

FIGURE 4 Overview of recent scenario comparison studies by type of organisation, purpose and communicating approach

Main focus	Energy transition and decarbonisation									Not specifically on decarbonisation				
	JRC	bp	dena	BNEF	IIASA	PIK	PBL	RMI	WEC	UoB	NREL	EMF	IEF	RFF
Type of organisation														
Research	✓	○	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	○	✓
Government	✓	○	✓	○	○	○	✓	○	○	○	✓	○	○	○
Private enterprise	○	✓	○	✓	○	○	○	○	○	○	○	○	○	○
International platform	○	○	○	○	✓	○	○	○	✓	○	○	○	✓	○
Main purpose of comparison														
Improve comparability		●		●	●					●	●		●	●
Support specific policies	●		●				●							
Assess trade-offs						●		●	●			●		
Communication approach														
Use of visualisation tools	○	○	○	✓	✓	✓	○	○	○	○	○	○	○	✓
Grouping of scenarios by relevance and by purpose	✓	✓	✓	○	○	○	✓	○	✓	○	○	○	○	○

FIGURE 5 Overview of the scope of the comparison studies

Main focus	Energy transition and decarbonisation									Not specifically on decarbonisation				
	JRC	**bp**	**dena**	**BNEF**	**IIASA**	**PIK**	**PBL**	**RMI**	**WEC**	**UoB**	**NREL**	**EMF**	**IEF**	**RFF**
Scenarios scope														
Number of scenarios compared	16	4+	6	7	414	16	6+	5+	27	33	3+	13	5	14
Includes 2°C or > 90% reduction of GHG	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	○	○	✓	✓
Includes 1.5°C or net-zero	✓	✓	○	✓	✓	✓	○	✓	○	○	○	○	○	○
System scope														
Whole energy system	●	●	●		●	●	●	●	●			●	●	●
Mainly on the power system				●							●			
Technology (hydrogen)										●				
Geographical scope														
Global		●		●	●		●	●	●	●			●	●
Region/country	● EU		● DE			● EU					● US	● US, MX, CA		
Milestone years														
2030 or 2040	✓	✓	✓	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	✓
2050	✓	✓	✓	✓	✓	✓	○	✓	✓	✓	✓	✓	○	○
2100	○	○	○	○	✓	○	○	✓	○	○	○	○	○	○

Notes: CA = Canada; DE = Germany; EU = European Union; MX = Mexico; US = United States.

Benchmarking of scenario comparison indicators

Different motivations behind scenario comparison studies lead to the selection of various indicators for comparison. A specific indicator can be either quantitative (input and output data) or qualitative (underlying scenario narratives). The underlying scenario modelling framework will determine if the scenario information is exogenous input or endogenous modelled results.

We screened 24 indicators that are relevant to the clean energy transition from scenarios aiming for net-zero GHG emissions. The benchmarking criterion is whether or not a specific comparison indicator is included in the study and whether it is a quantitative or qualitative comparison. The indicators are grouped into three broad categories: **1)** energy supply and power generation, **2)** demand and energy efficiency, and **3)** emissions and costs.

Figure 6 Benchmarking of indicators related to the total supply of energy and power generation shows the benchmarking of indicators for energy supply and power. Nearly all studies covering the total energy system compare total energy supply, fossil fuel use and share of renewable energy. Most of the assessed studies agree that increasing the share of renewables in the primary energy supply is crucial to achieving carbon neutrality in the long term. However, there is a gap in the inclusion of indicators required for a complete understanding of the potential trade-offs. On the supply side, there is a gap in reporting on biofuels and Power-to-X. On the demand side, there is a gap in reporting on zero-emission vehicles, electrification of final energy, heating of buildings, low-carbon materials and consumer behaviour. Other indicators that are often missing from the reporting are CO_2 use or sequestration, afforestation or other natural carbon sinks, and cost aspects.

Figure 7 compares energy demand and energy efficiency indicators, which, according to our analysis, are primarily absent from studies that do not explicitly focus on decarbonisation. The only comparisons that cover a wide range of indicators are those concerned with carbon neutrality, but they also have gaps. Some ongoing energy transitions are also missing, such as the electrification of end-use sectors like transport (vehicle fleet). A possible reason for this shortcoming is that only a limited number of the scenarios report such information transparently.

Figure 8 shows the benchmarking of emission and cost indicators. CO_2 emissions and CO_2 removal seem to be well covered by studies focusing on decarbonisation. However, indicators related to CO_2 utilisation, sequestration and natural carbon sinks are rarely included in the comparisons. Only one study provides explicit information on aspects of cost. Because these indicators are relevant to the energy transition, future comparison studies should expand their scope to include such indicators.

FIGURE 6 Benchmarking of indicators related to the total supply of energy and power generation

Main focus	Energy transition and decarbonisation									Not specifically on decarbonisation				
	JRC	bp	dena	BNEF	IIASA	PIK	PBL	RMI	WEC	UoB	NREL	EMF	IEF	RFF
Total supply														
1. Total supply of energy	●	●	○	●	●	●	●	○	●	○	○	○	●	●
2. Coal, oil and natural gas	●	●	○	●	●	●	●	○	●	○	○	●	●	●
3. Biofuels	●	◐	○	○	●	●	●	○	○	○	○	○	○	○
4. Share of renewables	●	●	●	●	●	●	●	○	●	○	●	○	●	●
Power														
5. Electricity by fuel	●	○	●	●	●	●	●	◐	○	○	○	●	○	●
6. Share of variable renewables	●	◐	●	●	●	●	○	◐	●	○	●	●	○	●
7. Power-to-X capacity	◐	○	●	○	○	○	○	○	○	○	○	○	○	○

● Quantitative comparison ◐ Qualitative comparison or based on only one range ○ Not compared

FIGURE 7 Benchmarking of indicators related to energy demand and energy efficiency

Main focus	Energy transition and decarbonisation									Not specifically on decarbonisation				
	JRC	bp	dena	BNEF	IIASA	PIK	PBL	RMI	WEC	UoB	NREL	EMF	IEF	RFF
Demand														
8. Zero-emission vehicles	●	○	●	○	○	●	○	○	●	○	○	○	●	○
9. Electric or district heating in buildings	●	○	●	○	○	●	○	○	○	○	○	○	○	○
10. Sectoral use of biofuels	●	○	●	○	●	●	○	◐	●	○	○	○	●	●
11. Sectoral use of hydrogen and e-fuels	●	◐	●	○	●	●	○	○	◐	●	○	○	○	○
12. Low-carbon materials	○	○	○	○	○	○	○	◐	○	○	○	○	○	○
Energy efficiency														
13. Reduction of final energy	●	○	○	○	●	●	●	○	●	○	○	○	○	○
14. Electrification final energy	●	◐	○	○	●	○	●	○	○	○	○	○	○	○
15. Building renovation	◐	○	●	○	○	●	○	○	○	○	○	○	○	○
16. Behavioural and modal shifts	●	○	○	○	○	●	○	○	○	○	○	○	○	○

● Quantitative comparison

◐ Qualitative comparison or based on only one range

○ Not compared

FIGURE 8 Benchmarking of indicators related to emissions and costs

Main focus	Energy transition and decarbonisation									Not specifically on decarbonisation				
	JRC	**bp**	**dena**	**BNEF**	**IIASA**	**PIK**	**PBL**	**RMI**	**WEC**	**UoB**	**NREL**	**EMF**	**IEF**	**RFF**
Emissions														
17. CO_2 emissions	●	●	●	●	●	●	●	●	●	●	○	○	○	●
18. CO_2 utilisation	○	◉	○	○	●	●	○	○	○	○	○	○	○	○
19. CO_2 sequestration	●	●	○	○	●	●	◉	○	○	○	○	○	○	○
20. Afforestation and other natural carbon sinks	○	◉	○	○	●	●	○	○	○	○	○	○	○	○
21. CO_2 removal technologies (negative emissions from DAC or BECCS)	●	◉	●	○	●	●	●	◉	◉	○	○	○	○	●
Costs														
22. Cost of electricity	○	○	○	●	○	○	○	○	○	○	●	●	○	○
23. System cost	○	◉	●	○	●	○	○	○	○	○	○	○	○	○
24. CO_2 price	○	○	○	○	●	○	○	○	○	○	○	◉	○	○

● Quantitative comparison ◉ Qualitative comparison or based on only one range ○ Not compared

Notes: BECCS = bioenergy with carbon capture and storage; DAC = direct air capture.

CHAPTER 3

OVERVIEW OF SCENARIO COMPARISON STUDIES

INSIGHTS FOR THE CLEAN ENERGY TRANSITION

THIS CHAPTER PRESENTS an inventory of the 14 scenario comparison studies evaluated, highlighting the scope, aim and main findings in line with the clean energy transition.

1. Towards net-zero emissions in the EU energy system by 2050 – JRC, 2020

SCOPE: Whole energy system – European Union

AIM: To identify the similar elements and diverging scenario results towards achieving at least a 50% GHG emission reduction by 2030 (compared with 1990) and near-zero emissions by mid-century in the EU28.

SCENARIOS COMPARED: Eight scenarios achieving more than 50% reduction in GHG emissions by 2030 compared to 1990, and 16 scenarios aiming for climate neutrality by 2050.

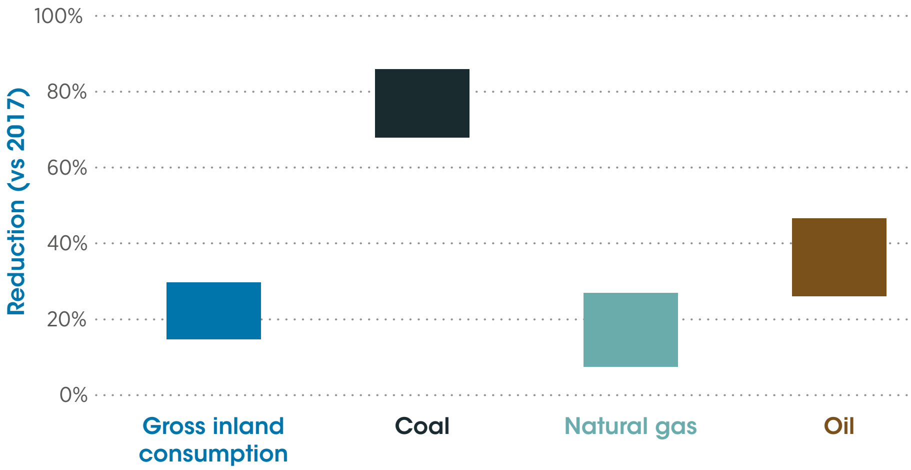
MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **By 2030, a reduction in total usage of coal (70%), natural gas (up to 25%) and oil (25-50%) is projected across scenarios reducing GHGs by around 55% CO_2 by 2030** (Figure 9). An emerging element is replacing fossil heating mainly by heat pumps and district heating in 10-35% of buildings. In the transport sector, vehicle stock is projected to consist of 30-50% zero-emission or plug-in hybrid electric vehicles.

- **By 2050, scenarios project the undisputed growth of wind and solar that will be strongly linked to the level of hydrogen/e-fuel production.** The EU hydrogen sector could become as large as the current power sector in some scenarios.

- **By 2050, climate scenarios project the vehicle stock to be 65-90% zero-emission vehicles and carbon removal technologies to reach 260 million tonnes of CO_2 per year.** There seems to be a necessity for CO_2 removal technologies (negative emissions from DAC or BECCS), afforestation or other natural carbon sinks.

FIGURE 9 Average fossil fuel use reductions across scenarios, 2017-2030



Source: JRC, 2020.

2. Energy Outlook 2020 – bp, 2020

SCOPE: Whole energy system – global

AIM: To explore the forces shaping the global energy transition up to 2050 and the key uncertainties surrounding that transition.

SCENARIOS COMPARED: The chapter on the net-zero global bp scenario, "Net Zero", includes a vast comparison of Net Zero with a range of IPCC scenarios.

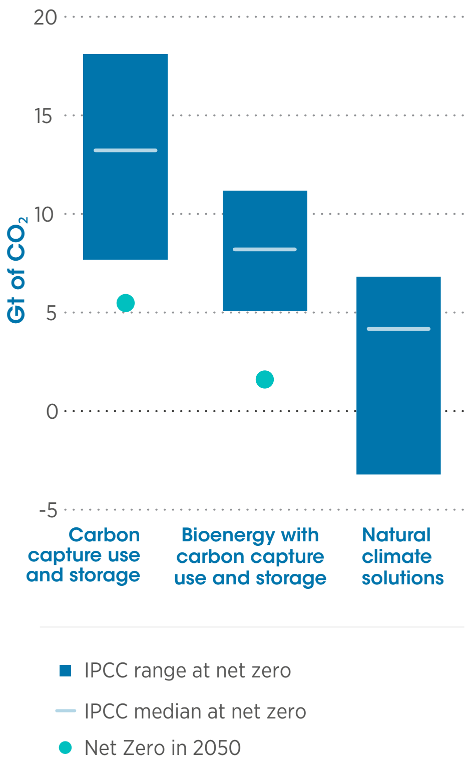
MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **Wind and solar power are the fastest-growing sources of energy over the next 30 years. Demand for oil falls over the next 30 years and depends on the increasing efficiency and electrification of road transport.** Natural gas's role is more resilient than oil's, underpinned by natural gas with CCUS in fast-growing developing economies.

- **CCUS in the Net Zero scenario reaches around 5 gigatonnes of CO_2, and negative emission technologies such as DAC may play an increasingly important role.** The amount of CCUS in the scenario is lower than any IPCC climate scenario (Figure 10), mainly because of the much lower use of BECCS. Negative emission technologies could play a role in offsetting any continuing emissions from hard-to-abate sources, as well as any overshoots in the carbon budget.

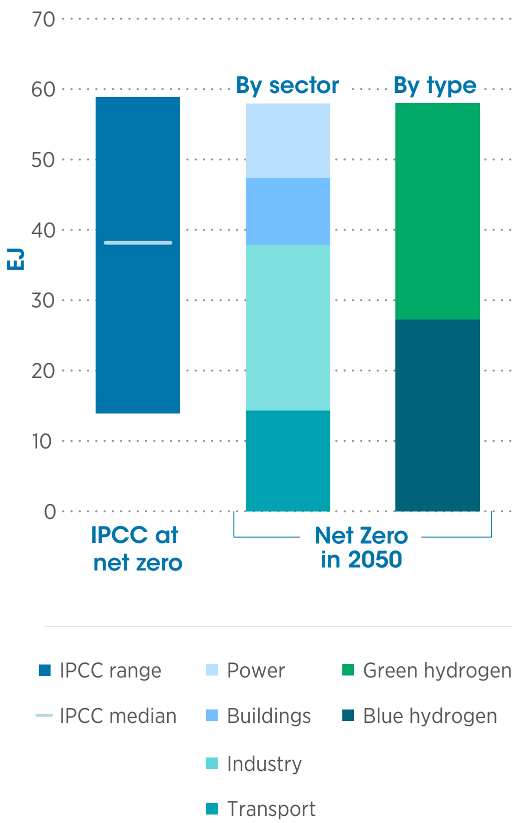
- **Hydrogen in the Net Zero scenario could provide around 15% of total final energy consumption.** It is used in all sectors of the economy by 2050 (Figure 11), especially in high-temperature industrial processes, long-distance road and marine transport, and storage and flexible energy sources in the power and buildings sectors. The production of hydrogen in the Net Zero scenario by 2050 is roughly evenly split between green and blue hydrogen.

FIGURE 10 Carbon captured in IPCC scenarios and Net Zero



Source: bp, 2020.

FIGURE 11 Hydrogen in IPCC scenarios and Net Zero



Source: bp, 2020.

3. Focusing expertise, shaping policy – energy transition now! Essential findings of the three baseline studies into the feasibility of the energy transition by 2050 in Germany – ESYS, BDI and dena, 2018

SCOPE: Whole energy system – Germany

AIM: To compare three fundamental 2050 studies on the feasibility of the energy transition target in Germany, to learn from differences in assumptions, identify common and robust insights and work out political recommendations from a broad stakeholder basis.

SCENARIOS COMPARED: Three studies from the ESYS initiative, the BDI and dena.

MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **An integrated approach is needed to managing the energy transition to enable investment.** All studies show the necessity for quick political measures to achieve Germany's political goals (80% to 95% GHG reduction). A long-term perspective and a continuous social dialogue will be needed for the great structural changes.

- **Renewable energy supply has to be deployed faster, and German wind and PV capacity growth should increase to at least 6 GW net per year. The government needs to ensure security of supply with demand-side management and back-up power plants.** To optimise sector coupling and flexibility for the various applications in the market, root-and-branch reform needs to be carried out. Grid operators, licensing authorities and policy makers need to collaborate to accelerate the expansion and optimisation of smart control systems and approaches.

- **There is a need to increase the extent and speed of energy refurbishment of buildings. There is an essential role for a new technology mix in the transport sector and power fuels (renewable synthetic fuels) as a missing link for the energy transition.** The projected capacity of key indicators is shown in Figure 12. The number of heat pumps in Germany would reach up to 17 million by 2050. Emissions in the industrial sector can be addressed with energy efficiency, renewable energy and new processes.

FIGURE 12 Comparison of results on electrical storage systems and flexible loads in Germany, 2050

Heat pumps, millions
80 to 95% GHG reduction

BDI	14-16
dena	7-17
ESYS[1]	11-15

Batery storage systems, GW
80 to 95% GHG reduction

BDI	10-23
dena	15-18
ESYS[1]	75-191

Power-to-X capacity, GW_{el}
80 to 95% GHG reduction

BDI	0-11
dena	53-63
ESYS[1]	77-112

BEV cars, millions
80 to 95% GHG reduction

BDI	21-28
dena	12-30
ESYS[1]	27-42

[1] **In the ESYS study:** 85-90% GHG reduction in the energy system
Notes: BEV = battery electric vehicle; GW = gigawatt; GW_{el} = gigawatt electrical.
Source: dena, 2019.

4. Comparing Long-Term Energy Outlooks 2020 – BNEF, 2021

SCOPE: Whole energy system – global

AIM: To compare and understand differences between BNEF's New Energy Outlook (NEO) and other long-term scenarios, provide valuable insights to clients and understand the change in outlooks over time.

SCENARIOS COMPARED: Six baseline and six climate scenarios from six publishers (the US Energy Information Administration [EIA], the IEA, bp, Equinor, ExxonMobil and Shell) and the Economic Transition Scenario (ETS) and NEO Climate Scenario (NCS) from BNEF's New Energy Outlook 2020. The BNEF NCS focuses on clean electricity and green hydrogen to limit warming to 1.75°C.

MAIN FINDINGS FOR THE ENERGY TRANSITION:

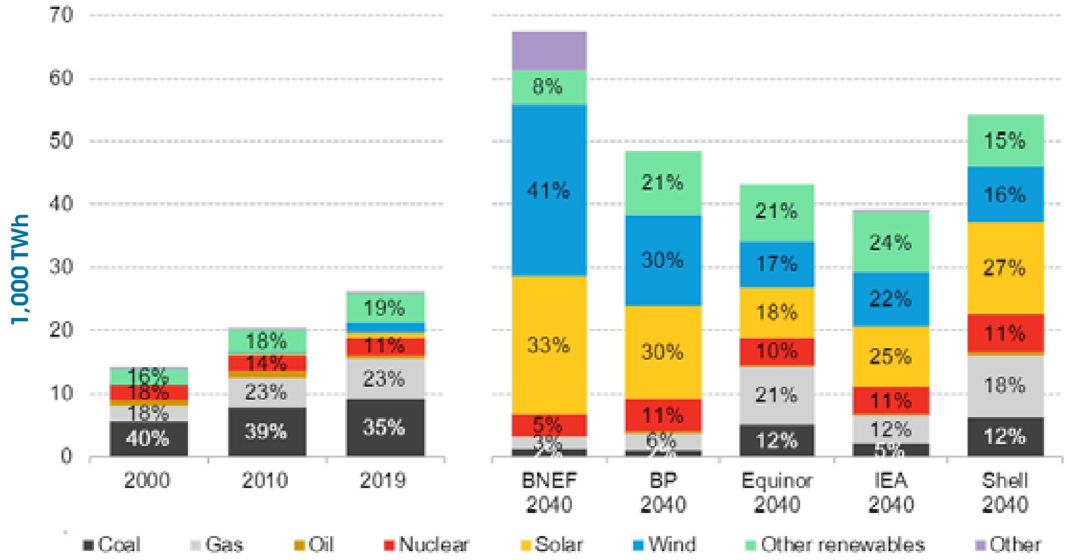
- **All climate scenarios show the power sector making up a larger fraction of the final energy mix over time.** Total global electricity generated in 2040 ranges from around 40 000 terawatt hours (TWh) in the IEA Sustainable Development Scenario (SDS) to nearly 70 000 TWh in the BNEF NCS where electricity generation grows two-and-a-half times from 2019 to 2040. This is due to electric vehicle uptake, electrification in industry and buildings and green hydrogen production.

- **By 2040, renewables play a key role, with a projected share between 56% (Equinor) and 82% (BNEF NCS) for electricity generation** (Figure 13)**. Renewables are between 29% (Shell)**

and 42% (BNEF NCS) of primary energy. Steep emissions reductions occur from 2020 onwards in all climate scenarios aside from Shell's Sky 1.5 Scenario.

- **Scenarios differ in assumptions regarding energy efficiency, CCUS, small modular nuclear reactors and nature-based offsets.**

FIGURE 13 Electricity generation by fuel for the year 2040, climate scenarios



Source: BNEF, 2021.

5. The curious case of the conflicting roles of hydrogen in global energy scenarios – UoB, 2020

SCOPE: Hydrogen – global

AIM: To examine the reasons for inconsistencies between scenarios, for example data or methodologies, and provide recommendations for representing hydrogen in energy scenarios.

SCENARIOS COMPARED: 35 scenarios from 12 global studies focusing on the projection of hydrogen production, use and technologies up until 2050.

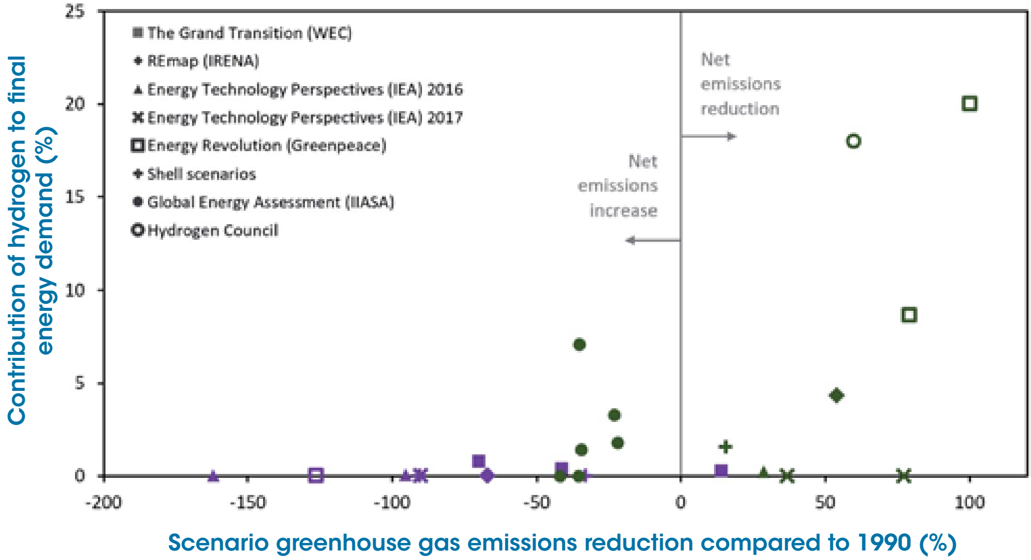
MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **Studies with more ambitious scenarios and a target closer to net-zero require a higher level of penetration of hydrogen and other emerging technologies.** In scenarios without carbon sequestration, hydrogen becomes much more attractive (Figure 14). Furthermore, with more variable renewable electricity, there is significantly more potential for balancing technologies such as power-to-gas.

- **Scenarios need to improve and provide a more consistent set of policy messages to support policy decisions with more confidence.** Energy scenarios result in a variety of policy messages, sometimes conflicting.

- **To improve comparison studies for policymaking, scenarios should be able to model inter-sectoral connectivity and consumer behaviour, with consistent and substantiated data assumptions.**

FIGURE 14 Effect of GHG emissions reduction on hydrogen prevalence in energy scenarios



Notes: A negative GHG emissions reduction represents an increase in emissions over the scenario time horizon. Explorative scenarios are displayed in purple, while normative are displayed in green.

Source: Quarton et al., 2020.

6. Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective – NREL, 2017

SCOPE: Whole energy system – United States

AIM: The study carried out a comparison of four leading US national-scale models on variable renewable energy (the Electric Power Research Institute, US EIA, the US Environmental Protection Agency and the NREL). The focus was on how they treat variable renewable technologies and identify opportunities for improvement across models.

SCENARIOS COMPARED: Three scenarios comprising business-as-usual and a range of low-carbon ambitions used to compare capacity expansion models at the US national scale, up to 2050.

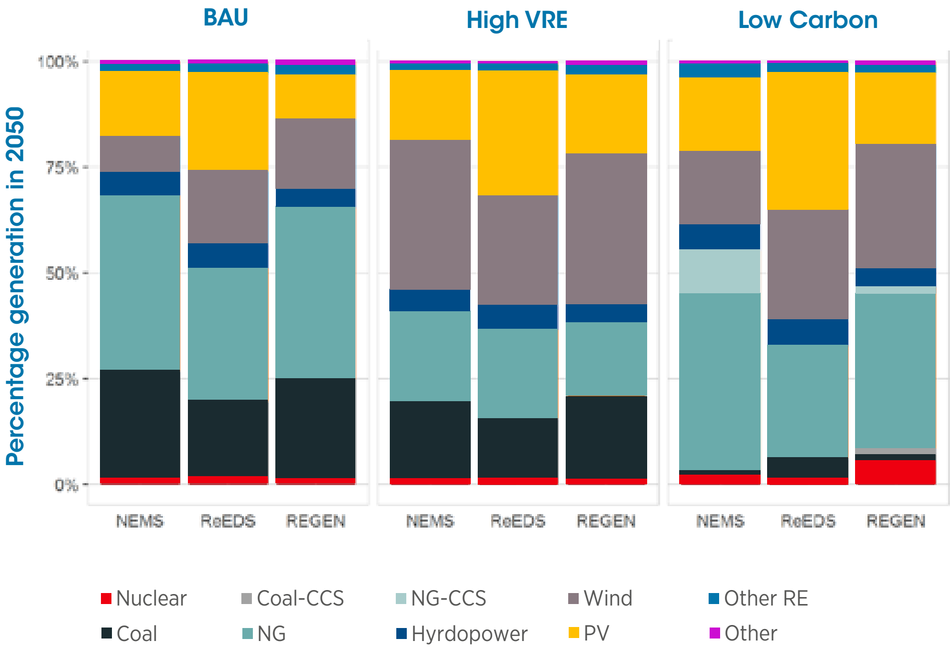
MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **All scenarios analysed showed anticipated growth in variable renewable energy, even in the absence of new policies.** The level of development still varies significantly between scenarios, even with harmonised inputs (Figure 15).

- **It is advised to increase efforts to compare assumptions on financing, planning reserve margin, weather year(s), resource supply curves and variable renewables integration parameters.** These model assumptions or formulations can substantially drive model outcomes. However, it is to be recognised that it is hard to measure the quality of financing assumptions, especially when considering that projections extend to 2050 or later.

- **For increased variable renewable energy, spatial and temporal resolution are essential. It is also recommended to improve how much (reserve) capacity is needed, especially for futures with a higher penetration of variable renewables.** Models typically rely on reference reserve margins or historical data to specify required capacity needs, but the current power system exceeds recommended levels. There might be value in incorporating more fundamental reliability metrics (e.g. loss-of-load probabilities) within the planning models. Still, most of the innovation concerning capacity expansion models utilise "out-of-optimisation" methodologies.

FIGURE 15 Percentage share of electricity generation by source, United States, 2050



Notes: BAU = business as usual; NG = natural gas; VRE = variable renewable energy.
Source: NREL, 2017.

7. Intermodal comparison: North American Energy Trade and Integration – EMF, 2020

SCOPE: Whole energy system – North America (United States, Canada and Mexico)

AIM: The study explored how the Canadian, Mexican and the US energy systems can respond to external factors and coordinated policies, focusing on crude oil, natural gas and power.

SCENARIOS COMPARED: 13 core scenarios comprising 17 energy system models of North America with projections until 2050.

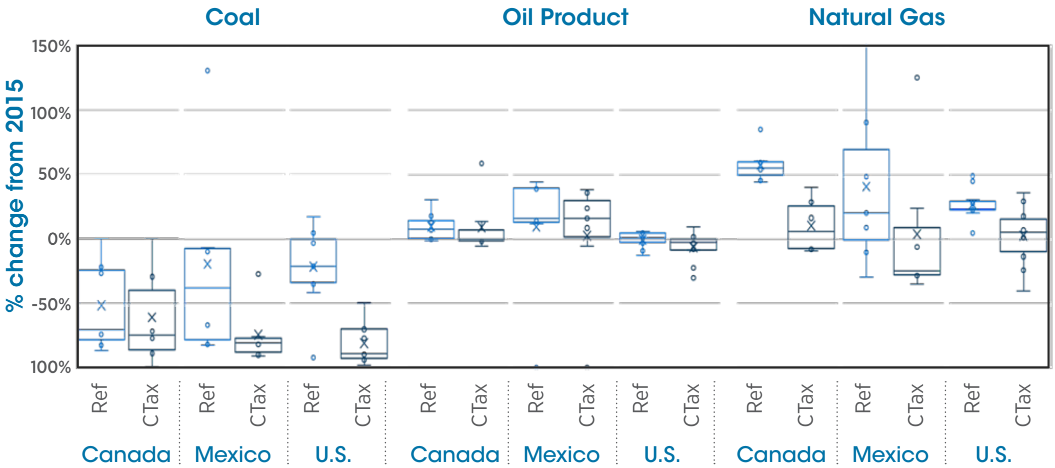
MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **There is a critical need for scenario developers to develop modelling frameworks that integrate major energy sources (oil, natural gas, coal and electric power) and North American countries.** The quality of policy depends on data quality, active exchange and transparency to facilitate cross-border analysis. Better data quality would improve policy decisions and facilitate model development and comparison across the United States, Mexico and Canada. More flexibility in the baseline conditions makes the derived policies more robust to a broader set of outcomes.

- **A carbon tax favours renewables at the expense of coal and some natural gas.** The uptake of intermittent renewables is influenced by the cost reduction of energy storage technologies, but only when coupled with renewable mandates or carbon taxes. Despite the inclusion of a carbon policy scenario, cross-border trade for natural gas, power and crude oil is expected to rise over time.

- **Oil production in particular is modestly responsive to energy prices.** None of the scenarios shows significant reductions in oil or gas consumption, even in a future with a (real) carbon tax that increases to USD 137 (2015). The models' results for natural gas are disparate (Figure 16).

FIGURE 16 Change in fuel consumption from 2015 to 2050 in Canada, Mexico and the United States



Notes: Ref = reference scenario; CTax = carbon tax scenario.
Source: EMF, 2019.

8. IEA-IEF-OPEC Outlook Comparisons Update – IEF, 2020

SCOPE: Whole energy system – global

AIM: The study aimed to elevate international energy dialogue on energy futures by making outlooks more readily comparable, covering IEA and OPEC scenarios to achieve 2°C goals.

SCENARIOS COMPARED: Compared and analysed five scenarios from the IEA and OPEC with projections up to 2050.

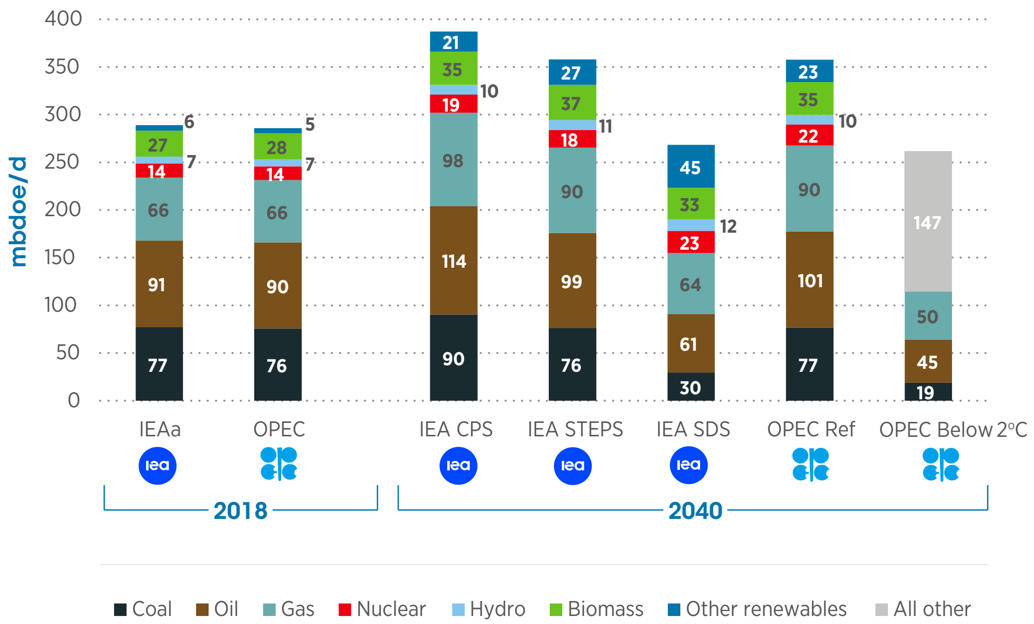
MAIN FINDINGS RELEVANT TO THE ENERGY TRANSITION:

- **Scenarios that aim to achieve below 2°C show a significant decline in oil consumption in the long term.** The IEA SDS and OPEC Below 2°C scenario evidence low oil shares in global primary energy demand by 2040 (Figure 17). Natural gas becomes the leading fossil fuel.

- **All scenarios compared in the study showed an increase in renewables' share, including biomass and hydropower.** Renewables' share in the global primary energy mix is the highest in the IEA SDS. The OPEC Below 2°C scenario shows that oil, gas and coal will provide less than half of total primary energy by 2040 (Figure 17).

- **There is a sharp decline in the share of coal in the global energy mix in the IEA SDS and OPEC Below 2°C scenario.** However, the IEA Current Policies Scenario (CPS), IEA Stated Policy Scenarios (STEPS) and OPEC Reference scenario, which consider policies that have been enacted as of mid-2019, show an increase in coal consumption by 2040 (Figure 17).

FIGURE 17 Global primary energy demand projections up to 2040



Note: mbdoe/d = million barrels of oil-equivalent per day.
Source: IEF, 2020.

9. IAMC 1.5°C Scenario Explorer – hosted by the IIASA, 2018

SCOPE: Whole system emissions – global energy and land use

AIM: The Scenario Explorer aims to present an ensemble of quantitative model-based climate change mitigation pathways underpinning the Special Report on Global Warming of 1.5°C (SR15) by the IPCC (IPCC, 2019).

SCENARIOS COMPARED: The IPCC 1.5°C Scenario Explorer gathered more than 400 global scenarios leading up to 2100 and a wide range of indicators from 25 different models.

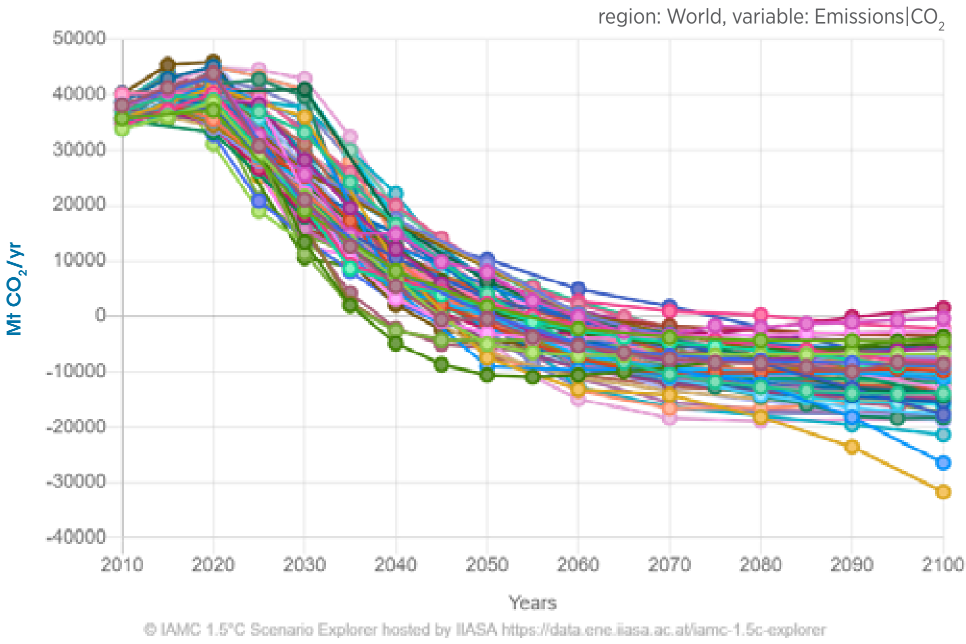
MAIN FINDINGS RELEVANT TO THE ENERGY TRANSITION:

- **Scenarios limiting global warming to 1.5°C with no or limited overshoot will have net-zero CO_2 emissions globally around 2050.** Figure 18 Global CO_2 emissions by 2100, scenario results from the IPCC 1.5°C special report shows the IIASA Climate Explorer ensemble of over 400 scenarios for global CO_2 emission pathways up to 2100, based on the IPCC 1.5°C special report.

- **1.5°C scenarios with no or limited overshoot involve carbon dioxide removal.** However, the amount varies across pathways, as do the relative contributions of BECCS and removals in the agriculture, forestry and other land use (AFOLU) sector.

- **1.5°C pathways have significant synergies with the UN SDGs.** 1.5°C scenarios that include low energy demand, low material consumption and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to the UN SDGs.

FIGURE 18 Global CO_2 emissions by 2100, scenario results from the IPCC 1.5°C special report



Notes: Mt = million tonnes; yr = year.
Source: Huppmann, Kriegler et al., 2018.

10. Pathways towards a fair and just net-zero emissions Europe by 2050: Insights from the EUCalc for carbon mitigation strategies – PIK, 2020

SCOPE: Whole energy system – European Union

AIM: The European Calculator (EUCalc) is an evidence-based platform that used the inputs of over 1 000 experts and intensive literature reviews to define four ambition levels and calculate emission pathways for Europe and member countries.

SCENARIO COMPARED: The tool covered 16 scenarios with projections from 2000 to 2050, covering over 50 sectors, including lifestyles.

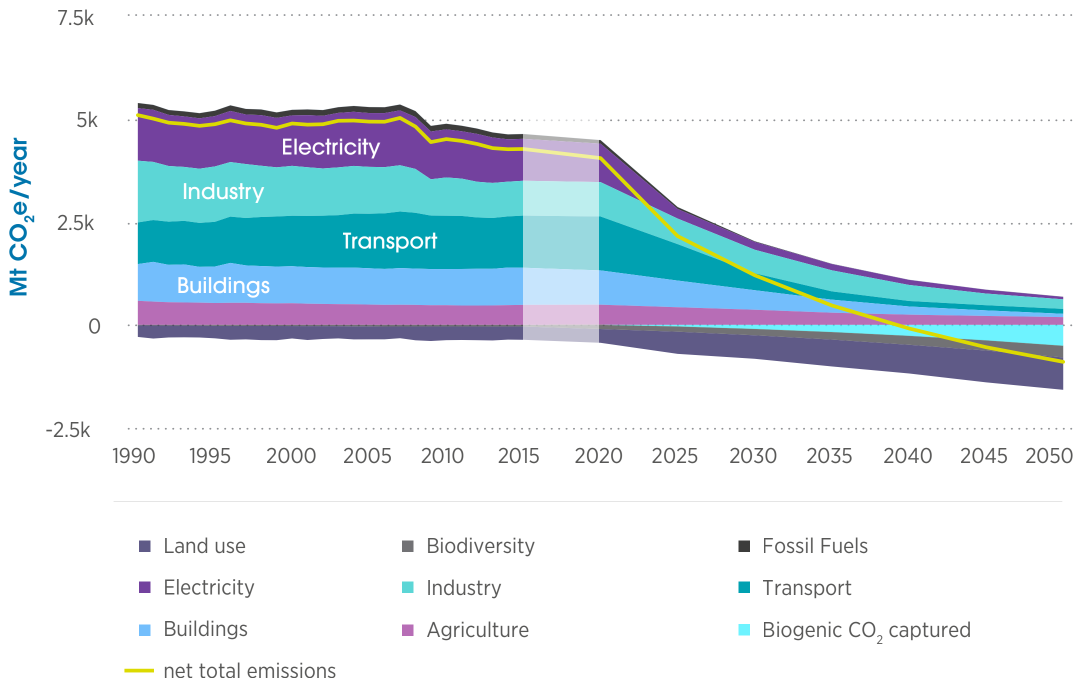
MAIN FINDINGS RELEVANT TO THE ENERGY TRANSITION:

- **Achieving net-zero GHG emissions in Europe involves unprecedented change on both the energy production and consumption sides, including significant behavioural changes and natural carbon sinks.** A net-zero GHG emission pathway would only be achievable by obtaining negative emissions in some activities (e.g. land use and biodiversity restoration) to counterbalance remaining emissions still coming from other sectors by 2050 (Figure 19).

- **Decarbonisation of the buildings sector is crucial to achieving carbon neutrality in Europe.** Reducing CO_2 emissions from buildings in Europe will require refurbishment through deep renovations of all existing buildings by 2050 and the use of decarbonised electricity and heat in buildings.

- **To stay aligned with the EU target of achieving carbon neutrality in 2050 requires increasing deployment of low-emission technologies in the transport sector.** The leading low-carbon technologies needed in the transport sector are hydrogen-fuelled cars, EVs, catenary highways for trucks and synthetic fuels for the aviation and shipping sectors.

FIGURE 19 Simulation of an approximate net-zero GHG emissions in Europe, based on the EUCalc "Ambitious" pathway



Note: Only includes GHG emissions within the European Union and excludes transboundary effects (product imports and exports).

Source: EUCalc, 2020a.

11. A comparison of key transition indicators of 2°C scenarios – PBL, 2019

SCOPE: Whole energy system – global

AIM: The comparison study aimed to showcase the relevance of reducing fossil fuel use in the short term to achieve the Paris Agreement's goal.

SCENARIOS COMPARED: 17 global scenarios from the IPCC, bp, the IEA, IRENA, Shell, the WEC and 3 national scenarios from India were compared with projections up to 2100.

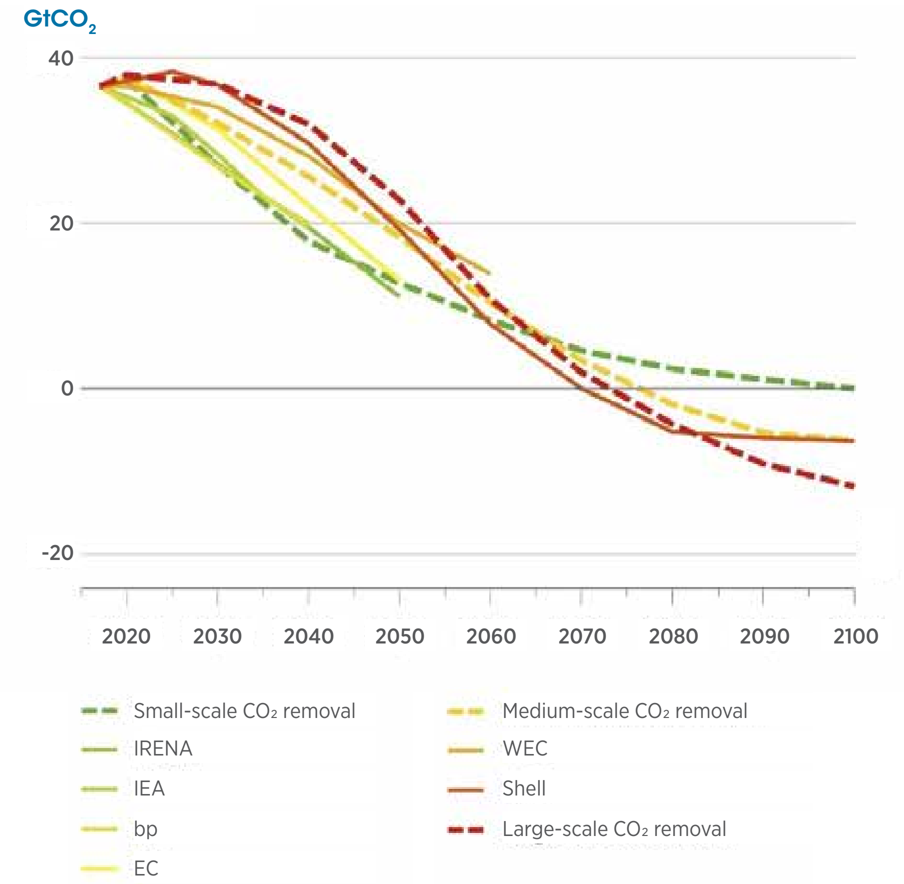
MAIN FINDINGS RELEVANT TO THE ENERGY TRANSITION:

- **The deployment of carbon removal technologies determines how rapidly emission reductions need to happen for net-zero.** Figure 20 shows that scenarios that rely only on small-scale CO_2 removal require immediate decarbonisation in 2020-2030. Scenarios that bet on large-scale CO_2 removal postpone the major emission reductions to 2040-2050.

- **Scenarios that avoid a heavy reliance on CO_2 removal achieve faster emissions reduction without increasing natural gas usage in the short term.** More immediate CO_2 emissions reduction is achieved through energy efficiency improvements, strong scaling up of renewables and a rapid phase-out of coal. Scenarios that avoid heavy reliance on CO_2 removal have higher short-term costs.

- **The two most promising options for large-scale CO_2 removal from the atmosphere are BECCS and reforestation.** However, they require a large amount of land that may negatively affect food security and biodiversity protection.

FIGURE 20 Emission pathways of various compared scenarios



Source: PBL, 2019.

12. The Map Is Not the Territory: New Routes to a 1.5°C Future – RMI, 2020

SCOPE: Whole energy system – global

AIM: The study focused on route finding to explore possible and improbable scenarios that might achieve 1.5°C and manage climate risks.

SCENARIOS COMPARED: The study compared long-term energy transition scenarios from Shell, bp, DNV GL, the IEA and the IPCC until 2040 and 2050.

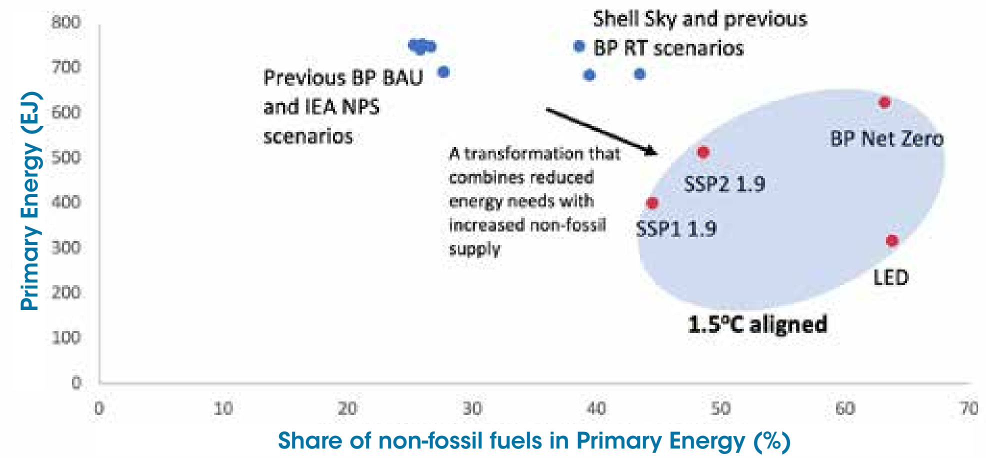
MAIN FINDINGS RELEVANT TO THE ENERGY TRANSITION:

- **Scenarios from oil companies have progressively shown an increase in the share of non-fossil fuels in primary energy.** In Figure 21 Total primary energy and non-fossil share of energy in 2040 for scenarios compared by RMI, bp's Net Zero scenario details a transformation that combines reduced energy needs and non-fossil fuels, providing over 60% of primary energy worldwide in 2040, signifying an extraordinary departure from past outlooks and representing an outlier relative to most major oil companies.

- **Deployment of innovative energy technologies is crucial to achieving net-zero emissions globally by 2050.** Advanced technologies envisioned to play critical roles include new high-energy-density batteries, large-scale high-temperature industrial electric heating, hydrogen-based steel plants and new bioenergy technologies.

- **Scenarios suggest we might have gone past the global peak demand for fossil fuels.** The bp and DNV GL scenarios suggest that global fossil fuel demand is in long-term decline. In at least one of the scenarios presented, it never retains 2019 levels due to the increasing competitiveness of renewable energy, the shift toward electrification of energy end uses, the enormous size of the energy efficiency resource, and other innovative market-based solutions.

FIGURE 21 Total primary energy and non-fossil share of energy in 2040 for scenarios compared by RMI



Source: RMI, 2020.

13. Global Energy Scenarios Comparison Review – WEC, 2019

SCOPE: Whole energy system – global

AIM: The comparison study benchmarked the WEC's long-term scenarios (World Energy Scenarios [WES]) against peer groups and explored lessons from contrasting and comparing different energy futures. The WEC categorised scenarios into outlooks, plausible scenarios and normative scenarios.

SCENARIOS COMPARED: The study explored 24 global scenarios from 12 publishers covering aggregated energy and power system projections until 2040 or 2060, including scenarios from Shell, Statoil, the IEA, IRENA, DNV GL and the IPCC.

MAIN FINDINGS RELEVANT TO THE ENERGY TRANSITION:

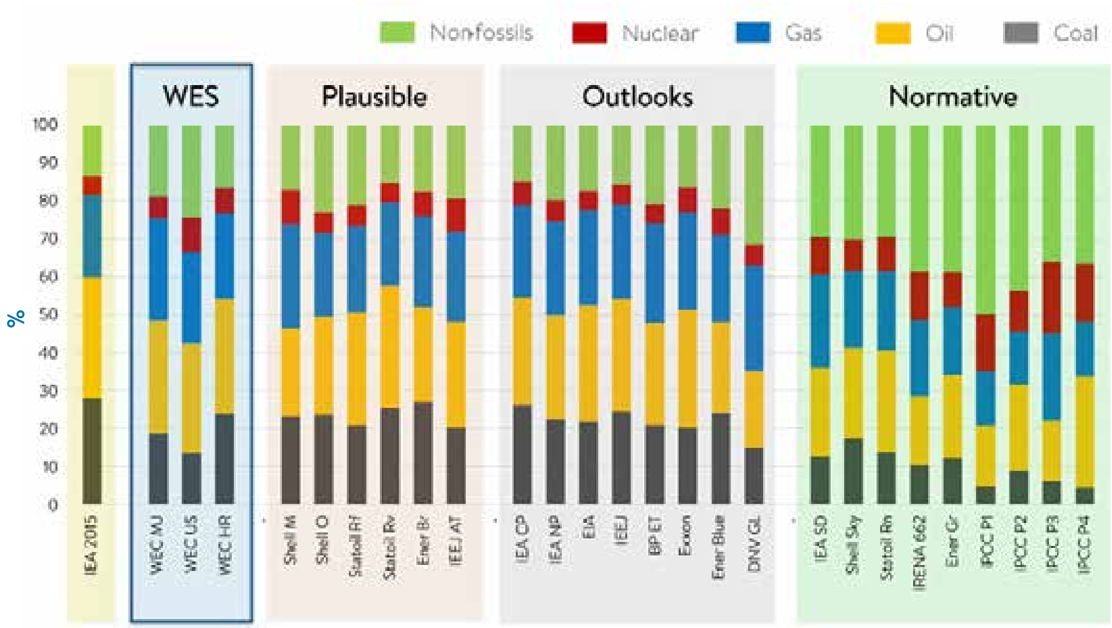
- **Assumptions of total energy demand vary significantly among scenarios.** Demand trends are higher in outlooks and generally lower, but with higher variance, in normative scenarios.

- **Rapid growth of renewables continues to be the key assumption in the shifting energy mix.** However, fossil fuels remain an important part of the energy mix across the majority of plausible scenarios, outlooks and even normative scenarios (Figure 22). The continued diversification of the energy mix is notable in all compared scenarios.

- **New demand-driven energy paradigms emerge**. A high rate of penetration of electric vehicles, supported by battery technologies, is assumed in most scenarios. However, even as the electrification of end uses accelerates, including mobility, heating and cooling, assumptions about the expanding and increasingly active role of consumers is one of major blind spots in the compared scenarios.

- **In normative scenarios the focus is usually on both economic growth and low emissions.** Emissions strategies all share three main pillars: **1)** reducing energy demand by increasing efficiency, **2)** electrification of end uses, and **3)** decarbonisation of electricity generation. There is also a strong focus on accelerating digitalisation in reducing energy demand, a strong role for governments, regional integration and global cooperation.

FIGURE 22 Global energy mix in 2040 for the WES, outlooks, plausible scenarios and normative scenarios



Source: WEC, 2019.

14. The Global Energy Outlook – RFF, 2020

SCOPE: Whole energy system – global

AIM: To provide a unique comparable platform of global energy projections from leading international organisations and corporations, providing insight into the range of potential futures for energy globally, regionally and nationally.

SCENARIOS COMPARED: 14 scenarios from nine publications with historical data back to 1800 and projections up to 2100 from bp, BNEF, US EIA, the IEA, the Institute of Energy Economics, Japan, OPEC and Shell with updates to include scenarios from IRENA and the IPCC.

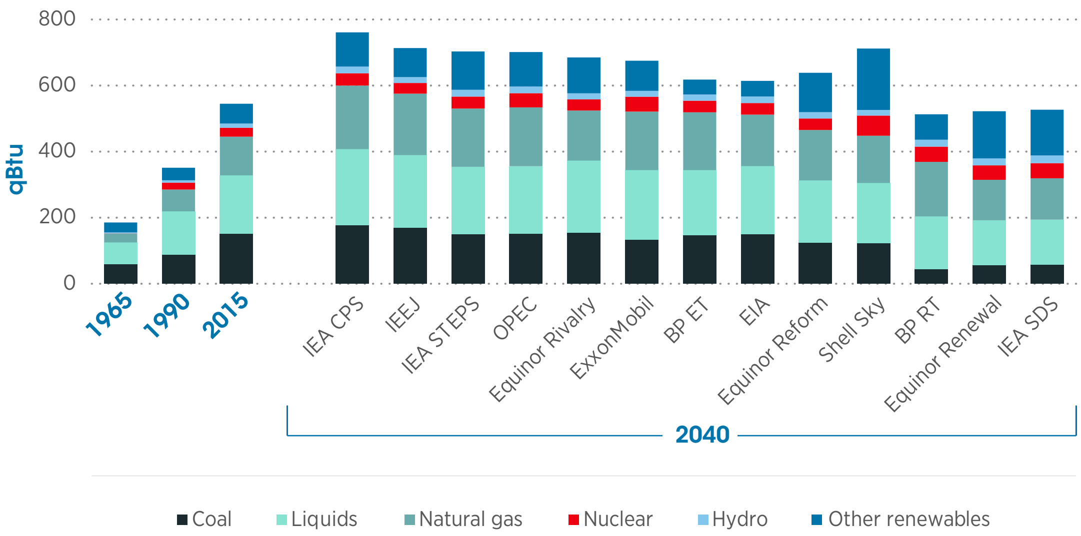
MAIN FINDINGS FOR THE ENERGY TRANSITION:

- **Most projections show continued additions to the energy system across fuels other than coal, but most ambitious climate scenarios envision a transition away from carbon-intensive fuels.** At a global scale, coal declines and liquids grow across most scenarios. Natural gas increases across all scenarios, and renewables grow to rival and – in ambitious climate scenarios – surpass some fossil sources (Figure 23).

- **For most ambitious climate scenarios, coal and oil decline in absolute terms, natural gas grows modestly, and renewables take a new leading role**. In several ambitious climate scenarios, global energy demand declines to 2040 despite a growing population and economy. In Europe and North America, signs of a true energy transition have emerged and are projected to continue across scenarios as coal and liquids consumption declines while renewables grow rapidly.

- **Global demand for electricity surges across all projections, growing by more than 60% above 2015 levels by 2040 under most scenarios.** For the large majority, non-hydro renewables dominate this growth, accounting for more than 50% of net growth in generation under all but two scenarios. Natural gas is the second fastest-growing source, though it varies widely. Nuclear rises under all scenarios. Hydropower also grows under all scenarios, but with a wide variation in outcomes.

FIGURE 23 Levels of global primary energy consumption by fuel



Notes: qBtu = quadrillion British thermal units; scenarios are ordered in decreasing levels of fossil energy. bp and US EIA exclude non-marketed biomass energy (e.g. wood, dung); others include this in "Other renewables".

Source: RFF, 2020.

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APPENDIX

JOINT IRENA-JRC WORKSHOP AGENDA

Day 1, Thursday, 10 September 2020
Scene setting & presentations

* Central European Time (CET)

15:00 – 15:15	**WELCOME REMARKS** **Dolf Gielen,** Director, Innovation and Technology Centre, IRENA **Stathis Peteves,** Head of Unit, Knowledge for the Energy Union, Joint Research Centre of the European Commission
15:15 – 15:30	**SCENE-SETTING** "The LTES Campaign and scenario comparison studies" **Asami Miketa,** Senior Programme Officer, Power Sector Investment Planning, IRENA
15:30 – 15:45	**KEYNOTE** "Towards net-zero emissions in the EU energy system" - Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal **Wouter Nijs,** Project Officer, Joint Research Centre of the European Commission
16:00 – 17:30	**PRESENTATIONS SESSION** Global panorama of energy scenario comparison studies – Brief expert talks on what can be learned from scenario comparison This session will showcase the work of leading institutions involved in energy scenario comparison exercises and provide a global mapping of the latest studies. The session will explore the following points: the main motivations behind comparing scenarios, the key features studied and the main findings of the studies. *See Annex A for a list of scenario comparison studies. **EXECUTIVE PRESENTATIONS** **GROUP A** **William Zimmern,** Head of Global Macroeconomics, bp **Christoph Jugel,** Director - Energy Systems, German Energy Agency **Matthias Kimmel,** Lead Analyst, Bloomberg New Energy Finance **Sheila Samsatli,** Assistant Professor, University of Bath **Trieu Mai,** Senior Energy Analyst, National Renewable Energy Laboratory **Anahi Molar-Cruz,** Research Associate, Technical University Munich
10-MINUTE BREAK	

	GROUP B **Christof van Agt,** Director of Energy Dialogue, International Energy Forum (IEF) **Edward Byers,** Research Scholar, Institute for International Applied System Analysis **Jürgen Kropp,** Department Head for Climate Resilience, Potsdam Institute for Climate Impact Research **Andries Hof,** Senior Researcher, Netherlands Environmental Assessment Agency (PBL) **James Newcomb,** Managing Director, Rocky Mountain Institute **Anastasia Belostotskaya,** Associate Director of Scenarios and Special Projects, World Energy Council **Daniel Raimi,** Senior Research Associate, Resources for the Future **MODERATOR** **Francesco Ferioli,** Policy Officer, European Commission, Directorate General for Energy
17:30 – 17:40	**FIRST DAY WRAP UP SESSION**

Day 2, Friday, 11 September 2020
Breakout group discussions (parallel)

* Central European Time (CET)

15:00 – 16:30	BREAKOUT GROUP A
Discussion amongst presenters (60 min). Expanded discussion with other experts (30 min).	Focusing the scenario comparison – What to explore when comparing energy transition scenarios? Different motivations for conducting scenario comparison studies can lead to the selection of different indicators for comparison. Some studies focus on benchmarking the input data and underlying assumptions (e.g. technology cost, GDP growth projections and emission targets) that drive ambitious transition scenarios, while other studies focus on the scenario output to highlight areas of uncertainty resulting from different energy and technology mixes (e.g. the role of hydrogen, the need for CCS, the rate of electrification of the energy system or investment needs). This session aims to identify the key inputs, results and indicators or metrics that need to be underpinned for scenario comparison studies, in particular which indicators or metrics are most relevant for policymaking in the context of clean energy transition. **See Annex B for an example of similarities and divergences between clean energy transition scenarios for the European Union.* **KEY QUESTIONS THAT WILL GUIDE THIS SESSION** • What are the most relevant indicators for decision making when comparing clean energy transition scenarios? • What are the main similarities and divergences in clean energy transition scenarios and what does this imply for advising policy makers in the pursuit of a low carbon energy system by mid-century? **MODERATOR** **Wouter Nijs,** Project Officer, Joint Research Centre of the European Commission

15:00 – 16:30 Discussion amongst presenters (60 min). Expanded discussion with other experts (30 min).	**BREAKOUT GROUP B** Improving the scenario comparison – How to enhance scenario comparisons for policymaking? Data transparency and diverse modelling approaches are amongst some of the challenges faced when comparing clean energy transition scenarios. Communicating the results of scenario comparison studies is similarly complex and requires some level of expertise to distil and summarise the findings so they can better inform decision making. This session aims to discuss how scenario comparisons can be improved to make results more robust, and how new communication tools can help make insights readily available to scenario practitioners and policy makers. **KEY QUESTIONS THAT WILL GUIDE THIS SESSION** • What new methods or systematic approaches can be used to improve and address the most common challenges for comparing clean energy transition scenarios? • How can the communication of comparison results and insights be improved for policy makers? • How can scenario comparison results be effectively used for policymaking and bring clear insights in a polyphony of – sometimes contradicting – views for the future? **MODERATOR** **Pablo Carvajal,** Associate Programme Officer, IRENA
16:30 – 17:00	**WRAP UP AND FINAL REMARKS – JOINT SESSION**

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