Second publication
(first release VGBE Energy Journal November 2023)

# Forecasts and Scenarios for Global Energy Supply up to 2050 – Synopsis of the Approaches and Results of Studies Published in 2023

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## Introduction

The development of global energy supply in the coming decades is of outstanding interest for the strategic orientation of companies and governments as well as the positioning of international stakeholders. Accordingly, a number of institutions regularly present detailed analyzes of the prospects for energy consumption and its coverage. These include government-backed international organizations, energy companies, consulting firms and scientific institutes. The analyzes produced are characterized by differences in the methods followed and the assumptions made. A fundamental distinction must be made between forecasts and exploratory and normative scenarios. The approaches and results of the studies will be characterized if they were published in 2023. The future paths indicated in these studies are assigned to the categories mentioned. The wide range in the results achieved on the future development of primary energy consumption and electricity generation is explained – differentiated according to energy sources. Furthermore, common messages that can be derived from the studies are identified. This is particularly true with regard to compliance with the climate targets decided by the global community. Increasing electrification and increased use of hydrogen are identified as key technological drivers. For political support, the most globally harmonized pricing of $CO_2$ as well as increased international cooperation are advocated.

## Development of global energy supply from 1985 to 2022

A presentation of the methods and results of the projections and scenarios in which statements are made about the period up to the middle of the century will be preceded by the main features of the global development of energy supply and demand in the period 1985 to 2022. First of all, primary energy consumption **(Figure 1)**.

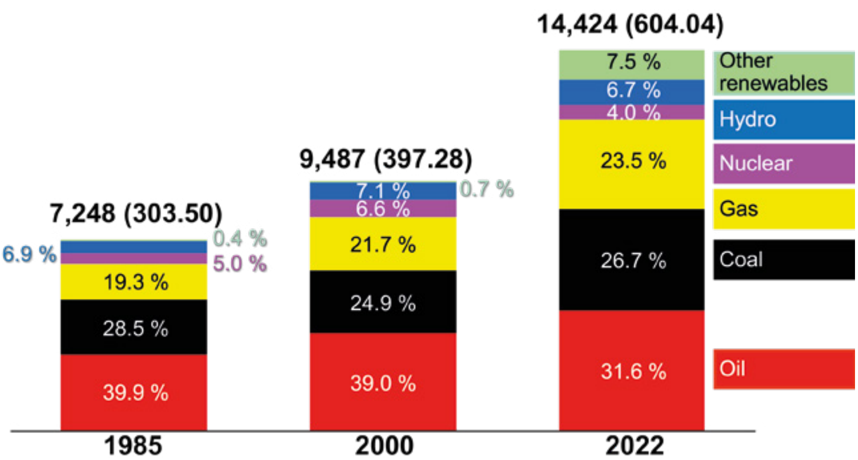


**Fig. 1.**
Global Primary Energy Consumption 1985 to 2022
in Million toe* resp. in Exajoules (EJ)
* tons of oil equivalent
Source: Energy Institute, 2023 Statistical Review of World Energy, June 2023 (Workbook)

From 1985 to 2022, global primary energy consumption has doubled. The main drivers of this development were the increase in the population by almost two thirds and the tripling of global economic output (adjusted for inflation). The energy mix has changed as follows over these 37 years:

- The increase in energy consumption was largely covered by fossil fuels. All fossil energies have made growing contributions to covering the increased consumption.

- The share of fossil fuels in primary energy consumption in 2022 was only 5.9 percentage points lower than in 1985. In 2022, 81.8 % of total energy consumption was from coal, oil and natural gas - compared to 87.7 % in 1985.
- The share of nuclear energy has decreased from 5.0 % to 4.0 %.
- The contribution of renewable energies almost doubled from 7.3 % to 14.2 %.

Global electricity generation tripled from 1985 to 2022 **(Figure 2)**. Here too, a comparable development can be seen with regard to the role of fossil energies:

- The growth in electricity generation was primarily based on a significantly increased use of coal and natural gas.
- The use of fossil fuels in electricity generation has hardly decreased - from 64.1 % in 1985 to 61.5 % in 2022.
- The relative contribution of nuclear energy fell from 15.1 % to 9.2 %.
- Renewable energies were able to compensate for the relative losses of nuclear energy and fossil energies with share gains of 8.5 percentage points. Hydropower, wind and solar energy as well as biomass and geothermal energy accounted for 29.3 % of global electricity generation in 2022 – compared to 20.8 % in 1985.

The coming decades will be fundamentally different from the development shown in the past.

## Forecasts and scenarios for global energy supply until 2050

In 2023, various institutions published perspectives on future global energy supplies up to 2050. These include government-sponsored international organizations, industrial groups, consulting firms and scientific research institutions. Eleven institutions have presented updated global energy projections in 2023, covering all energy sources and technologies. From among the international organizations supported by governments, these are the International Energy Agency (IEA)[1], the International Renewable Energy Agency (IRENA)[2] and the U.S. Energy Information Administration (EIA)[3]. Of the energy companies, BP[4], the Norwegian Equinor[5], ExxonMobil[6] and the international classification and certification company DNV[7] based in Norway have published forecasts and scenarios in 2023 on the prospects for global energy supply up to 2050. In addition, the management consultants McKinsey[8], Wood Mackenzie[9] and Enerdata[10] as well as The Institute of Energy Economics, Japan (IEEJ)[11] presented corresponding studies in 2023.

## Categorization of forecasts and scenarios

The institutions indicated have chosen different approaches to show the prospects for future energy supply. The studies by DNV and ExxonMobil are forecasts, while the other institutions modeled scenarios. Eight of the nine institutions that relied on scenarios calculated both exploratory scenarios and one normative scenario. The U.S. EIA, on the other hand, has limited itself to a reference scenario that is supplemented by sensitivity calculations. One of the common features of the published analyzes is that the assessments of global development are supported by data and facts differentiated by region of the world.

The fundamental differences between forecasts and scenarios can be outlined as follows:

Forecasts present future developments based on parameters that are assumed to be probable, including demographic developments, economic performance, technological innovations, world market prices for energy and the expected political framework. Corresponding assumptions are included in the modeling as input parameters and lead to quantitative results. Institutions that create forecasts strive to reflect what is considered likely from today's perspective.

In contrast, scenarios are plausible and comprehensible alternative views into the future that help to understand how different factors can interact and thus shape the future. A distinction can be made between exploratory and normative scenarios.

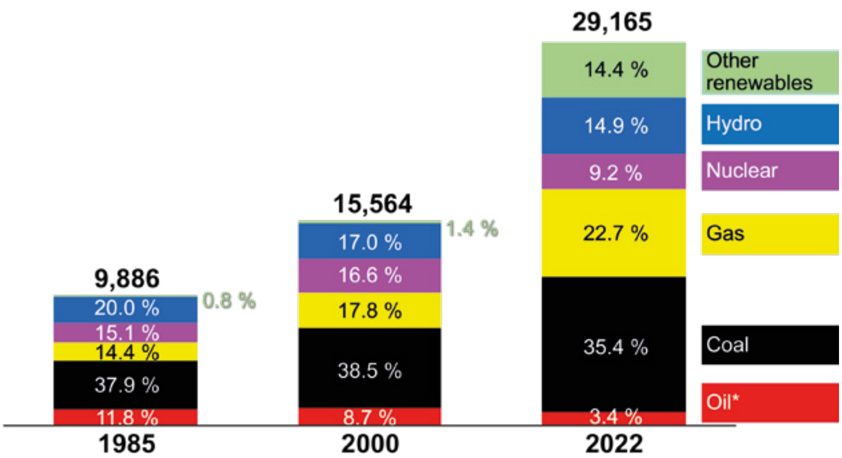


**Fig. 2.**
Global Power Generation Mix 1985 to 2022
in TWh
* including other non-renewable energies
Source: Energy Institute, 2023 Statistical Review of World Energy, June 2023 (Workbook)

- In exploratory scenarios, a development path is shown that starts from the present and – depending on the input parameters chosen – characterizes possible paths for the future. Exploratory scenarios can also be categorized according to whether they are more qualitative or whether the focus is on quantification. Even if the focus is on a narrative, this can be quantitatively supported by a model.
- In contrast to this “bottom-up” approach, in normative scenarios the starting point is a target state in the future. Starting from the defined target state, it is determined top-down which development path can lead to achieving the specified target state. The target state chosen in most of the scenarios examined is to maintain the goal of limiting temperature rise to 1.5 °C compared to pre-industrial levels. In some cases, however, an expanded set of goals is also specified, which can include, for example, access for all people to affordable energy or improved air quality.

Both scenario types are explicitly not predictions. Probabilities of occurrence are not assigned to exploratory or normative scenarios. Both types of scenarios can serve to provide the basis for successful strategy and policy in a world characterized by uncertainty. This applies to both business and political strategies.

When comparing the results of various studies on the prospects of energy supply, it is of crucial importance which approach was chosen and which input parameters were used. The forecasts and scenarios that have recently been presented by the eleven institutions mentioned are assigned to the individual categories **(Figure 3)**.

## Forecasts for global energy supply until 2050

Global energy supply forecasts were presented by ExxonMobil and DNV in 2023. The results obtained differ significantly. In order to understand this, the underlying assumptions must first be explained.

### Characterization of ExxonMobil and DNV forecasts

ExxonMobil has published the company‘s latest view of demand and supply dynamics through 2050. It forms the basis for the company‘s business planning and is underpinned by a deep understanding of long-term market fundamentals. In addition to assessing trends in economic development, technology advances and consumer behavior, the outlook seeks to identify potential impacts of climate related government policies.

The company projects demand for services across 15 sectors covering needs for personal mobility, residential energy, production of steel, cement and chemicals, plus many others. Then it matches that demand across multiple energy sources, taking into account current use and potential evolution. It also projects liquid and natural gas supply and trade flows.

According to ExxonMobil, an energy transition is underway, but it is not yet happening at the scale or on the timetable required to achieve society‘s net-zero ambitions. Three key drivers are available, all involving broad collaboration among governments, companies, universities, and others.

- First, continued public policy support. Incentives like those in the U.S. Inflation Reduction Act can provide the necessary catalyst to begin scaling up low-carbon solutions.
- Second, technology advances. A broad technology approach, where governments avoid picking winners and losers, will lead to the most cost-efficient solutions produced in a timely manner.
- And third, market-driven solutions. Governments across the world can’t afford to pay in perpetuity to reduce the amount of emissions needed to be removed or avoided. Ultimately, to achieve global emission-reduction goals, the world will need to move to widespread adoption of markets where society as a whole incentivizes driving emissions down.

| Organization | Forecasts | Scenarios: non determined (exploratory) scenarios – more qualitatively led | Scenarios: non determined (exploratory) scenarios – more quantitatively driven | Scenarios: normative scenarios |
|---|---|---|---|---|
| **WEC** (2019) World Energy Scenarios 2019 (to 2060) | | – Modern Jazz (MJ)<br>– Unfinished Symphony (US)<br>– Hard Rock (HR) | | |
| **IEA** (2023) World Energy Outlook 2023 | | | – Stated Policies Scenario (STEPS)<br>– Announced Pledges Scenario (APS) | – Net Zero Emissions by 2050 Scenario (NZE) |
| **EIA** (2023) International Energy Outlook 2023 | | | – Reference Scenario (incl. sensitivities) | |
| **Equinor** (2023) Energy Perspectives 2023 | | – Walls | | – Bridges |
| **BP** (2023) Energy Outlook 2023 edition | | – New Momentum<br>– Accelerated | | – Net Zero |
| **ExxonMobil** (2023) Outlook for Energy | – Forecast | | | – IPCC Average Lower 2 °C |
| **Wood Mackenzie** (2023) Energy Transition Outlook | | | – Base Case<br>– Country Pledges | – Net Zero Scenario |
| **DNV** (2023) Energy Transition Outlook 2023 | – A single forecast of the energy future | | | – Pathway to Net Zero Emissions |
| **McKinsey** (2023) Global Energy Perspective 2023 | – Further Acceleration | – Fading Momentum<br>– Current Trajectory<br>– Achieved Commitments | | – 1.5 °C Pathway |
| **IRENA** (2023) World Energy Transitions Outlook 2023 | | | | – 1.5 °C Scenario (1.5-S) |
| **Enerdata** (2023) EnerFuture 2023 | | | – EnerBase<br>– EnerBlue | – EnerGreen |
| **IEEJ** (2023) IEEJ Outlook 2024 | | | – Reference Sc.<br>– Advanced Technologies Sc. | |

**Fig. 3.**
Categorization of outlooks of different organizations on global energy supply

DNV also presents a single forecast for the global energy future, known as the “Best Estimate”, broken down into ten regions of the world. In addition, DNV has presented a “Pathway to Net Zero Emissions” that shows what could be possible, although the associated challenges are considered very significant. The aim of this additional “backcasting” is to demonstrate the gap between the “Best Estimate Future” and the “Net Zero Pathway”.

The forecast, which is the focus of the DNV analysis, is based on the following parameters:

- Consideration of longer-term dynamics and not short-term imbalances
- Continued development of existing technologies, without assuming, from today‘s perspective, uncertain breakthroughs
- Inclusion of key policy trends, with non-resilient commitments (NDCs) being included with caution
- Changes in behavior, particularly in relation to increased requirements for environmental and climate protection

The model structure and the input data are shown in detail in the study.

## Results of ExxonMobil and DNV forecasts

ExxonMobil and DNV come to different conclusions regarding the prospects for global energy supply. This is illustrated by the forecast development of primary energy consumption by energy technology **(Figure 4)**.

ExxonMobil assumes that global primary energy consumption in 2050 will exceed the level of 2022, given the population increase of around 2 billion and economic output more than twice as high as today. The energy mix will change significantly. Energy from solar and wind is projected to more than quintuple, from 2 % of the world‘s supply to 11 % in 2050. Coal will increasingly be displaced by lower-emission sources of electricity production – not just renewables but also natural gas. Natural gas use is projected to increase by more than 20 % by 2050 given its utility as a reliable and lower emissions source of fuel for electricity generation, hydrogen production and heating for both industrial processes and buildings. Oil use is expected to decline significantly in personal transportation but will remain essential for the industrial processes and heavy-duty transport like shipping, long-haul trucking and aviation. Oil and gas are projected to still make up more than half of the world‘s energy supply in 2050. The expected decline in coal consumption will lead to losses in the share of coal in total primary energy consumption from 27 % in 2022 to 14 % in 2050.

The contribution of all fossil energies to covering total primary energy consumption will decrease from 80 % in 2022 to 68 % in 2050. Nuclear energy will then amount to 7 % (compared to 5 % in 2022). The share of renewable energies in primary energy consumption will grow from 16 % in 2022 to 25 % in 2050.

Global electricity consumption is increasing significantly faster than primary energy consumption. Electricity demand in 2050 is expected to exceed current levels by 80 %. According to ExxonMobil, the use of natural gas to generate electricity will swell in the future, while the use of coal in 2050 will be more than a third lower than today. Nuclear energy is increasing by around 50 %. The contribution of wind and solar energy to electricity generation is growing the most. By 2050, solar energy is expected to increase tenfold and wind power is expected to increase sixfold compared to 2021 levels.

As a result of model calculations carried out by ExxonMobil, energy-related $CO_2$ emissions will fall by 25 % to 25 billion tons by 2050. This would mean that the Paris climate target would be clearly missed. In order to limit the temperature increase to less than 2 °C compared to pre-industrial levels, energy-related $CO_2$ emissions would have to fall to 11 billion tons by 2050, according to the group‘s analyses.

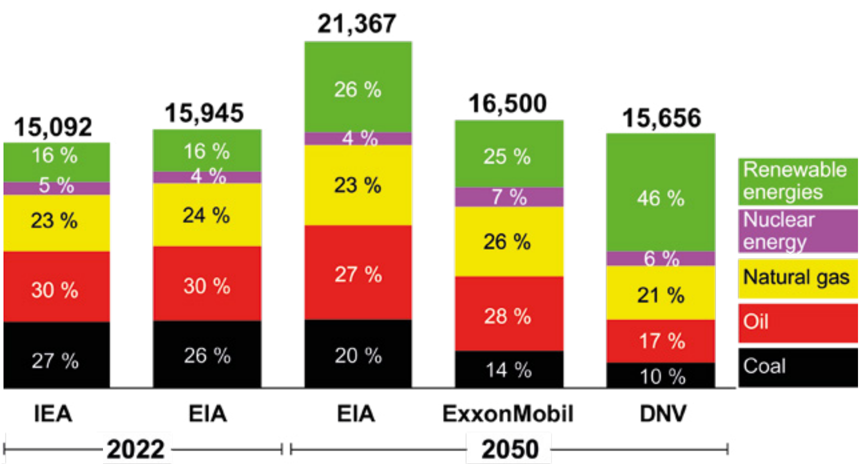


**Fig. 4.**
Global primary energy consumption – Synopsis of EIA’s IEO 2023 **Reference Case** and the **forecasts** from ExxonMobil and DNV in 2050 in Mtoe
Source: IEA, World Energy Outlook 2023; EIA, IEO 2023; DNV, Energy Transition Outlook 2023; ExxonMobil, 2023 Global Outlook

In contrast to ExxonMobil, DNV comes to the conclusion that global primary energy consumption will peak at 663 exajoules in 2038, exceeding today‘s level by 9 %. As

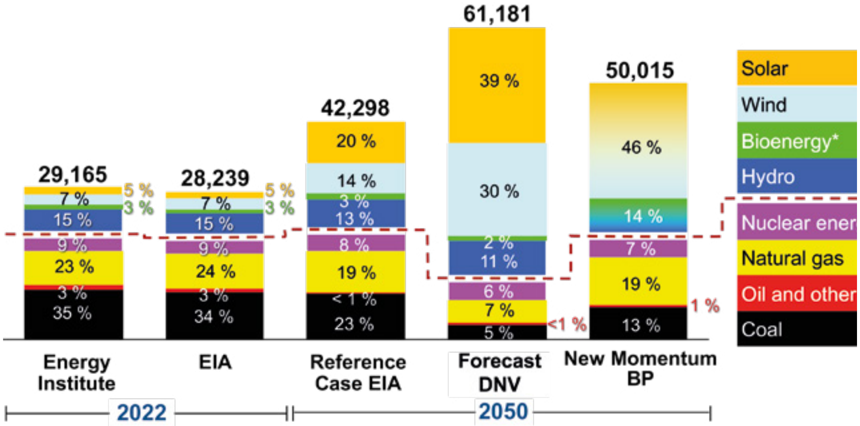


**Fig. 5.**
Global power generation – Comparison of the results between the EIA **Reference Case** with BP's **New Momentum Scenario** and DNV's **forecast** in TWh

* Including geothermal energy

Source: EIA, IEO 2023; DNV, Energy Transition Outlook 2023; BP, Energy Outlook 2023

Solar energy will account for 54 % of global electricity generation capacity in 2050, according to DNV calculations. The share of the PV generation fed into the grid will be 39 %. In 2022, the global share of solar PV was just under 5 %. Electricity generation from wind power is expected to increase from 2.0 PWh in 2022 to 18.3 PWh in 2050. This corresponds to a ninefold increase. This means that wind will account for 30 % of total global electricity generation in 2050, compared to 7 % in 2022. Hydropower will grow by 50 %. The share of hydropower will therefore decrease from 15 % in 2022 to 11 % in 2050. The remaining renewable energy shares come from bioenergy and geothermal energy.

a result, it is expected to decline to 655.6 exajoules or 15,656 Mtoe in 2050.

The contribution of fossil energies to covering consumption will decrease from currently around 80 % to 48 % by the middle of the century. The share of coal falls from 27 % to 10 %. Oil consumption is reduced by 38 percent. This will be accompanied by a reduction in the share of oil in primary energy consumption from 30 percent in 2022 to 17 % in 2050. Global gas demand will reach its highest level in 2036 and then fall to a level that is 10 % below today's level. The share of natural gas in primary energy consumption will decrease from around a quarter to 21 % over the forecast period.

The peak of electricity generation based on nuclear energy is expected in 2047 at a level that exceeds the current level by 41 %. The share of nuclear energy in primary energy consumption will increase from 5 % in 2022 to 6 % in 2050. Renewable energies are experiencing a rapidly accelerating growth trend. Their percentage contribution to covering global primary energy consumption will triple to around 46 % by 2050.

According to DNV, the transformation of energy supply is primarily characterized by increased use of electricity. At 61 petawatt hours (PWh), global electricity consumption in 2050 will be more than twice as high as in 2022, for which 29 PWh is reported. This means that the share of electricity in covering global final energy consumption will increase from 19.5 % in 2022 to 35 % in 2050. But electricity consumption is not only growing, it is also becoming greener. According to DNV, in 2022, 31 % of net electricity generation worldwide was based on the use of renewable energies **(Figure 5)**. By 2050, their share is expected to increase to 82 %, around half of which will come from solar energy.

Hydrogen and its derivatives are seen as crucial for the decarbonization of sectors that are difficult to electrify directly, such as aviation and shipping, heavy transport and high-temperature processes in industry. According to DNV estimates, global hydrogen production will increase from just under 100 million tons in 2022 to over 300 million tons in 2050. However, hydrogen only accounts for 3 % of final energy consumption. In order to meet the 1.5 degree target, there would have to be a much stronger ramp-up, namely to a contribution of around 15 % of final energy consumption.

DNV finds that energy-related global $CO_2$ emissions will fall only slightly over the current decade, from 33.4 billion tons in 2022 to 32.1 billion tons in 2030, and then only in the following two decades, to 18.1 billion tons in 2050. This development would result in an increase in global temperatures of 2.2 °C compared to pre-industrial levels.

## Scenarios for world energy supply until 2050

Exploratory and normative scenarios for the development of global energy supply were presented in 2023 by the International Energy Agency, the U.S. Energy Information Administration and IRENA, Equinor and BP, McKinsey, Wood Mckenzey and Enerdata as well as IEEJ. The selected scenarios differ significantly. The exploratory scenarios are characterized by the assumptions made in each case and express what can be expected if one starts from the specifications outlined differently for the scenarios. The normative scenarios explain what would have to happen in order to achieve the specified goal or set of goals.

## Characterization of the scenarios

The International Energy Agency (IEA) examined three scenarios for global energy supply by 2050 in

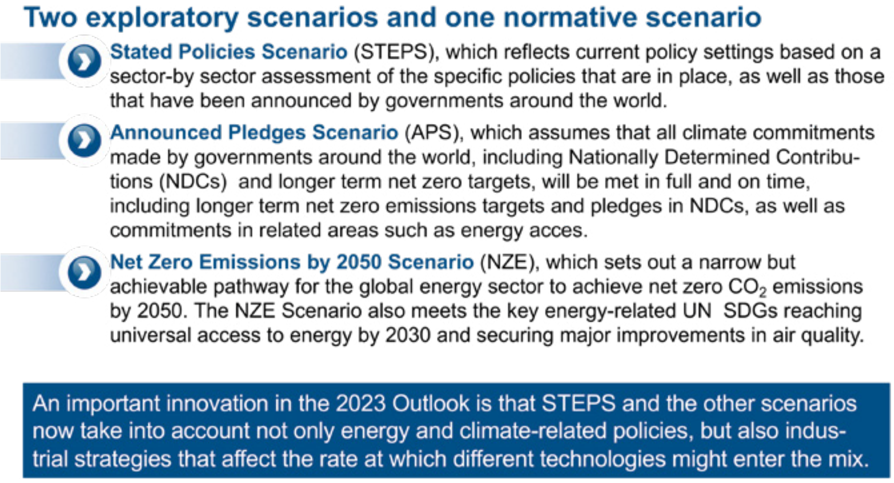


**Fig. 6.**
IEA's World Energy Outlook 2023

the World Energy Outlook 2023. Two of these, the Stated Policy Scenario (STEPS) and the Announced Pledges Scenario (APS), belong to the group of exploratory scenarios. The third, the Net Zero by 2050 Scenario (NZE), can be classified as a normative scenario **(Figure 6)**. In addition to statements on global perspectives, the publication also contains analysis results differentiated by world regions.

IRENA's World Energy Transitions Outlook 2023 builds on two key scenarios to capture global progress toward meeting the 1.5 °C climate goal: The Planned Energy Scenario (PES) is the primary reference case for this study, providing a perspective on energy system developments based on governments' energy plans and other planned targets and policies in place at the time of analysis, with a focus on G20 countries. The 1.5 °C Scenario describes an energy transition pathway aligned with the 1.5 °C climate target to limit global temperature increase by the end of the present century to 1.5°C, relative to pre-industrial levels. It prioritizes readily available technology solutions, which can be scaled up to meet the 1.5 °C goal and outlines a vision for the transition of the energy landscape to reflect the goals of the Paris Agreement.

The International Energy Outlook 2023 (IEO 2023) of the U.S. Energy Information Administration (EIA) explores long-term energy trends across the world and in 16 regions through 2050. The organization uses the World Energy Projection System (WEPS), an integrated economic model that captures long-term relationships between energy supply, demand, and prices across regional markets. Besides the Reference Scenario, the IEO 2023 includes a series of cases that reflect different assumptions related to macroeconomic growth, technology costs, and fuel prices. Neither the Reference Scenario nor the cases can be interpreted as predictions. Rather, the IEO 2023 is based on current laws and regulations as of March 2023; the U.S. projections refer to laws and regulations as of November 2022. That means: The EIA represents a set of policy-neutral baselines against which future policy action can be evaluated.

Equinor has presented one exploratory scenario (Walls) and one normative scenario (Bridges). The Walls scenario builds on current trends in market, technology and policy, assuming them to continue developing at a slowly accelerating pace in the future. Economic growth remains the key driver for growing energy demand, and national governments continue to prioritize short-term economic growth over long-term climate goals. The Bridges scenario is a normative back-cast aligned with the 1.5 °C global warming ambition in the Paris Agreement. This scenario requires the establishment of a benign geopolitical landscape, supporting renewed cooperation and friendly competition among nations. Energy markets become more integrated and technological advancements are shared more readily. Climate action remains the key driver, and all regions increase the expansion of renewable capacity, improve energy efficiency and make drastic behavioral changes.

BP's report builds on two exploratory scenarios and one normative scenario. New Momentum is designed to capture the broad trajectory along which the global energy system is currently progressing. It places weight both on the marked increase in global ambition for decarbonization seen in recent years and the likelihood that those aims and ambitions will be achieved, and on the manner and speed of progress seen over the recent past. Accelerated is conditioned on the assumption that there is a significant tightening of climate policies leading to a pronounced and sustained fall in $CO_2$-equivalent ($CO_{2e}$) emissions. The fall in emissions in Net Zero is aided by a shift in societal behavior and preferences which further supports gains in energy efficiency and the adoption of low-carbon energy sources. Neither the two exploratory scenarios nor Net Zero are predictions of what is likely to happen. Rather, the three scenarios taken collectively are used to explore the range of possible outcomes over the next 27 years.

McKinsey has published a range of scenarios **(Figure 7)**. The four bottom-up scenarios are equal in granularity (i.e. 300+ million datapoints for each scenario); they combine a combination of long-term fundamental economic modeling and

| Scenario | Description | Implied $CO_2$ price $/t $CO_2$, 2030 – 50 | Temperature increase |
|---|---|---|---|
| **Fading momentum** | Fading momentum in cost reductions, climate policies, and public sentiment will lead to prolonged dominance of fossil fuels. | **< $ 60** | **2.9 °C** (2.4 - 3.5) |
| **Current trajectory** | Current trajectory of renewables cost decline continues, however currently active polices remain insufficient to close gap to ambition. | **$ 60 - $ 90** | **2.3 °C** (1.9 - 2.8) |
| **Further acceleration** | Further acceleration of transition driven by country-specific commitments, though financial and technological restraints remain. | **$ 60 - $ 140** | **1.9 °C** (1.5 - 2.3) |
| **Achieved commitments** | Net-zero commitments achieved by leading countries through purposeful policies; followers transition at slower pace. | **$ 130 - $ 180** | **1.6 °C** (1.3 - 2.0) |
| **1.5 ° pathway** | A 1.5 ° pathway is adopted globally driving rapid decarbonization investment and behavioural shifts. | **$ 180+** | **1.4 °C** (1.1 – 1.7) |

**Fig. 7.**
Description of the five McKinsey Global Energy Perspective 2023 scenarios

| Szenario | Region | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| **Stated Policies Scenario** | Canada | 130 | 150 | 155 |
| | Chile and Colombia | 13 | 21 | 29 |
| | China | 28 | 43 | 53 |
| | European Union | 120 | 129 | 135 |
| | Korea | 42 | 67 | 89 |
| **Announced Pledges Scenario** | Advanced economies with net zero emissions pledges[1] | 135 | 175 | 200 |
| | Emerging market and developing economies with net zero emissions pledges[2] | 40 | 110 | 160 |
| | Other emerging market and developing economies | - | 17 | 47 |
| **Net Zero Emissions by 2050** | Advanced economies with net zero emissions pledges | 140 | 205 | 250 |
| | Emerging market and developing economies with net zero emissions pledges | 90 | 160 | 200 |
| | Selected emerging market and developing economies[3] | 25 | 85 | 180 |
| | Other emerging market and developing economies | 15 | 35 | 55 |

**Fig. 8.**
$CO_2$ prices for electricity, industry and energy production in selected regions by scenario USD (2022, MER) per tonne of $CO_2$
1) includes all OECD countries except Mexico
2) Includes China, India, Indonesia, Brasilia and South Africa
3) without Net Zero obligations
Source: International Energy Agency, World Energy Outlook 2023, Page 297

thinking on learning curves (quantitative) with assessment of policy (which could be quantitative as well, e.g. in case of subsidies) and ramp-up/readiness/constraints (e.g. looking at supply and potential bottlenecks) (more qualitatively). It can be argued that right now we are more on the Further Acceleration path. The fifth scenario is top-down and illustrates a pathway the world would need to follow to reach the 1.5 °C target.

Wood Mackenzie has published three scenarios, a Base case, a so-called Country pledges and Net zero 2050. These scenarios, two exploratory and one normative, are defined by different policy assumptions and various enablers. Base case: Evolution of current policies and aligned with the Wood Mackenzey‘s commodity outlooks released in H1 2023. Steady advancement of current and nascent technologies is assumed. Country Pledges: Aligned with net zero pledges announced in the run up to COP28. Incorporates policy response to the current energy crisis, and geopolitical challenges facing global economy. Net Zero 2050: Aligned with the most ambitious goal of the Paris Agreement. Immediate peak energy; rapid hydrogen and carbon removal deployment; consumer shift. These trajectories are consistent with 2.5 °C global warming (Base case), below 2 °C warming (Country pledges) and 1.5 °C warming (Net zero 2050) respectively.

Enerdata has chosen three scenarios in EnerFuture 2023 to explore possible futures to global energy systems. EnerBase: Continuation of existing policies and trends aligned with a temperature increase above 3°C. EnerBlue: Achievement of new NDC’s submitted up to the end of 2022 aligned with a temperature rise around 2.5°C. EnerGreen: Ambitious GHG emission budget in line with the Paris Agreement by limiting the temperature increase below 2°C. EnerFuture is relying on the recognized Poles-Enerdata model, an energy-economy-environment model of the global energy system, covering 66 countries and regions, with dedicating modelling of the individual end-use sectors, energy supply, prices and GHG emissions.

The Institute of Energy Economics (IEEJ), Japan, quantifies the global energy supply and demand structure up to 2050. The IEEJ Outlook 2024 contains two exploratory scenarios. In the Reference Scenario, the prevailing changes will continue against the backdrop of current energy and environmental policies. The Advanced Technologies Scenario is a scenario in which energy and environmental technologies are introduced to the maximum extent possible to ensure a stable supply of energy and strengthen measures against climate change. According to the Reference scenario, energy-related $CO_2$ emissions in 2050 will still be at the same level as today, while in the Advanced Technologies Scenario they will fall to 14.7 billion tons and thus by around half – comparable with IEA’s APS. The IEEJ Outlook 2024, using econometric models and other tools, presents results both at the global level and for different countries.

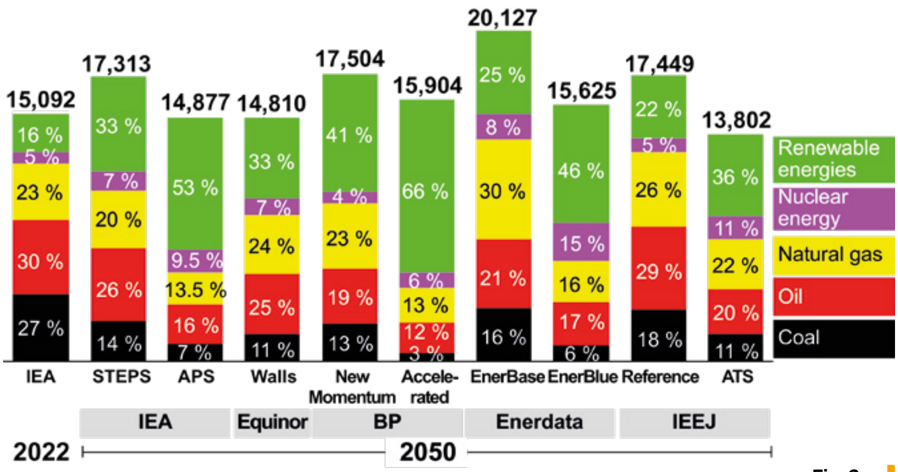


**Fig. 9.**
Global primary energy consumption – Synopsis of the results of IEA, Equinor, BP, Enerdata and IEEJ **exploratory scenarios** by 2050 in Mtoe

Source: IEA, World Energy Outlook 2023; Equinor, Energy Perspectives 2023; BP, Energy Outlook 2023; Enerdata, EnerFuture 2023; IEEJ Outlook 2024

Other organizations also show comparable tendencies – depending on the basic assumptions underlying the respective scenarios. This applies, for example, to Equinor's Walls scenario, which shows a similar energy mix to the IEA's STEPS scenario – although, in contrast to STEPS, Equinor expects primary energy consumption for 2050 to be approximately the same as in 2022. EnerBase from EnerData is based on a smaller change in global energy supply than STEPS and Walls. At EnerBase, fossil energies will still account for two thirds of primary energy consumption in 2050. In the IEEJ Reference Scenario, fossil energies even contribute 73 % to covering primary energy consumption in 2050. In IEEJ's Advanced Technology Scenario, fossil fuels account for 53 % in 2050. Even the Advanced Techlogies Scenario is far from achieving global carbon neutrality in 2050.

## Results of exploratory scenarios in comparison

Most institutions whose analyzes are included here have published at least one, sometimes two or more, exploratory scenarios. Behind this are different assumptions regarding political decisions, such as at the IEA, at BP, at Wood Mackenzie, at McKinsey and at Enerdata, or technological advances, such as at IEEJ. The assumptions about $CO_2$ pricing entered into the modeling as input parameters also differ greatly between the scenarios. This applies, for example, to McKinsey **(Fig. 7)**, but also to the IEA **(Figure 8)**, among others.

An example are the scenarios of the World Energy Outlook 2023, in which the International Energy Agency comes to different results based on the various assumptions **(Figure 9)**.

- In the Stated Policy Scenario (STEPS), global primary energy consumption will continue to rise until 2050, but only at an annual average rate of 0.5 %. Global demand for coal as well as oil and natural gas will reach its highest level before 2030. The peak will be followed by a decline - particularly pronounced for coal. The share of coal will decrease from 27 % in 2022 to 14 % in 2050. According to this scenario, all fossil energies will still cover 60 % of primary energy consumption in 2050. In 2022 it was just under 80 %. The contribution of renewable energy increases from 16 to 33 %. Nuclear energy will reach 7 % in 2050 compared to 5 % in 2022
- In the Announced Pledges Scenario (APS), global primary energy consumption will remain largely constant in the coming decades despite an increase in population and economic output. The contribution of fossil energies to covering primary energy consumption will fall to 37 % by 2050. Renewable energies then come to 53 %, and nuclear energy makes a contribution of almost 10 %.

The Enerdata scenarios also show clear differences between the results for EnerBlue and EnerBase. Due to the assumptions made by EnerBlue that differ from EnerBase, the total primary energy consumption in 2050 will be only slightly higher than the comparable number for 2022. This also applies to the Accelerated scenario compared to BP's New Momentum. In IEEJ's Advanced Technology Scenario, the total primary energy consumption in 2050 – unlike in IEEJ's Reference Scenario – remains below the comparable level of 2022.

Above all, however, the energy mix has a completely different structure than in the scenarios that are more based on a baseline. The contribution of renewable energies to covering primary energy consumption increases significantly more in the exploratory scenarios that assume an increased focus on climate protection than in the scenarios that are more geared toward a continuation of the status quo. In the "baseline" scenarios STEPS (IEA), Walls (Equinor), New Momentum (BP), EnerBase (Enerdata) and Reference (IEEJ), renewable energies will reach shares of between 22 % and 41 % in 2050. In contrast, the range for the exploratory scenarios of these institutions aligned with more ambitious climate policies or stronger enforcement of advanced technologies ranges from 36 % in IEEJ's ATS, over 46 % in Enerdata's EnerBlue, 53 % in IEA's APS and 66 % in Accelerated by BP.

In electricity generation, the differences depending on the basic assumptions made in the exploratory scenarios become even more visible than in primary energy consumption. The International Energy Agency assumes a significantly greater electrification of the energy supply in the APS than in the STEPS **(Figure 10)**. The share of renewable energies in electricity generation increases from around 30 % in 2022 to 71 % in STEPS and 82 % in APS, whereby for both scenarios it applies that not only the entire increase in electricity generation is covered by renewable energies but also renewable energies partly replace fossil energies – but to a greater extent in the APS than in the STEPS. Nuclear energy increases in absolute terms in both scenarios. However, their contribution remains proportionally limited to 8 %.

The other institutions also come to comparable results **(Fig. 9)**. In the scenarios Advanced Technology from IEEJ, EnerBlue from Enerdata and Further Acceleration from McKinsey, renewable energies reach shares of between 73 and 79 % of total global electricity generation in 2050. In contrast, the share of renewable energies in global electricity generation determined for the Reference scenarios by IEEJ and EnerBase by Enerdata will still remain to around 50 % in 2050. According to all exploratory scenarios, there is broad agreement that the greatest growth potential is seen for wind power and solar energy. Hydrogen is also playing an increasing role in electricity generation.

The various institutions, such as the IEA or McKinsey, also make statements in the studies presented about the expected consequences for global temperature developments. The IEA comes to the conclusion that, according to STEPS, a temperature increase of 2.4 °C compared to pre-industrial levels would be expected, while in the APS a limit of 1.7 °C would be maintained **(Figure 11)**. McKinsey, for example, sees this in a similar way. For the Current trajectory scenario, a temperature increase of 2.3 °C is assumed compared to 1.9 °C in Further Acceleration **(Fig. 7)**. Wood Mackenzie‘s Base Case is broadly consistent with a 2.5 °C global warming view by 2050 and the scenario Country pledges with 2°C. In both cases, the different assumptions underlying the respective $CO_2$ pricing scenarios play an important role.

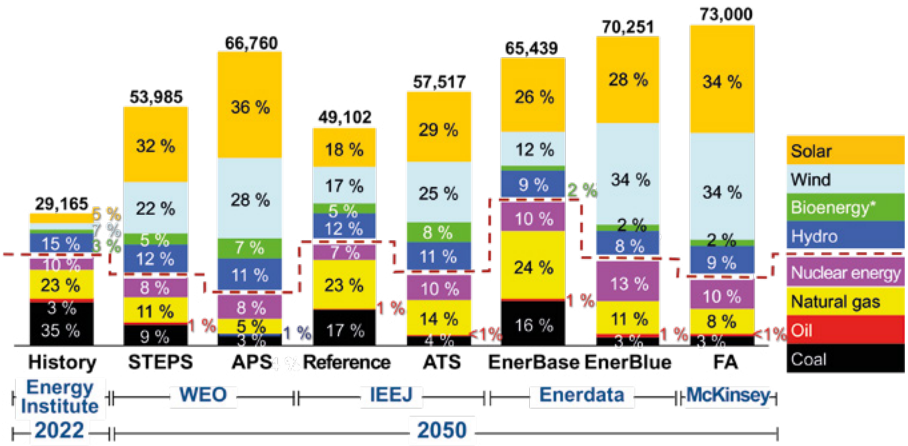


**Fig. 10.**
Global power generation – Comparison of the results of different **exploratory scenarios** in 2050 in TWh
Source: IEA, World Energy Outlook 2023; Enerdata, EnerFuture 2023; McKinsey, Global Energy Perspective 2023; IEEJ Outlook 2024

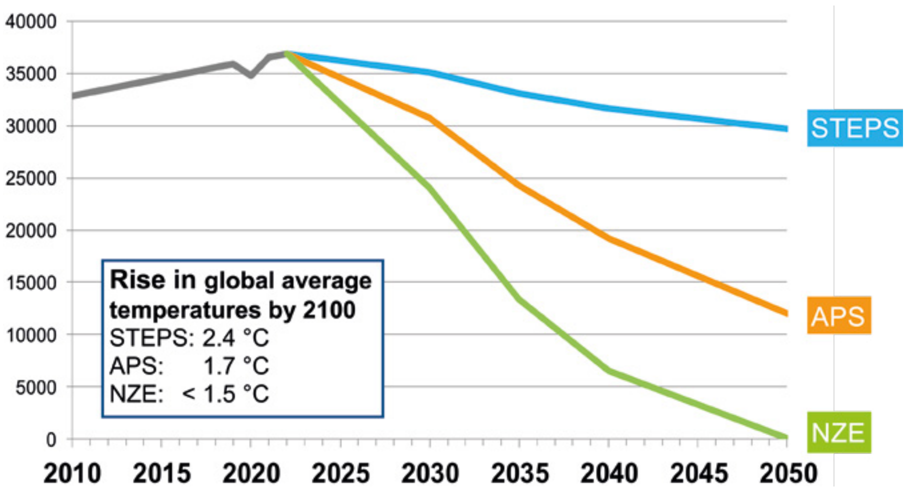


**Fig. 11.**
Development of global $CO_2$ emissions according to the IEA's WEO 2023 scenarios
Source: International Energy Agency, World Energy Outlook 2023

## Comparison of the results of normative scenarios

The results obtained for the normative scenarios compared to the exploratory scenarios show the gap that would have to be closed in order to meet the 1.5 °C target. Almost all institutions that have published scenarios for future energy supply have modeled a normative scenario in addition to exploratory scenarios. The results of the normative scenarios differ from the results of the exploratory scenarios in three main points:

- Total global primary energy consumption will fall in the next few years and will therefore be lower in 2050 than in 2022 **(Figure 12)**.
- Global electricity generation will double to triple by 2050, and the share of electricity in final energy consumption will increase significantly, in Wood Mckenzie‘s scenario Net zero 2050 to 50 % in 2050.
- The share of renewable energies in primary energy consumption is significantly higher. The scenarios EnerGreen from Enerdata,

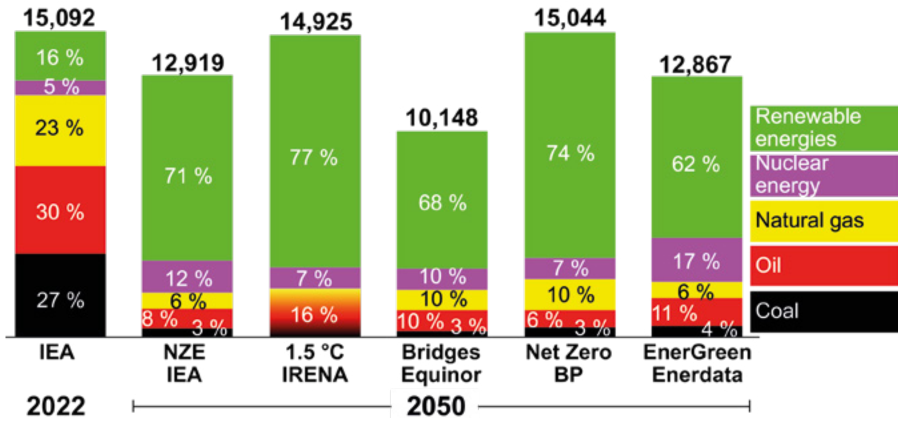


**Fig. 12.**
Global primary energy consumption – Synopsis of the **normative Scenarios** from IEA, IRENA, Equinor, BP and Enerdata by 2050
in Mtoe
1) Exajoule equals 23.88 million tons of oil equivalent (Mtoe)
Source: IEA, World Energy Outlook 2023; BP Energy Outlook 2023 (Net Zero); Equinor, Energy Perspectives 2023; IRENA, World Energy Transitions Outlook 2023; Enerdata, EnerFuture 2023

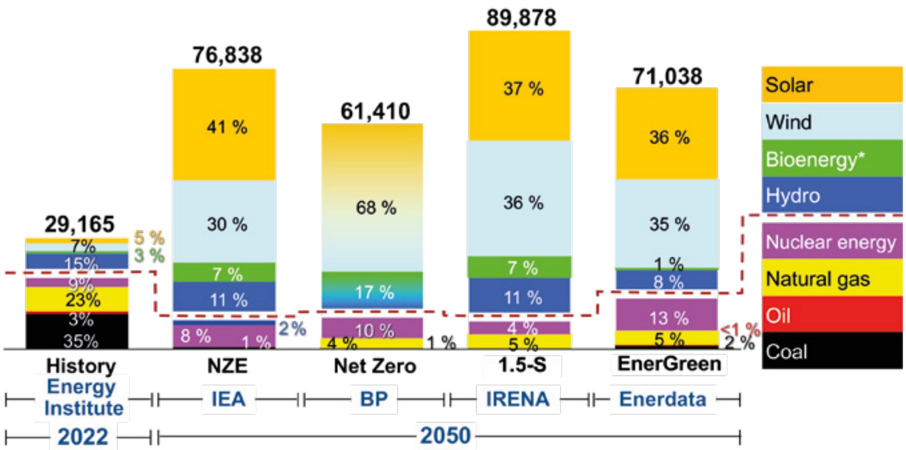


**Fig. 13.**
Global power generation – comparison of the results of different **normative scenarios** (net zero by 2050)
in TWh
* including geothermal energy and hydrogen
Source: IEA, World Energy Outlook 2023; IRENA, World Energy Transitions Outlook 2023; BP, Energy Outlook 2023; Enerdata, EnerFuture 2023

Bridges from Equinor, NZE from the IEA, Net Zero from BP and 1.5 °C from IRENA for the year 2050 show shares of renewable energies in primary energy consumption between 62 and 77 %. And in electricity generation, these studies even estimate contributions from renewable energies to be between 80 and 90 % by 2050 **(Figure 13)**.

- Nuclear energy is also attributed a greater contribution than in the exploratory scenarios, as is the case with the IEA or Enerdata.
- The share of fossil energy will fall to less than a quarter by 2050, and in some of the normative scenarios even to less than a fifth of global primary energy consumption.
- The capture and storage or use of $CO_2$ in power generation and industrial processes is given greater importance than in the exploratory scenarios.
- Global hydrogen production is picking up significantly. Hydrogen is increasingly being used in areas that are difficult to decarbonize using electricity. These are certain industrial processes, heavy goods traffic on the road as well as shipping and air traffic. Global production of low-emissions hydrogen will increase from 1 million tons in 2022 to 420 million tons in 2050. More than three quarters of this production takes place in electrolysis plants. The remaining part is generated based on fossil energies with carbon capture and storage or usage.

A key factor for these top-down results is the higher $CO_2$ price set in the normative scenarios compared to the exploratory scenarios.

The energy transition leads to a significant growth in the demand for critical minerals and materials. This increasing demand results from the low-carbon energy system, including the construction of wind and solar plants, hydrogen and $CO_2$-pipelines, new storage facilities, expansion in the power grid and distribution systems used to connect renewable assets and deliver electricity to its end use **(Figure 14)**.

As an example, the statements in the BP study on the Net Zero Scenario focussed on three critical minerals: copper, lithium, and nickel. Copper's future growth is dominated by its use in the transition of low-carbon power and the electrification of transport. As a consequence, in Net Zero, BP expects global copper demand to triple to around 60 million tonnes by 2050. The growing demand for lithium is driven by its use in electric vehicles. In Net Zero, the total global demand for lithium is assumed to increase by a factor of approximately 20 compared to today's level. Around 90 % of the additional demand for lithium accounts for electrification of transport. The demand for nickel is also driven by its role in the electrification of transport. In Net Zero, total nickel demand increases four times by 2050 – approximately 80 % of that growth is due to the increasing use of lithium-ion batteries in electric vehicles.

| | | Main | Other |
|---|---|---|---|
| 27 Co | Cobalt | • EV batteries | • Battery storage<br>• Bioenergy<br>• Electrolysers |
| 29 Cu | Copper | • Electricity grid<br>• EV batteries<br>• Solar PV | • Battery storage<br>• Bioenergy<br>• CSP<br>• Electrolyser<br>• Geothermal<br>• Hydro |
| 66 Dy | Dysprosium | • EV motors<br>• Wind | |
| 6 C | Graphite | • EV batteries | • Battery storage |
| 77 Ir | Iridium | • PEM Electrolysers | |
| 3 Li | Lithium | • EV batteries | • Battery storage |
| 25 Mn | Manganese | • EV batteries | • Battery storage<br>• CSP<br>• Electrolysers<br>• Geothermal<br>• Hydro<br>• Wind |
| 60 Nd | Neodymium | • EV motors<br>• Wind | |
| 28 Ni | Nickel | • Electrolyser<br>• EV batteries | • Battery storage<br>• Bioenergy<br>• CSP<br>• Geothermal<br>• Hydro<br>• Solar PV |
| 78 Pt | Platinum | • PEM Electrolysers | |

**Fig. 14.**
Selected energy-related technology applications of critical materials
Notes: CSP = Concentrated solar power; EV = electric vehicles; PV = photovoltaic
Source: IRENA (2023). Geopolitics of the Energy Transition: Critical Materials

The critical minerals mining and processing landscape is geographically concentrated, with a select group of countries playing a dominant role. Australia (lithium), Chile (copper and lithium), China (graphite, rare earths), the Democratic Republic of Congo (cobalt), Indonesia (nickel) and South Africa (platinum) occupy leading positions in the mining of critical minerals. The degree of concentration in the processing phase is significantly greater than in mining – characterized by an even more pronounced market position of China.[12]

However, the risks associated with the supply of fossil energy and the supply of critical raw materials for the energy transition must be assessed differently. Renewable energy plants that have already been built could continue to operate even if the supply of critical raw materials was interrupted. Therefore, unlike fossil fuels the risk associated with interruptions in the supply of critical minerals does not involve disruption to the ongoing operations of facilities that have already been constructed. However, there could be a slowdown in the pace of the implementation of the energy transition.[13]

## Conclusion

The future of energy supply looks significantly different than the past. This is shown by the forecasts and scenarios presented by international institutions in recent months. A change is taking place from an age dominated by fossil fuels to a world in which renewable energies dominate. The decisive keys to achieving the climate goals are the accelerated improvement of energy efficiency, the massive expansion of renewable energies, the widespread implementation of the technology for the capture and use or storage of $CO_2$ and the reliance on hydrogen in those sectors that are difficult to develop for electrification. Nuclear energy is also seen as playing an important role in the transformation of the energy supply in a number of countries. How quickly and to what extent this change occurs depends on factors such as the energy and climate policy orientation of governments, technological developments and consumer behavior. In order to meet the goal of limiting the global temperature rise to well below 2°C, the pricing of $CO_2$, if possible at a comparable level worldwide, technology-neutral support mechanisms by governments and increased international cooperation are seen as crucial.

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