IAEA
International Atomic Energy Agency

Nuclear Energy in Climate Resilient Power Systems

"Increasingly frequent extreme weather conditions and rapidly growing shares of renewable energy generation place a growing premium on climate resilient energy sources. A diverse and resilient energy foundation from decarbonized energy sources like nuclear, hydropower, geothermal and others will play an important role in accommodating renewables and successfully decarbonizing global energy systems" [1].

World Meteorological Organization

Extreme heat conditions, heavy precipitation, droughts, coastal and river floods, and tropical cyclones will make the design and the implementation of climate resilience plans for the global energy system even more complex, but all the more necessary.

Nuclear energy can facilitate the integration of high shares of renewables and support long term energy security. The climate resilience of the global nuclear fleet makes it an excellent complement to other low carbon energy sources as climate risks increase.

Reductions in nuclear output due to cooling water availability and other climate events are small — in 2022 these energy losses accounted for 0.3% of global nuclear generation. Historical data show that extreme events such as heat waves, storms and droughts have a minimal impact on the operations of nuclear plants, making nuclear energy a key partner with renewables in decarbonized energy systems.

Despite extreme heat and aridity, French nuclear production losses attributed to environmental reasons in 2022 totalled 501 gigawatt-hours (GWh), less than 0.2% of annual production from the affected power stations. The spring of 2022 was characterized by record low river flow rates and was followed by the second hottest summer on record in France.

1.1°C

The increase in global surface temperature in 2011–2020 above 1850–1900 levels [2].

Two forces — both growing exponentially — will require a complete rethink of how to ensure continuous operations of the world's energy system. Increasingly frequent extreme weather conditions and rapidly growing shares of renewable energy generation introduce an unprecedented level of volatility and uncertainty in power markets.

Concurrent climate change induced threats escalating at pace and in intensity have growing implications for the supply, demand and infrastructure of the world's energy system. Climate change will impact every aspect of the energy sector: the output of each energy generating technology, the volume of energy demanded and the combined physical and nonphysical infrastructure that ensures safe and reliable operations during extreme weather events.

Together these two forces place a growing premium on the concept of climate resilient energy, or the ability of an energy technology to consistently meet demand amid a fluctuating energy supply. Extreme heat conditions, heavy precipitation, droughts, coastal and river floods, and tropical cyclones will make the design and the implementation of climate resilience plans for the global energy system even more complex, but all the more necessary. Ensuring climate resilience of energy systems will require both actions to mitigate the impact of climate change — deploying climate resilient energy technologies to act as a stabilizing mechanism — and adaptation measures like technological improvements to support operations in a climate volatile future. Nuclear power has the potential to support decarbonized, climate resilient energy systems.

Climate change will impact every aspect of the energy sector.

As energy systems become more dependent on renewable energy sources to meet large shares of demand, it will be increasingly important to value and maintain firm energy sources to ensure security of energy supply.

UNDERPINNING CLIMATE RESILIENT ENERGY SYSTEMS WITH NUCLEAR

Nuclear electricity and heat can play an important role in helping achieve and maintain climate resilient energy systems. A diverse and resilient energy foundation, with nuclear energy as a key component, can unlock the successful integration of renewable energy technologies in global energy systems, minimize the cost of economy-wide decarbonization, create meaningful and long lasting jobs and strengthen energy security. Given this critical role, this booklet will explore and quantify the ways in which nuclear energy can contribute to climate resilient energy systems.

Nuclear energy can play a critical role in a technology diversified, climate resilient energy system. Nuclear power plants can operate continuously, providing a stable source of electricity that is not affected by weather conditions. Nuclear power plants are also capable of performing load following functions, adapting output for daily shifts in renewable generation.

In the context of climate change, nuclear energy can help to reduce greenhouse gas emissions in the electricity sector as well as potentially providing low carbon heat for other applications such as hydrogen production, desalination of water and district heating. By displacing fossil fuel fired power plants for these applications, nuclear power can help to reduce emissions of carbon dioxide and other greenhouse gases, and thereby help to mitigate climate change.

Data show that nuclear power plants experience extremely minimal operational interruptions due to extreme weather conditions.

EXAMINING NUCLEAR AS A SOURCE OF CLIMATE RESILIENT ENERGY

Despite extreme weather conditions becoming increasingly frequent, weather related energy losses amounted to less than a third of one percent of reactor output — 0.3% — on average in 2022 (Fig. 1). Climate related weather events like floods, storms, droughts and heat waves may affect the amount of electricity generated by nuclear power stations. An extreme weather event can cause nuclear reactors to decrease their production or even shut down altogether to maintain safe operations.

The IAEA is working to collect data, case studies and best practices from Member States surrounding the adaptation of nuclear plant designs to mitigate the risk of production loss. While the temperature and availability of cooling water is one of the climate variables most relevant to sustaining high levels of nuclear production, nuclear technology is proven to be resilient to other climate variables, including heavy precipitation, high winds, extreme cold and storms that more readily impact other energy generating technologies or energy infrastructure. Nuclear plant operators already employ a variety of quantifiable engineering and plant management solutions, including the timing of refuelling outages to avoid periods of elevated energy demand due to climate related events.

Losses in generation are attributed to a variety of causes, allowing for in-depth analysis of how different kinds of outages have evolved over time. As adverse but also extreme weather conditions become more frequent due to climate change, the ability of nuclear generation to perform under degraded conditions must be quantified and measured. This quantification allows for an unbiased comparison of energy technologies and can safeguard that energy systems meet demand at all hours, rather than compelling energy consumers to heavily adapt consumption patterns to the operations of the energy system.

What is an energy loss?

Energy loss measures the difference between a power plant's potential output and what it actually produces. In nuclear power plants, energy losses can occur for refuelling (which requires the plants to partially or fully turn off), but this booklet focuses on reductions in electrical output which can be attributed to climate change. Here we classify weather related losses attributed to storms (hurricanes, floods, tornados), extreme hot or cold temperatures (blizzards, heat waves) and the ways in which these events directly impact the nuclear plant — necessitating reduced output to either maintain safe operations or accommodate the temperature or availability of cooling water.

Extreme weather events that do not directly impact the power plant but do disrupt the wider power grid and may require a nuclear power plant to reduce output at the request of the grid operator are not considered in this context.

The size of an energy loss is measured in both scale (in units of power like megawatts or gigawatts) and volume (duration of the energy loss in hours). To reflect the changing size of the global nuclear fleet over time, we show energy losses as a share of reactor production — to compare the scale of unavailable energy to reactor output during a specified time period.

Nuclear technology is proven to be resilient to other climate variables, including heavy precipitation, high winds, extreme cold and storms.

Annual energy losses due to adverse weather events comprise about 1% of the nuclear fleet's total losses and a much smaller portion of total nuclear electricity output. Figure 1 compares total nuclear energy generated and lost to adverse weather events by nuclear power plants across the world. To put these numbers in context, the world's nuclear power fleet in 2021 could have supplied two times the entire yearly electricity consumption of India — whereas the total amount of nuclear energy lost due to weather events was approximately 88 minutes of electricity consumption in the Emirate of Dubai [3, 4].

Data show that nuclear power plants experience extremely minimal operational interruptions due to extreme weather conditions. While nuclear energy can be paired with other low carbon technologies such as wind, solar, hydropower and geothermal for the mitigation of climate change, nuclear can also be a source of climate-resilient energy. The following section will examine the climate resilience of nuclear power operations over time, focusing on the small portion of energy losses attributed to extreme weather to best understand how nuclear power plants have performed during harsh weather events in the past, as an indicator for climate change adaptation in the nuclear industry.

Historical evidence shows that nuclear power has proven its resilience amid increasingly frequent and severe weather events.

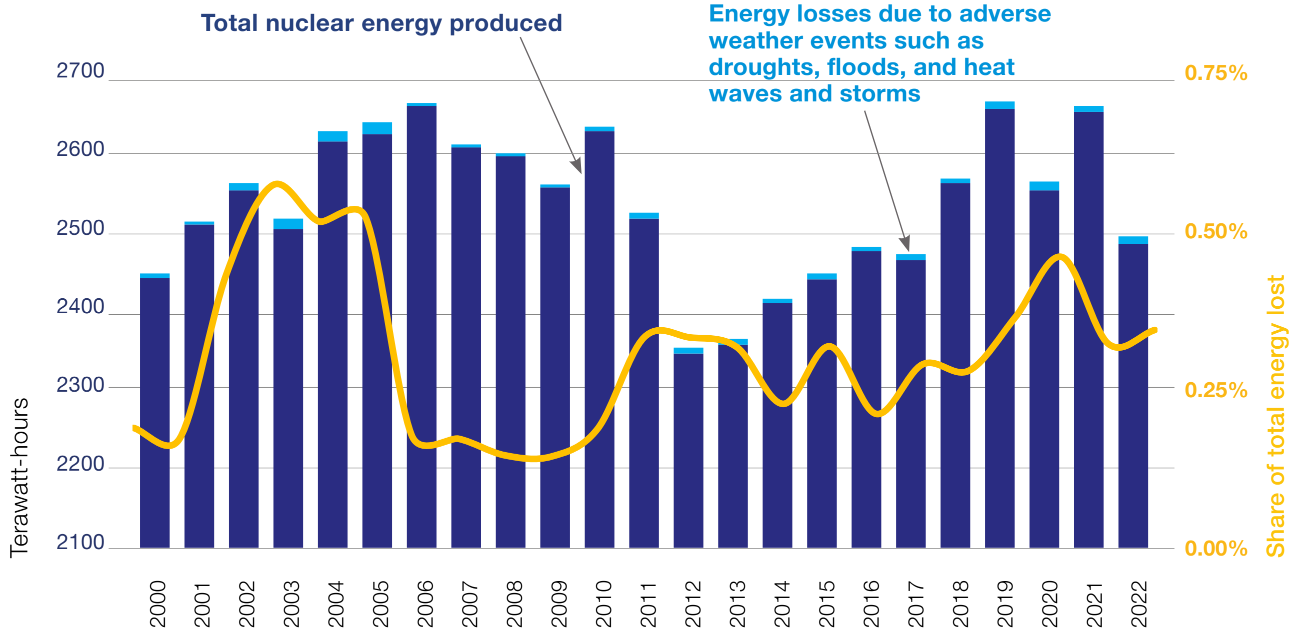


Fig. 1. Annual nuclear energy production and weather-related losses between 2000 and 2022 [5].

Note: Data represented in Ref. [5] are subject to availability and reporting by IAEA Member States. The publication does not include Ukrainian reactor units as operational data were not submitted for the year 2022 by the time of publication.

ONE THIRD OF ONE PERCENT

Historical evidence shows that nuclear power has proven its resilience amid increasingly frequent and severe weather events. As the effects of climate change become more disruptive to global energy systems and many world leaders call for the retirement of the world's fossil-powered fleet, nuclear may be increasingly utilized as a firm energy source to counterbalance renewable energy sources. While nuclear energy losses due to weather events are small, they are not zero. This section will examine the conditions under which these energy losses occur to fully assess the ability of nuclear to perform an integral role in climate resilient energy systems.

Of the 460 gigawatts of nuclear capacity online at any time between 2000 and 2022, 48% of capacity was located by the sea, 36% by a river, and 16% by a lake. Climate related weather events reported to the IAEA by nuclear plant operators show that over the past 22 years, weather events caused the highest GWh losses at nuclear power plants located on rivers, whereas nuclear plants near lakes and on the sea coast historically reported relatively lower energy losses caused by weather events (Fig. 2).

The next generation of nuclear reactors is likely to be even more concentrated by the sea coast so less affected by cooling water issues. Under construction and planned reactors officially reported to the IAEA by Member States total more than 100 gigawatts of capacity; of this, more than 60% are planned near the sea coast [5]. Some reactors do not yet have a specified plant location.

Most nuclear power plants are in the Northern Hemisphere, allowing for seasonal comparisons. Nuclear power plants located inland near rivers or lakes record more weather related nuclear energy losses between May and October, while plants located on the sea coast tend to experience weather related energy losses spread throughout the year (Fig. 3). Some plants experience energy losses spanning multiple months, illustrated in Fig. 3 by wide peaks and plateaus — oftentimes, these longer running energy losses are attributed to higher temperature or reduced availability of cooling water.

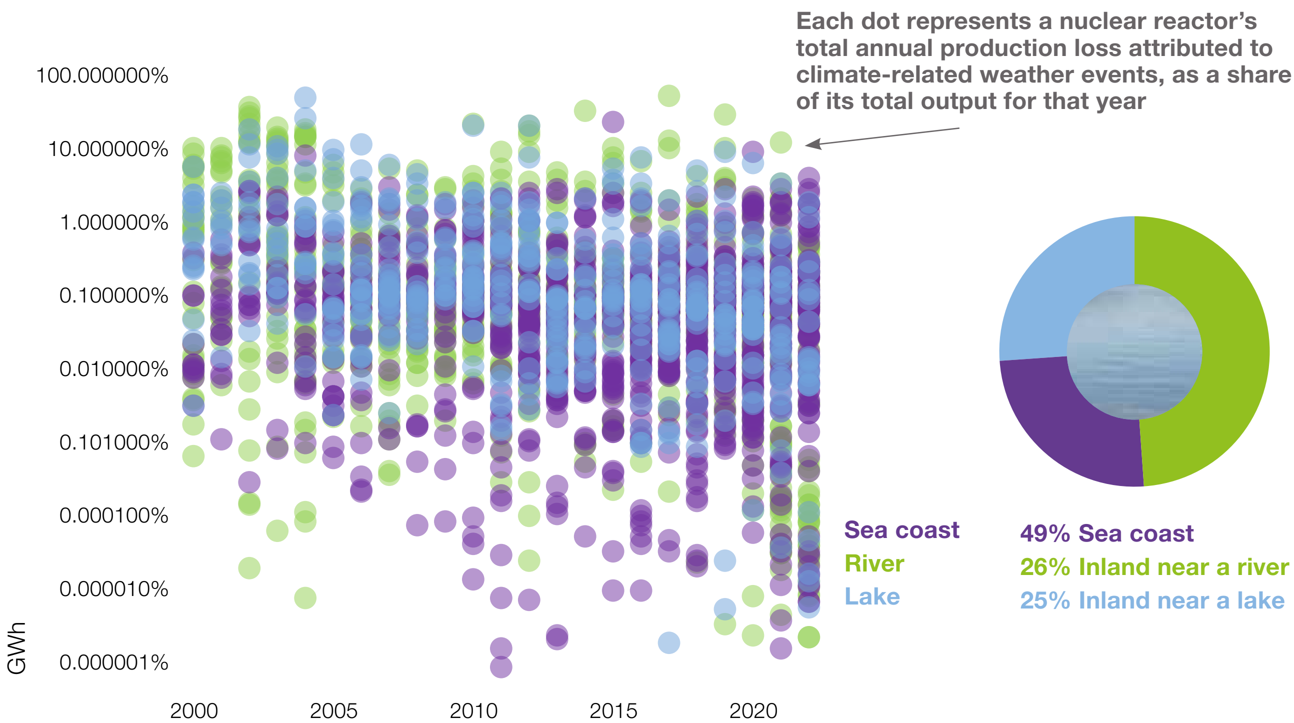


Fig. 2. Annual weather-related nuclear energy losses as a share of reactor generation (left) and share of weather-related nuclear energy losses by reactor location (right) between 2000 and 2022 [5].

Note: Data represented in Ref. [5] are subject to availability and reporting by IAEA Member States. The publication does not include Ukrainian reactor units as operational data were not submitted for the year 2022 by the time of publication.

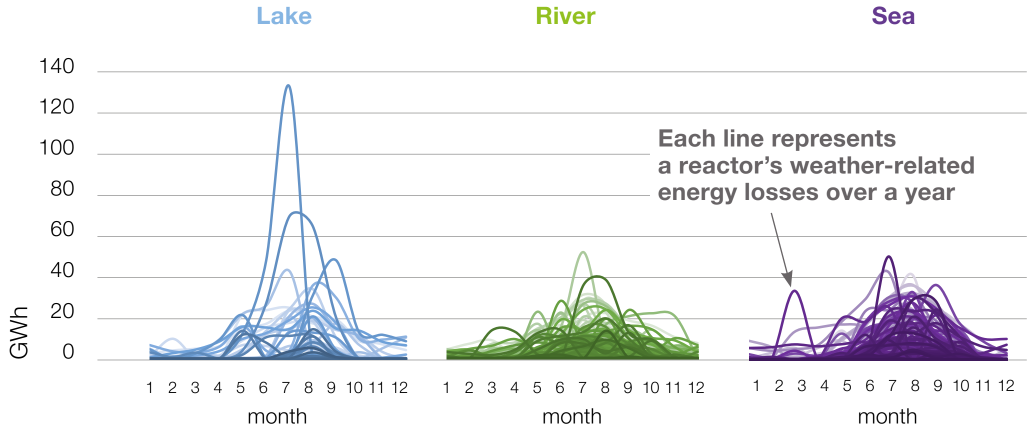


Fig. 3. Annual nuclear energy production and weather-related losses between 2000 and 2022 [5].

Note: Data represented in Ref. [5] was subject to availability and reporting by IAEA Member States. The publication does not include Ukrainian reactor units as operational data were not submitted for the year 2022 by the time of publication. Outliers exceeding three standard deviations from the mean (>0.1% of values) were excluded from the charts.

The source of cooling water for the nuclear power plant impacts the scale and volume of energy losses due to extreme weather events. The production from power plants located by rivers and lakes is highly reliant on the availability of cooling water, access to which is rigorously regulated to ensure minimal impact to the surrounding ecosystem. Because of this, plants located by rivers and lakes are more susceptible to extreme weather conditions like high heat, aridity, flooding or storms relative to plants located by the sea. For example, a record breaking heatwave occurred in Europe in the summer of 2003, causing historic decreases in nuclear production (Fig. 4). The event was a learning opportunity for the European nuclear fleet — in 2016, temperatures again reached high levels but resulted in fewer terawatt-hours of energy losses due to weather. Over time, sustained periods of extreme warm weather significantly impact the heat content and availability (due to regulatory limits on discharge) of sea water used for cooling — this subset of the world's nuclear fleet has also experienced a slight upward trend in weather related energy losses.

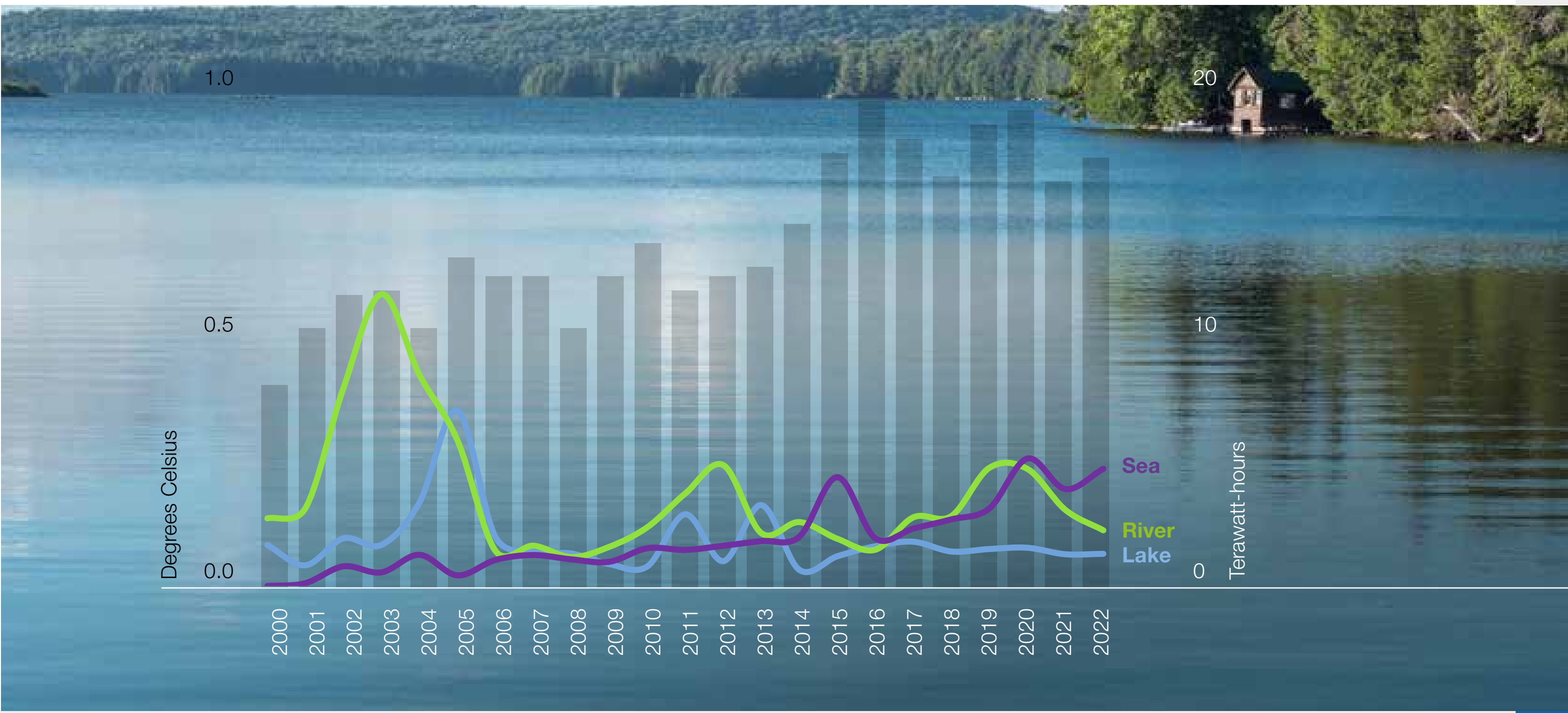


Fig. 4. Global land and ocean temperature anomalies compared to the 1910–2000 average (left axis) and annual weather-related nuclear energy losses (right axis), 2000-2022 [5, 6].

Note: Data represented in Ref. [5] is subject to availability and reporting by IAEA Member States. The publication does not include Ukrainian reactor units as operational data was not submitted for the year 2022 by the time of publication.
Weather related energy losses do not include seismic events.

CONTRIBUTION BY **THE UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE**

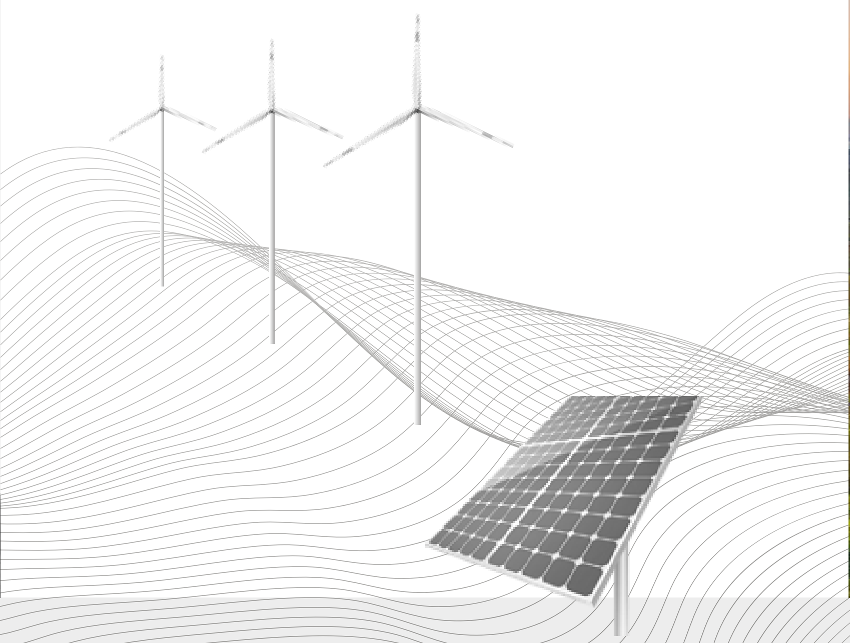
BUILDING RESILIENT AND CARBON NEUTRAL ENERGY SYSTEMS

A number of crises, including COVID-19, climate change and geopolitical situations have exposed the vulnerability of energy systems worldwide. To respond to these challenges the international community has decided to take action and help countries design and build resilient and carbon neutral energy systems.

A resilient energy system is based on:

1. **Energy security that ensures energy needed at any time through diversity of supply;**
2. **Affordability of sustainable energy that reduces the costs of electricity, heating, cooling, and transport while increasing systemic energy efficiency;**
3. **Environmental sustainability that lowers the carbon footprint and enhances efficiency across the energy supply chain in line with the Paris Agreement and the Agenda 2030 for Sustainable Development.**

Policy makers across the globe need tools that will enable them to make informed decisions to design and build resilient energy systems and prepare for the uncertainties that the future brings. The IAEA is joining forces with the United Nations Economic Commission for Europe, the World Meteorological Office, the International Energy Agency, the Organization for Security and Co-operation in Europe and the European Investment Bank, among others, to launch a Platform on Resilient Energy Systems that is tailored to effective policy making. This platform will provide two main services: i) an AI powered tool to support tailored and targeted policy and decision making and ii) a unique forum for information exchange and inclusive multistakeholder dialogue.



“Energy is critical to supporting peace, cooperation, economic and social development, and quality of life in our region and beyond. Experts have found clear pathways for policymakers to attain a resilient and carbon neutral energy system. Energy efficiency improvements, renewable energy deployment, high-efficiency fossil fuel technologies with carbon capture, use, and storage, nuclear power (including advanced nuclear power), hydrogen, and integrated and sustainable management of natural resources are all part of the solution to attain carbon neutrality. Only bold, immediate, and sustained action can develop resilient energy systems that ensure affordable access to energy and decarbonize our energy systems in time to avoid a climate disaster.” [7]

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EXECUTIVE SECRETARY OF THE UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

The IAEA collects data, case studies and best practices from Member States surrounding the adaptation of nuclear plant designs to mitigate the risk of production loss.

CONTRIBUTION BY
THE INTERNATIONAL ENERGY AGENCY

TRANSFORMING THE ENERGY SYSTEM TO MITIGATE AND ADAPT TO CLIMATE CHANGE

The growing impacts of climate change threaten the affordability and security of the energy system. An increasing amount of energy infrastructure that was built for a cooler, calmer climate is no longer reliable or resilient enough as temperatures rise, and weather events become more extreme. A complete transformation of energy systems is needed to stave off even more severe climate change and to cope with existing climate change impacts. The IEA's World Energy Outlook 2023 [8] identifies four key areas requiring urgent attention for the transformation of global energy systems. Nuclear energy can be employed to address these areas in order to ensure a rapid, secure, affordable and inclusive transition (see Figs 5 and 6).

Scale up clean energy investment in emerging market and developing economies

The progress of electrification will depend on reducing the cost and improving the availability of capital. Increases in financing costs have the biggest impact on large scale projects involving capital intensive technologies such as offshore wind, grids or new nuclear power plants. Innovative, large scale financing mechanisms are required to support clean energy investments, particularly in emerging and developing economies.

Ensure a balanced mix of investment

The IEA's 2023 Net Zero Emissions by 2050 Scenario calls for more than a doubling in nuclear energy installed capacity; renewables and nuclear power displace most fossil fuel use in the Net Zero Emissions by 2050 Scenario [9].

Large scale reactors remain the dominant form of nuclear power in all scenarios, but the development of and growing interest in small modular reactors increases the potential for nuclear power in the long run. Together, lifetime extensions of existing nuclear power plants and projected new construction in countries open to nuclear power lead to increases in nuclear capacity in all IEA modelling scenarios.

Electricity demand

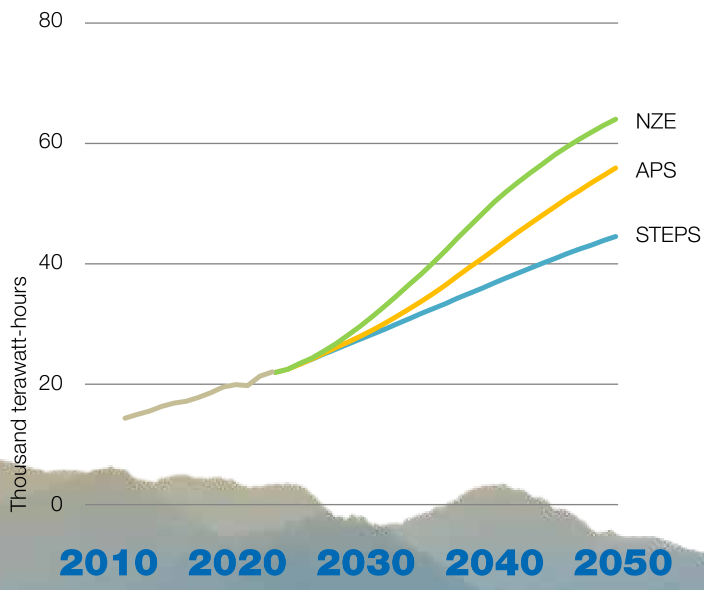

Fig. 5. Global electricity demand, 2010–2050. Adapted from Ref. [8] with permission. **Note:** STEPS — stated policy scenario, APS — announced pledges scenario, NZE — net zero emissions.

Make transitions resilient, inclusive and affordable

The share of wind and solar photovoltaic in total electricity generation is set to rise from 12% to about 30% by 2030, putting power system flexibility at the heart of electricity security.

Low emissions technologies such as nuclear, hydropower, fossil fuels with carbon capture, utilization and storage, bioenergy, hydrogen and ammonia can serve as important providers of seasonal flexibility to safeguard an energy secure transition.

Find ways for governments to work together

The continued role of nuclear power in the electricity sector relies on decisions to extend the lifetime of existing reactors and the success of programmes to build new ones. Governments need to take the lead in ensuring secure energy transitions by tackling market distortions — notably fossil fuel subsidies — as well as correcting for market failures.

However, energy transitions are unlikely to be efficient if they are managed on a top-down basis alone. Scaling finance for clean energy will require a shift from direct financing of projects towards more project de-risking with the aim of leveraging much higher multiples of private finance.

Electricity generation

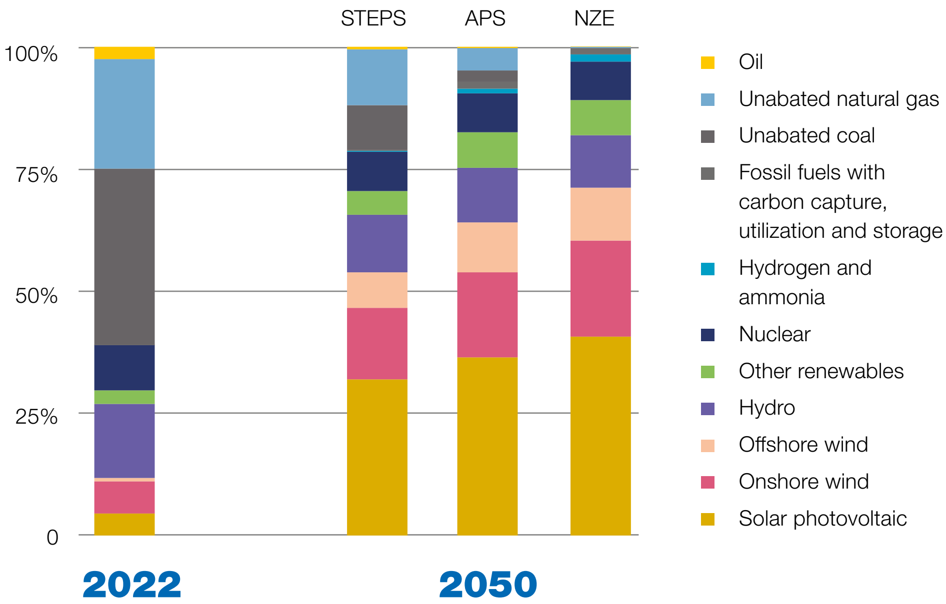

Fig. 6. Electricity generation mix by scenario, 2022 and 2050. Adapted from Ref. [8] with permission.
Note: STEPS — stated policy scenario, APS — announced pledges scenario, NZE — net zero emissions.

CONTRIBUTION BY **ÉLECTRICITÉ DE FRANCE**

MEASURING THE IMPACT OF ENVIRONMENTAL CONDITIONS ON FRENCH NUCLEAR ENERGY

The summer of 2022 was the second hottest on record in France after 2003, with particularly high temperatures in the southern and western regions of the country and three successive heat waves. Related to the heat, France also experienced particularly low river flow rates beginning in early spring, with record setting minimum flow rates on the Rhône and Garonne rivers. Électricité de France, the owner and operator of the French nuclear fleet, studied the functioning of the country's nuclear fleet in the summer of 2022 in comparison to previous years.

In 2022, total production losses (see Fig. 7) attributed to environmental reasons totalled 501 GWh, less than 0.2% of annual production from the affected power stations. Energy losses were incurred at French nuclear power stations in order to meet regulatory limits to preserve water temperatures and ecosystems.

Originally, environmental monitoring and corresponding regulatory limits on the thermal output of nuclear power plants had two layers in France: one for normal climatic conditions and one for exceptional climatic conditions. Following the heat waves which occurred in 2003, 2005 and 2006, the French regulatory framework was adapted to allow for an adjustment of these regulatory limits in case of exceptional circumstances such as electrical network security.

The current energy crisis driven by the war in Ukraine was also considered an exceptional circumstance in 2022, due to the necessity to produce more electricity from nuclear to save gas for the winter period. The application of temporary changes to the thermal requirements in exceptional circumstances preserved 452 GWh from nuclear power stations, corresponding to approximately 80 million cubic metres of natural gas or 12 hours of full capacity from the Nord Stream pipeline.

Summer 2022 was an exceptional one for France's nuclear fleet, which makes up about 15% of global nuclear capacity. The summer of 2022 can be characterized as an operational anomaly in France due to several factors: historically high air temperatures, low water levels and a global energy crisis which caused high natural gas prices and required France's nuclear power plants to postpone maintenance in favour of providing low cost electricity to the European grid.

Energy losses related to compliance with thermal limits were relatively low in 2022, but portions of temperature sensitive sites were shut down due to preventative maintenance. Since 2003, annual environmental energy losses at nuclear sites have averaged 0.3% of production. Regulatory limits were changed for 24 days at the Golfech, Blayais, Saint-Alban and Bugey nuclear power plants in the summer of 2022 under exceptional circumstances in order to maintain the stability of electricity supply. Certain units or sites that could have been constrained by temperature or river flow rate requirements include: Chooz units 1 and 2; Civaux units 1 and 2; portions of capacity from Cattenom units 1, 3 and 4; Bugey units 3 and 4; Saint-Alban unit 2; Tricastin unit 3; and Golfech unit 1 all of which were at a standstill due to maintenance work due to stress corrosion and therefore were not the subject of power reductions for environmental reasons.

Électricité de France has been collecting data on environmental conditions over the past 40 years in cooperation with a public research institute to understand and measure any potential thermal impacts from the operation of nuclear power plants. In 2022, no major changes were observed in the biotope (impact on fish, wildlife, etc.) and the biotope was comparable to previous observations during normal climatic conditions. The main observed changes in the biotope over the past 40 years are due to global changes, whereas the thermal impacts of nuclear power plants are small and localized to a few kilometres downstream from the plant.

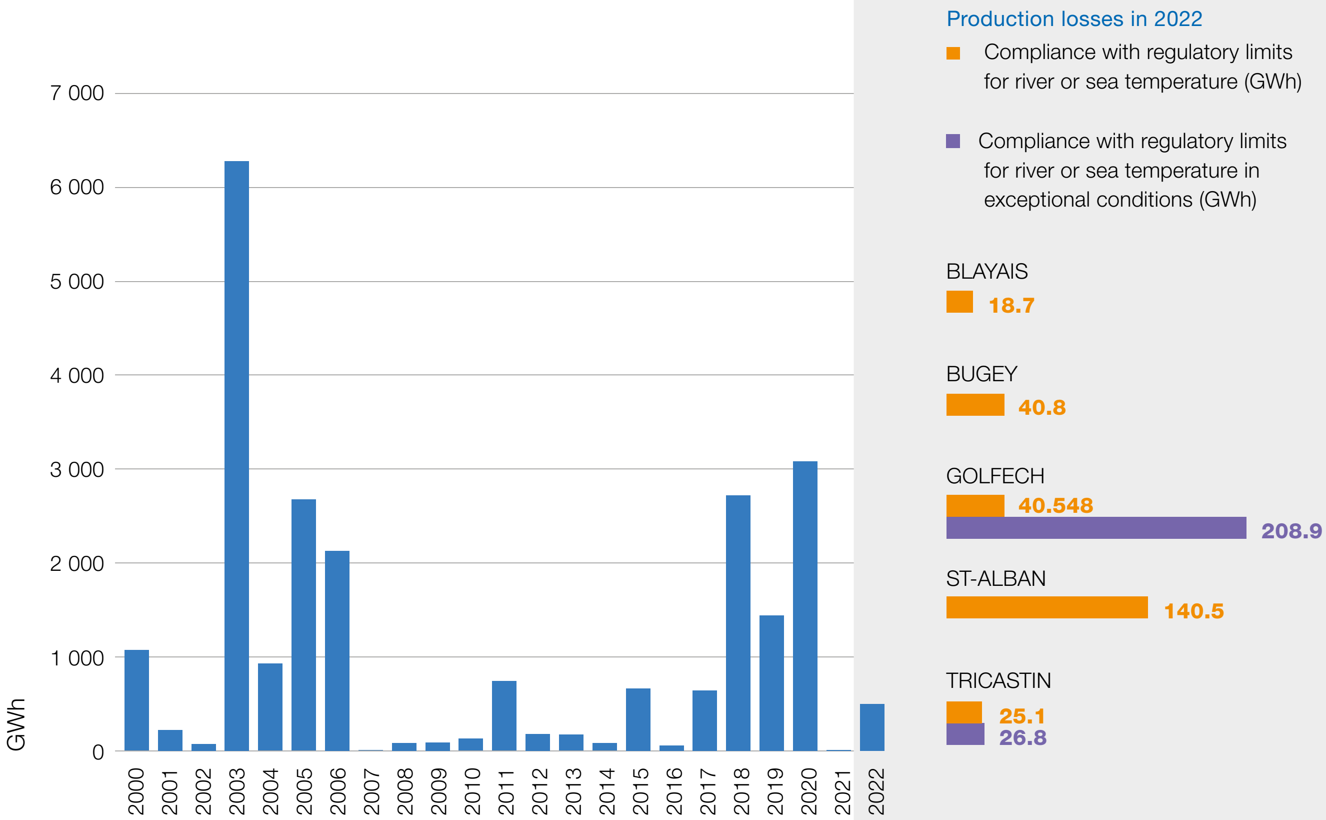

Fig. 7. Production losses due to thermal regulatory limits for the environment between 2000 and 2022. Courtesy of Électricité de France.

PLANNING AT A SYSTEM LEVEL TO MITIGATE CLIMATE IMPACTS

While individual climate risks have historically been mitigated where possible, the growing hazard of simultaneous concurrent weather events must be captured in infrastructure and energy supply planning. As energy systems become more dependent on renewable energy sources to meet large shares of demand, it will be increasingly important to value and maintain firm energy sources to ensure security of energy supply.

With this consideration in mind, the IAEA has initiated a technical project drawing on the most recent experience of Member States in the application of climate predictive methods for assessment of site hazard and safety for existing and new nuclear sites. The project aims at integrating a prediction model for climate change effects into the development of natural hazards, providing state-of-the-art methods for uncertainty minimization by means of sustainable techniques. The project will integrate statistical and numerical modelling competences with meteorological and hydrological competences in order to develop a sustainable framework for the development of time-dependant hazards. Measures will aim at increasing the robustness and resilience of nuclear power plants against climate change impacts. The project will also identify new generation site monitoring systems oriented to the site hazard continuous assessment for timely management of plant reaction.

The IAEA collects data from Member States on safety events which impacted nuclear power plant electrical components; serviced water systems, the primary system and structure; triggered unplanned shutdowns or led to plant modifications to prevent further losses in its Incident Reporting System. A recent review of the entire IRS database to identify reports having a relation to external events identified that about 130 of them were related to external events, most of which were attributed to weather related scenarios, which could be affected by climate change. Looking at these events and the potential effect of climate change on nuclear installations underlines the need for clear definitions of the overall

Data science informed policies are critical to encourage innovation in the domain of energy system climate resilience.

objectives and performance levels for the plant, site and power distribution networks. For these important components, two critical objectives may be defined: the safety of the physical infrastructure and the reliability of the provided energy services. These two objectives are highly correlated; safety of the nuclear installation must be ensured with minimum interruptions in power availability. For a more detailed look at safety related events captured in the Incident Reporting System and the multidimensional hazard assessment framework for the nuclear sector, see the IAEA's publication Climate Change and Nuclear Power 2022.

In addition, the IAEA is convening an expert group to develop a publication detailing performance related technical solutions recently selected or under consideration by countries to reduce production losses caused by environmental changes and climate variability before safety and protection measures are triggered. The publication will provide illustrative examples of modifications to physical assets and operating procedures that maximize plant economics under conditions such as warmer hot seasons, longer dry seasons and more frequent storms and episodes of aquatic organism ingress into cooling water intake structures.

Many uncertainties remain surrounding the future state of the climate and the associated costs of risk mitigation measures. Estimation methods to measure the benefits of adaptation measures against investments need to be expanded and standardized to improve and evaluate the ramifications of cascading and compounding impacts of extreme weather events on populations, infrastructure, supply chains and services. Data science informed policies are critical to encourage innovation in the domain of energy system climate resilience. Sufficient financial support is also essential to develop systemic risk management strategies and implement solutions down to the local level.

"With further warming, climate change risks will become increasingly complex and more difficult to manage. Multiple climatic and non-climatic risk drivers will interact, resulting in compounding overall risk and risks cascading across sectors and regions." [10]

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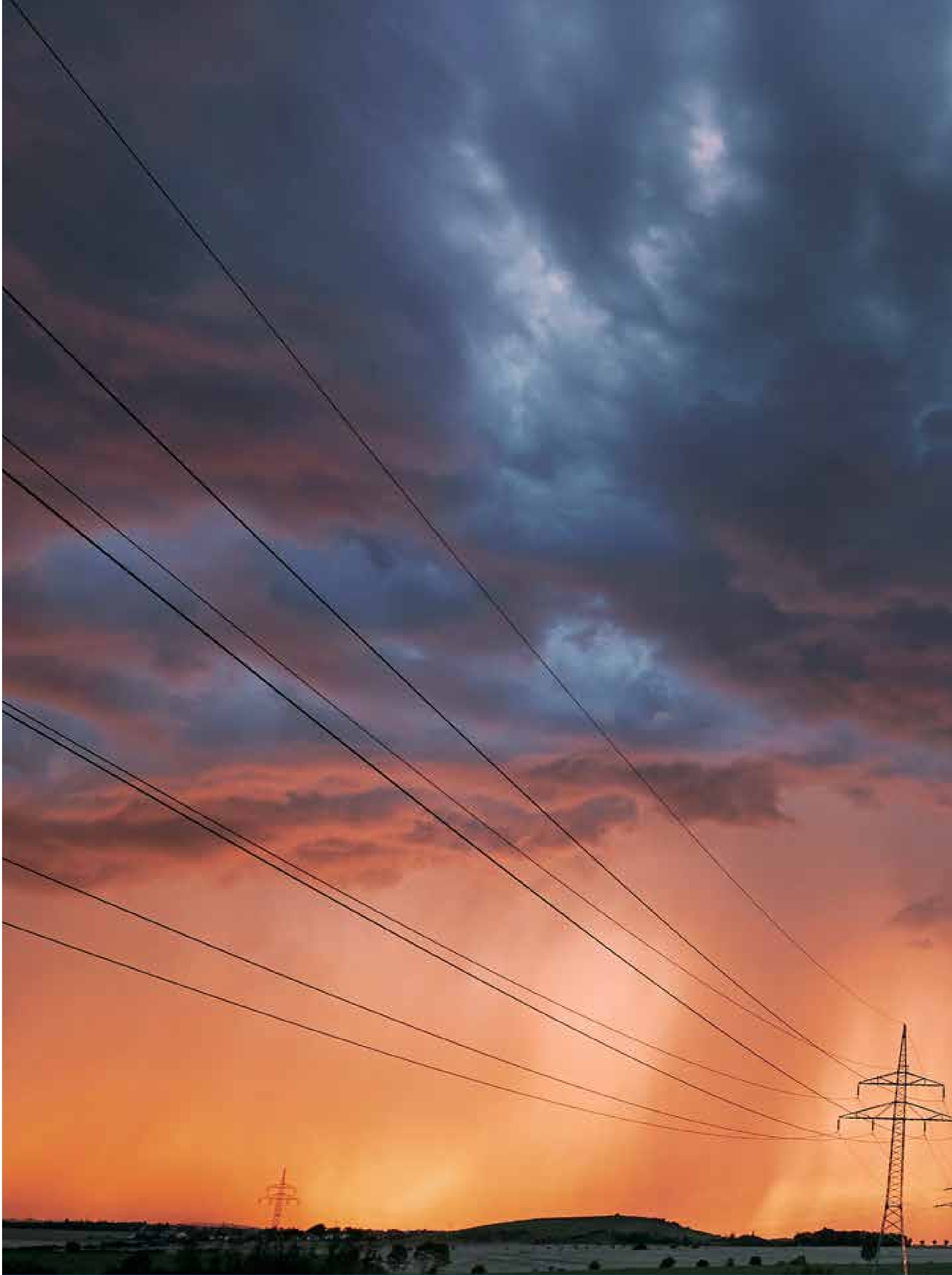

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