Integrated Weather and Climate Services in Support of Net Zero Energy Transition

Best Practices from the WMO Commission for Weather, Climate, Water and Related Environmental Services and Applications

2023 edition

WEATHER CLIMATE WATER

WORLD
METEOROLOGICAL
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WMO-No. 1312

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EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at https://public.wmo.int/en/meteoterm.

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FOREWORD

The transition towards renewable energy sources is globally recognized as critical to meet the goals of the 2030 Agenda for Sustainable Development and the Paris Agreement on climate change. To achieve net zero emissions by 2050, a rapid decarbonization of energy systems is required, with much of the energy generation capacities being replaced by renewable energy, including wind, solar and hydropower.

Renewables are susceptible to fluctuating weather patterns and are intermittent since they are dependent on climatic factors. In addition, climate change is expected to increase the frequency, intensity and impacts of extreme weather events, leading to the need for more climate-resilient energy systems to ensure energy security. Taking into consideration all these factors, it is apparent that the role of weather, water and climate services for energy is compelling for an effective and timely transformation towards climate-resilient energy systems.

WMO published the Global Framework for Climate Services (GFCS) *Energy Exemplar to the User Interface Platform of the Global Framework for Climate Services* in 2017. It served as a guide to WMO Members and Partners on how to develop and deliver tailored climate products and services for supporting renewable energy projects, to improve energy efficiency and to reduce the risks of hydrometeorological hazards on energy assets.

Built on the GFCS Energy Exemplar, this publication provides well-timed support for this crucial decade of energy transition to net zero. Through enabling WMO Members and their National Meteorological and Hydrological Services, as well as energy sector companies and practitioners, to deliver and uptake integrated weather and climate services (W&CSs), national strategies on clean and sustainable energy for all can be achieved in a timely and effective manner. Focusing on the full value chain/cycle of the integrated W&CSs in the energy sector, this publication reviews the current state of knowledge in this area, identifies key weather and climate data, products and services, highlights gaps and barriers to uptake these services, benchmarks best practices and describes implementation approaches to assist with the deployment of these services.

Sustainable collaborations between the energy system experts and the W&CS community is needed for the key role that meteorology and energy have in driving low-carbon and resilient energy solutions for a sustainable world.

Prof. Petteri Taalas
Secretary-General, WMO

PREFACE

These best practices have been compiled under the aegis of the WMO Study Group on Integrated Energy Services as part of the Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM).

The Intergovernmental Panel on Climate Change special report on Global Warming of 1.5 °C and the Sixth Assessment Report are urging the world's nations to define strategies to stabilize global rises in temperature in order to advert the worst impacts of climate change. One approach, being pursued by many governments, is decarbonization of the energy sector, which currently accounts for two thirds of global anthropogenic greenhouse gas emissions. As the government bodies at the vanguard of weather and climate sciences, National Meteorological and Hydrological Services have a central role to play in providing services to support the siting and operation of renewables, as well as in de-risking future energy security from evolving extreme events.

WMO SERCOM has placed a high level of importance on supporting Members and relevant stakeholders in their provision of sustainable services for the energy sector, as demonstrated by the establishment of a Study Group on Integrated Energy Services. This effort builds on the mandate of the Global Framework for Climate Services in supporting and supplementing existing initiatives for the development of user-driven climate services for the energy sector.

This publication looks to provide additional context and guidance based on "good practices" to support Members' efforts to accelerate the transition towards net zero emissions through the enhanced development and wider promotion of integrated weather and climate services.

On behalf of SERCOM, I wish to express my gratitude to all those who have contributed to the development of this publication, and trust that WMO Members and stakeholders in the wider community will find them useful.

Mr Ian Lisk
President, WMO Commission for Weather, Climate, Water and
Related Environmental Services and Applications (SERCOM)

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EXECUTIVE SUMMARY

WMO published the *Energy Exemplar to the User Interface Platform of the Global Framework for Climate Services* in 2017. This Exemplar served to guide WMO Members and Partners in identifying key climate data and products, as well as mechanisms needed to develop user-driven climate services for the energy sector[1] to support increasing resilience, a faster renewable energy deployment and energy efficiency measures. Since then, there has been an acceleration in the race to achieve net zero carbon emissions by the middle of the twenty-first century, to meet international goals, particularly those set at the Conferences of the Parties under the auspices of the United Nations Framework Convention on Climate Change.

For the energy sector, achieving net zero emissions requires a rapid decarbonization of the energy system (for example, generation, infrastructure and transport) with much of the capacity being replaced with variable renewable energy. Such decarbonization also includes a drastic increase in energy efficiency and system resilience, a thorough digitalization for smart decisions and boosted investment in low-carbon innovations. As a result, the energy sector has recently begun an epochal infrastructure, technological and societal transformation.[2] In this context, weather and climate services (W&CSs) for energy are indispensable enablers of an effective and timely energy transformation.

This publication provides the background and guidelines required to strengthen the development, and enable a widespread uptake, of integrated W&CSs for the energy sector, which are needed to accelerate the transition towards net zero emissions. Its objectives are to:

- Review the current state of knowledge on W&CS value chains in the energy industry
- Benchmark best practices and identify knowledge gaps and barriers to the uptake of these services
- Describe implementation approaches, including business models, public–private–academic partnerships and capacity-development programmes to assist with the deployment of these services

The overall aim is to guide WMO Members (typically their National Meteorological and Hydrological Services), other service providers, and energy sector companies and practitioners in identifying key weather and climate data and products. Moreover, it aims to support defining the mechanisms needed to develop user-driven climate services for the energy sector to support resilience, renewable energy development and energy efficiency.

In addition, while effort is made to specialize the content of this publication to the energy sector, it is inevitable that some of the components constituting W&CSs for the energy sector are also valid for other sectors (for example, production of weather and climate data, and stakeholder engagement). These will therefore be presented in a rather general way; however, specific examples are also presented (for example, in boxes) to link them back to the energy sector.

From an energy sector user perspective, there are several areas served by W&CSs:

- Characterization of past weather/climate events using **historical data**. Perhaps this is the most important element, as it provides a baseline, or first-order approximation, of the current risks and opportunities and is thus key to managing energy production and distribution.
- **Nowcasting/short-term weather forecasts** for load balancing by maximizing the usable component of the generated power.

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[1] In the Energy Exemplar and in this publication, when referring to the energy sector, it mostly means the electricity component of this sector.

[2] "Transformation" is used to indicate the fact that the net zero target requires achieving a very different energy system structure from the current one. Transformation can thus be viewed as an outcome. On the other hand, "transition" is the process of achieving an outcome, the energy transformation in this case. Consistency in the use of these two terms will is attempted in this publication, although transformation is generally preferred, as it can also be interpreted as the '"process of transformation'", therefore with strong overlap with transition, while more clearly conveying the required sense of urgency implied in the net zero target.

- **Sub-seasonal to seasonal climate forecasting** for maintenance of infrastructure and resource and risk management purposes.

- **Decadal climate forecasting** for multi-year resource risk management; these forecasts effectively extend the seasonal forecast range to typically 10 years ahead, thus allowing a longer risk assessment horizon.

- **Multidecadal climate projection** for infrastructure risk assessment, planning and design purposes. This includes providing authoritative data on the possible evolution of climate considering different emissions scenarios, including those aligned with policies.

The production of weather and climate information (in the form of data, visualizations and briefs) that underpins services for the energy sector (and indeed for other sectors too) is ultimately based on simulation of the Earth system (or relevant components, depending on the specific problem). Simulating the Earth system involves extremely complex technology, which has been developing over many decades, with huge investments at the national/international levels. This remains the case, even when just the atmospheric component is simulated, which is necessary in, for example, the prediction of wind power up to several days ahead. Recently, machine learning methods have emerged as being more cost-effective (in terms of development and computations) and which provide reasonable results for more targeted problems. However, they often use the output of Earth system models amongst their input, particularly for predictions longer than a few hours.

Energy conversion models are defined as the models that link meteorological and energy variables. These models can be either statistical or physical, or a combination of both approaches. Given the focus of this publication on W&CSs, only the effect of weather and climate variations on energy demand and generation is considered. In this context, energy system components are sensitive to weather and climate. Thermal power generation, including nuclear energy, is less sensitive, whereas wind and solar photovoltaic power generation is highly dependent on weather variables such as wind speed, solar radiation and air temperature.

Actor interactions are at the heart of the W&CS co-creation process. We distinguish among knowledge producers (for example, National Meteorological and Hydrological Services), intermediaries (for example, W&CS providers) and users (for example, grid operators) that represent the three broad groups of actors involved in this process. The co-production steps for W&CSs are (see also the figure):

- **Understanding user needs and solutions:** This includes understanding context, building partnerships, identifying common ground and co-exploring needs.

- **Data generation and selection:** The starting point for the development of new services is the systematic collection and analysis of user requirements. The outputs of this initial phase can then be used to inform either the selection of available data or the generation of new data, or both.

- **Service co-production:** This may include co-design of a project or initiative and co-developing the solutions to be applied. This process allows user needs and knowledge producer capacities to be considered, taking into account the ability and interest of intermediaries in participating and facilitating this process.

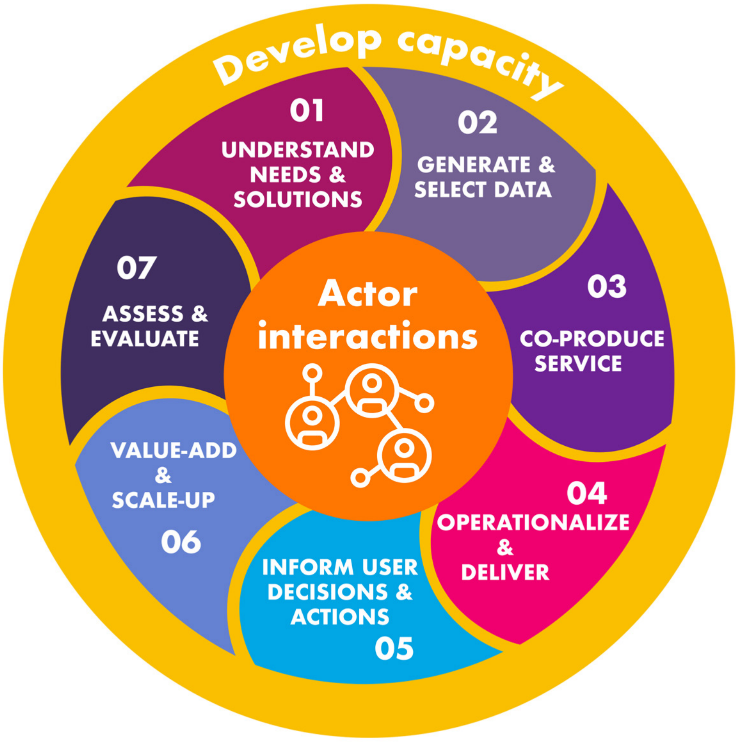
- **Operationalization and delivery:** A robust and real-time information production workflow is critical to providing a timely and effective service so it can be used, for instance, to manage predicted extreme events and major disruptions to the grid.

- **User decisions and actions:** Utilizing the information provided by the service, also based on semi-automated decision-making processes (for example, based on decision trees) and support tools (for example, interactive visualization platforms), enables users to properly embed weather and/or climate data into their decision-making.

- **Value addition and scalability:** Assessing a value, be it economic, social or environmental, ensures the outcome of a service is understood and appreciated by the funders or users. Assigning a value is critical for communicating the benefit of the service, and potentially for scaling it up to other geographies and/or sectors and/or typology of users.

- **Assessment and evaluation of services**: Setting benchmarks and key performance indicators is critical to ensuring services are effective and successful. In this context, evaluation can be understood as having several layers: (i) meteorological/climatological evaluation, (ii) evaluation of energy-related service components, (iii) socioeconomic assessment and (iv) performance of the delivery of the service, including user support.

- **Capacity development:** This takes place across all stages of the co-creation process and may include individual, procedural, infrastructural and organizational spheres of capacity and targeted activities to build these.



Framework for co-developing integrated W&CSs

Overall, there is a strong need to develop collaborative approaches among weather, climate and energy, which are still too fragmented. Additional multidisciplinary projects, including effective and well-supported networks, are needed. Critically, these should be embedded within long-term collaboration frameworks, to overcome the limited lifespans of projects and corresponding (intense) collaborations within them. The lack of sustainable collaboration is exacerbated because there are still critical disconnects between the W&CS community on the one side, and energy system modelling on the other side. However, some efforts in this direction are under way, due to the increasing recognition by the latter that weather and climate data should play a more important role in energy modelling.

Accordingly, this publication proposes the following 10 recommendations:

1. Improve mapping of user requirements
2. Improve the science and technology supporting W&CSs for the energy sector
3. Improve postprocessing methods and energy conversion models
4. Improve data access, exchange and policy
5. Refine co-production approaches, including data visualization, support and guidance, and use of delivery channels
6. Explore new energy sector applications using W&CSs
7. Refine business models for sustainable W&CSs

8. Implement capacity-building activities
9. Enhance communication activities
10. Strengthen existing and create new collaborations across organizations and sectors

This publication is structured as follows. Chapter 1 provides the background and overall motivation, starting from the policy drivers. Chapter 2 continues by discussing the underlying information production of W&CSs, namely weather and climate data. Chapter 3 discusses energy conversion models, using the weather and climate data introduced in Chapter 2 to meet the industry needs. Chapter 4 then looks into co-production approaches, while Chapter 5 looks at enabling uptake of W&CSs through realizing socioeconomic benefits, harnessing business models, identifying key policies, and creating partnerships and collaborations. Chapter 6 discusses capacity development. Finally, Chapter 7 provides concluding remarks and recommendations.

The publication is compiled under the aegis of the WMO Study Group on Integrated Energy Services (SG-ENE),[3] part of the Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM), with contributions from leading experts. Established in 2020, SG-ENE has as its main purpose to support the WMO Strategic Plan by helping Members and relevant stakeholders to create and sustain services delivery for the energy sector, as well as to contribute mainly to Sustainable Development Goal 7 on harvesting affordable and clean energy and the Paris Agreement on climate change mitigation and adaptation.

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[3] https://community.wmo.int/activity-areas/sercom/SG-Energy.

1. WEATHER AND CLIMATE SERVICES IN THE GLOBAL ENERGY TRANSFORMATION

The energy sector is one of the main emitters of greenhouse gases (GHGs). It must therefore be a key actor in trying to avert the ever-worsening damage caused by the impacts of climate change. In this context, the global energy transition towards renewable energy, in line with the decarbonization targets stipulated in the 2015 Paris Agreement, is critical to reducing emissions towards achievement of the net zero emission target. This transition is an ongoing process that aims to shift the world's energy systems away from fossil fuels and towards renewable sources such as solar, wind and hydroelectric power. Such decarbonization also includes a drastic increase in energy efficiency, thorough digitalization for smart decisions and boosted investment in low-carbon innovation. The energy transition is of paramount importance, but the resilience of energy systems also needs to be strengthened to ensure continuity of supply, and to mitigate damage to infrastructure. In other words, the energy sector can and needs to contribute to mitigation and adaptation actions.

Weather and climate services (W&CSs) play a crucial role in the decarbonization process. For example, the generation of solar and wind power is highly dependent on weather conditions, such as solar radiation and wind speed. Accurate weather forecasting and climate modelling helps energy companies and utilities predict the amount of power that will be generated by these systems and plan accordingly. This allows them to better manage the integration of variable renewable energy sources into the grid and reduces the need for power generation based on fossil fuels as a backup.

In addition to helping optimize the operation of renewable energy systems, W&CSs can also play an important role in the planning and development of new renewable energy projects. For example, wind and solar resource mapping based on historical data (observations and model-based output) helps identify the most suitable locations for wind and solar farms. Together with climate projections, they support decisions about the type and size of renewable energy systems that should be installed. In doing so, W&CSs also ensure these energy systems are designed and built to withstand the increasing number of extreme weather events, such as storms and heatwaves, which can damage equipment and reduce the overall efficiency of systems.

W&CSs can also play an important role in the development of energy storage systems, which are critical to success of the global energy transition. Energy storage systems, such as batteries and pumped hydro, can help smooth out fluctuations in power generation from variable renewable sources and ensure reliable supply of power. However, weather conditions, such as temperature and humidity, can affect the performance and longevity of these storage systems. Accurate weather and climate information can help energy companies and utilities design and operate these systems in a way that maximizes their efficiency and extends their lifespan.

Another important area where W&CSs can be applied to further assist the global energy transition is in the field of energy efficiency. Weather and climate information can be used to improve the energy efficiency of buildings, transportation systems and industrial processes. For example, by incorporating weather data into energy models of buildings, architects and engineers can design buildings that are better insulated and more energy efficient, which can help reduce the amount of energy needed to heat and cool them. Similarly, by incorporating weather and climate data into transportation systems, such as the use of electric vehicles and public transport, energy companies and governments can optimize the energy consumption of these systems, which helps to reduce the overall energy demand.

Overall, the global energy transition is a complex and challenging process that will increasingly benefit from the regular use of W&CSs, in order to boost the chance of success and to support energy system sustainability. Weather and climate data play a crucial role in the development and operation of renewable energy systems, the planning and development of new renewable energy projects, the development of energy storage, the energy efficiency of buildings, and the improvement of transportation systems and industrial processes.

The remainder of this introductory chapter presents the main elements of the climate and energy policy landscape and the challenges faced by the energy transition towards net zero emissions. W&CSs for the energy sector, which form the backbone of this publication, are then formally introduced, followed by a description of a framework for the design of W&CSs.

1.1 The climate and energy policy context

The global climate and energy policy context has changed substantially since the publication of the *Energy Exemplar to the User Interface Platform of the Global Framework for Climate Services* in 2017 (WMO, 2017[4]). The Paris Agreement, adopted in December 2015, entered into force in November 2016. The agreement marked an acceleration of global efforts to tackle climate change, with the energy sector being one of the main players in this effort to dramatically reduce emissions.

In 2018, the Intergovernmental Panel on Climate Change (IPCC) published a special report on limiting global warming to 1.5 °C (IPCC, 2018). The report stated that to limit global warming to 1.5 °C, global anthropogenic CO_2 emissions need to reach net zero by around 2050. The report can be seen as central to fuelling the race to net zero emissions, which has considerably accelerated since its publication.

In its Sixth Assessment Report, IPCC re-iterates that the efforts to limit global warming to less than 2 °C will require immediate, steep reductions in emissions. The longer action to reduce emissions is postponed, the more the climate will warm and consequently lead to a high likelihood of dire consequences to humans and the natural environment (IPCC, 2021).

During the twenty-sixth session of the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP 26), governments agreed to explore ways to bridge gaps between their current emissions pledges and actions required to reach net zero and reduce climate change impacts[5] (UNEP, 2021). Moreover, during COP 27, it was emphasized that there is an urgent need for immediate and sustained reductions in global GHG emissions by Parties across all applicable sectors, including through increase in low-emissions and renewable energy, just energy transitions partnerships and other cooperative actions. It was also recognized that the unprecedented global energy crisis in 2022 underlines the urgency to rapidly transform energy systems to be more secure, reliable and resilient, including by accelerating clean and just transitions to renewable energy during this critical decade of action (UNFCCC, 2022).

The energy sector is central to efforts to dramatically reduce emissions, with the sector accounting for over two thirds of global GHG emissions (Our World in Data, 2020[6]). Within the energy sector, CO_2 emissions for the subsectors as of October 2022 are broken down as shown in Figure 1.1.

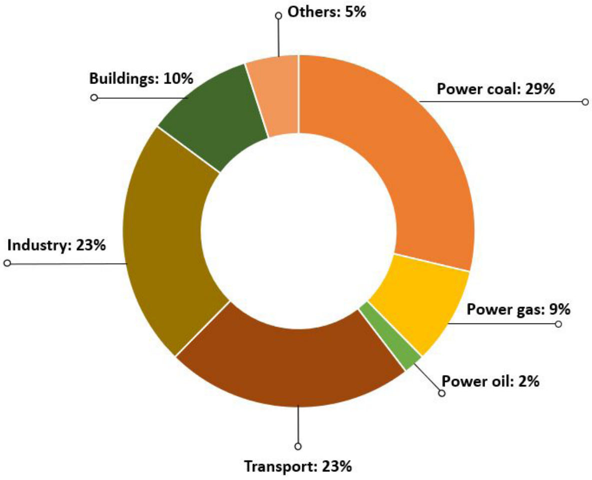

Figure 1.1. Global energy-related CO_2 emissions by subsector

Source: Adapted from IEA (2022a[7]), as of October 2022

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[4] The Energy Exemplar (https://library.wmo.int/doc_num.php?explnum_id=3581) was published in 2017, but the bulk of the work was completed in 2015 and 2016.

[5] https://unfccc.int/news/4-key-achievements-of-cop26.

[6] https://ourworldindata.org/ghg-emissions-by-sector.

[7] https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector.

With the backdrop of an essentially continuous and increasing rate of global CO_2 emissions over the past 150 years (as reflected by CO_2 concentrations of ca. 290 ppm in 1870 and nearly 420 ppm in 2021 (Our World in Data, 2017; NASA, 2022[8]), global CO_2 emissions decreased by about 6% in 2020, due to the coronavirus disease (COVID-19) pandemic and associated global lockdowns. However, global energy-related CO_2 emissions were projected to increase by 4.8% in 2021, as demand for coal, gas and oil rebound (IEA, 2021a).

In May 2021, the International Energy Agency (IEA) published a flagship report on a road map for reaching net zero by 2050 in the global energy sector (IEA, 2021b). Figure 1.2 illustrates the key points of this road map. In brief, to reach net zero energy emissions by 2050, it is foreseen that net zero electricity emissions will be

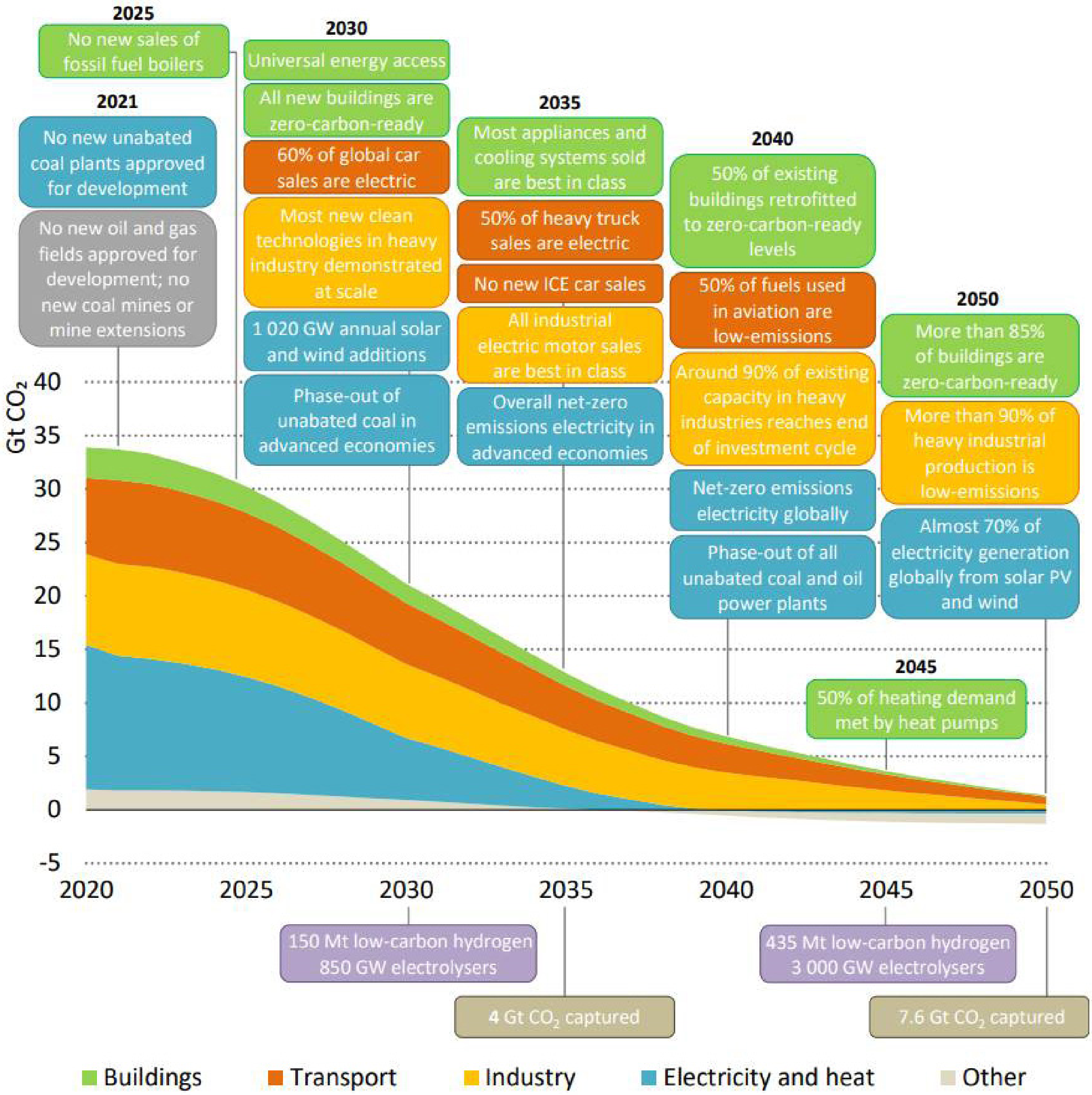

Figure 1.2. Priority actions for reaching net zero energy emissions by 2050

Note: ICE = internal combustion engine.
Source: IEA (2021b)

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[8] https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions; https://climate.nasa.gov/vital-signs/carbon-dioxide.

achieved, with almost 70% of global electricity being generated through solar and wind power by 2050. In addition, massive efforts to electrify the transport and heating sectors are expected.

In this context, W&CSs provide key support technology to ensure the net zero emissions goal is achieved effectively. First, these services are key to improving the accuracy of energy demand estimates, with demand being the main target in energy provision (trivially, if there were zero energy demand, there would be no need for energy systems, let alone power production). Second, these services are essential for supporting continuity in the delivery of renewable energy services. Third, they can support improved management of challenges for transmission and distribution management, as well as resilience of the energy systems. Fourth, they enable greater efficiency in final energy use. Finally, W&CSs can support energy innovations (for example, exploiting highly accurate weather data to assist in the development of bifacial solar photovoltaic (PV) panels, or sophisticated machine learning approaches to estimate electricity demand at a high granular level). These fundamental elements of the energy system, constituting its value chain, are the target of the W&CSs discussed in this publication, and are illustrated in Figure 1.3.

1.2 Challenges in the net zero energy transition

Effective climate change adaptation and mitigation actions, including those towards the net zero emissions target, require a significant transformation in the way energy is produced, distributed, stored and consumed, while preserving or even enhancing the security of energy services as well as the overall system balance. This transformation in the energy sector takes place against a variable and changing climate, which can affect energy systems through acute (or rapid) or chronic (or slowly evolving) events.

Electricity systems are already exposed to climate change in many ways, some of which are listed in Table 1.1. And although the energy transformation has already started, it is important to consider that around 80% of current energy consumption is still provided by sources based on fossil fuels. Therefore, the challenge of achieving the net zero emissions target is momentous.

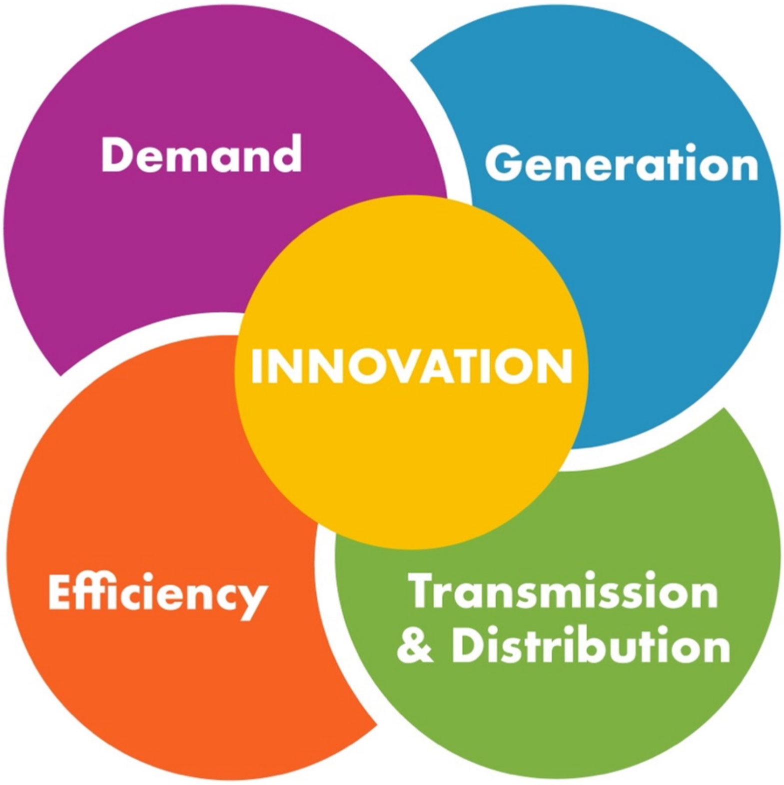


Figure 1.3. Fundamental energy system elements, or value chain, addressed in this publication in the context of W&CSs

Table 1.1. Overview of main potential impacts on the electricity system due to climate change

Climate impact	*Generation*	*Transmission and distribution*	*Demand*
Rising global temperatures	• Efficiency • Cooling efficiency • Generation potential • Need for additional generation	• Efficiency	• Cooling and heating
Changing precipitation patterns	• Output and potential • Peak and variability • Technology application	• Physical risks	• Cooling • Water supply
Sea-level rise	• Output	• Physical risks • New asset development	• Water supply
	• Physical risks		
	• New asset development		
Extreme weather events	• Physical risks • Efficiency	• Physical risks • Efficiency	• Cooling

Source: IEA (2021c)

From a technological point of view, decarbonization can be achieved in several ways. However, the two main areas are: (i) the widespread adoption of low-emission power generation and (ii) the electrification of other sources of energy. In principle, power generation is relatively easy to decarbonize, by shifting from fossil fuels to renewables and/or nuclear energy generation, even if, in practice, there are many factors at play that preclude this transition from happening in a faster way (for example, lifespan of current fossil fuel power plants). Phasing out the use of fossil fuels altogether is notoriously challenging and involves transforming the transport, heating and cooling sectors. However, increasing the share of electrification in all sectors is an essential component of the energy transition.

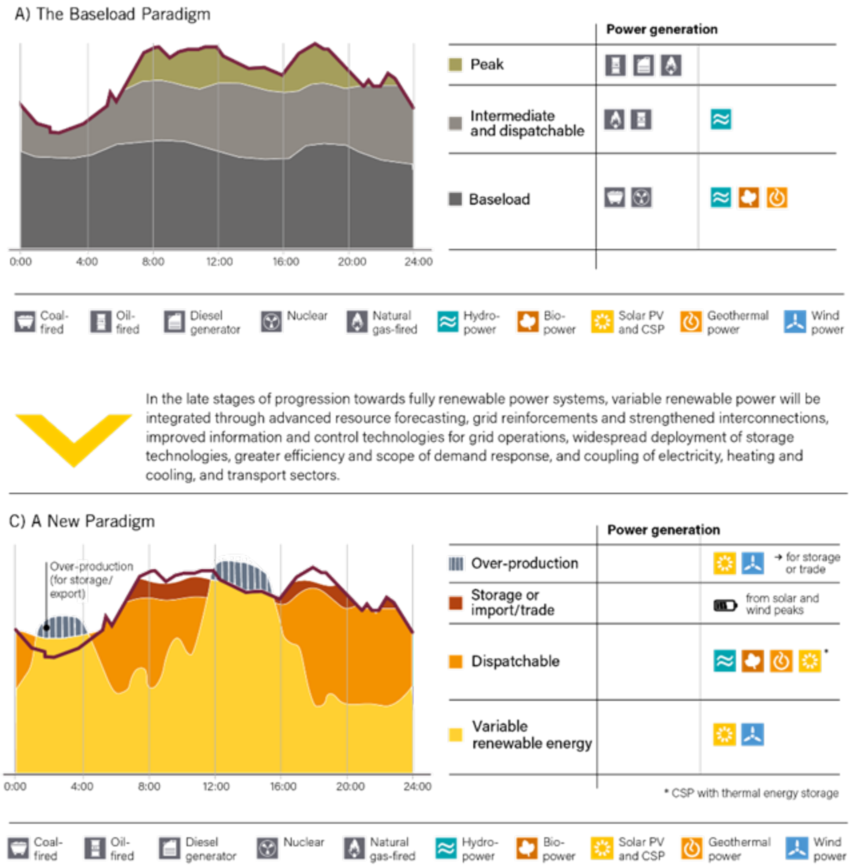
To achieve the net zero emissions target, energy transformation needs to address challenges in the following energy system areas, which are closely aligned with the value chain in Figure 1.3:

- Energy consumption (or demand)
- Power generation (or supply)
- The power network, including transmission and distribution
- Energy efficiency
- Innovation, including system reliability and design

1.2.1 Demand-side challenges

The transition from fossil-fuel-based to renewables-based electricity generation involves changes to the supply profile. These changes involve a paradigm shift away from the traditional baseload, which relies heavily on slowly varying power outputs from fossil fuel and/or nuclear power plants. This is coupled with dispatchable fossil fuel and hydropower plants, to supply patterns that vary more in synchronization with variable renewable resources such as wind and solar. The new paradigm baseload is combined with more diverse and advanced flexibility offerings than that existing in the current baseload paradigm. These include storage, power trade through interconnected networks, demand-side management and advanced power plants to support the flexibility required to balance demand and supply (Figure 1.4).

Demand is typically forecast at the power bidding zone level. Such zones vary in size but are generally at least as large as a country like Belgium. Local changes are therefore not resolved by the demand models. Distributed generation and demand-side management forecasting has traditionally been based on weather variables such as temperature, cloud cover and relative humidity (aside of course from non-weather factors), and has now become considerably more complex as it needs to account for local generation from variable sources such as rooftop PVs as well as self-consumption.



In the late stages of progression towards fully renewable power systems, variable renewable power will be integrated through advanced resource forecasting, grid reinforcements and strengthened interconnections, improved information and control technologies for grid operations, widespread deployment of storage technologies, greater efficiency and scope of demand response, and coupling of electricity, heating and cooling, and transport sectors.

Figure 1.4. Illustration of the paradigm change in the power sector: (top) traditional baseload paradigm and (bottom) new, renewable generation based, paradigm

Note: CSP = concentrating solar thermal power.
Source: REN21 (2017)

In addition, the adoption of new electricity uses (for example, local and bulk storage, electric vehicles, heat pump conversions and hydrogen generation), along with other technological and social developments, will significantly modify the daily and weekly demand patterns, as will load-following technologies. In general, the demand patterns will be more complex and more variable, and will require new flexibility options, which will also depend on social acceptance. Demand patterns are expected to change from a well-known daily/weekly/seasonal cycle to a more variable picture. Weather and climate forecasting will therefore become much more important.

1.2.2 Supply-side challenges

Increasing the use of renewable energy sources will make energy generation more variable. This is particularly the case for wind and solar power on short timescales (up to a few days ahead), but also for hydropower (from days to months ahead). Wind and solar (predominantly PV) power are the most rapidly growing sources of renewable energy.[9] Other renewable sources are increasing too, including hydropower (particularly in China), biofuels, geothermal and marine power (mainly wave and tidal); however, their growth is considerably smaller (REN21, 2021).

Wind speed and solar radiation are highly variable in time and space. They can produce generation ramps, which are strongly positive or negative gradients in energy output over very short times. The network must be able to absorb these potentially strong variations, which can occur over a range from seconds to hours.

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[9] In 2020, 140 GW of solar power was installed, for a total of 760 GW, and 90 GW of wind power was installed, for a total of 740 GW.

Therefore, forecasts need to be continually improved to minimize the impacts of power ramps and more generally optimize power integration into the grid.

Advanced power forecasts are produced from the blending of different sources of information, including high-resolution numerical weather prediction (NWP), nowcasting based on meteorological observations (in situ measurements and remotely sensed data) and integration of real-time generation information. Several regions have demonstrated that such blended forecasting systems improve significantly the accuracy of power output forecasts, and allow a smoother operation of the system and a better financial outcome (see, for example, Kosovic et al. (2020)[10] and references therein). However, such complex systems are not yet operational in all contexts, countries and companies. They require strong expertise and significant processing capabilities, notwithstanding access to real-time generation data, which is still problematic in many cases, notably for confidentiality issues.

Hydropower generation is sensitive to longer-term variations, from days and weeks, up to several months and even years ahead. Reservoirs must be operated based on the seasonal cycle of water inflows, particularly in watersheds where there are multiple uses of the available water for energy generation: domestic consumption, irrigation for agriculture, flood control and recreation. Historically, water inflows have been forecast based on climatological data, often using analogue methods. However, there is growing evidence of human-induced observed changes in heavy precipitation and droughts (IPCC, 2021); therefore, using historical data to forecast future water incomes without taking the effects of climate change into account is becoming increasingly less accurate.

Significant progress in hydropower forecasting has been made in the past decade, also utilizing the latest machine learning technology (Ho et al., 2020). Yet, forecasting skill remains moderate in some regions, and forecasting products are still not tailored enough to be used operationally, even if some recent projects, like the European Union's SECLI-FIRM[11] project, have demonstrated the potential of seasonal forecasts for hydropower applications.

Climate change can affect all energy production sources, due to climate variability and changes in extreme meteorological events. For instance, a reduction in cooling system performance can affect thermal power generation, including nuclear power. These systems use water from the sea or rivers, and/or cooling towers. In the former case, the cooling efficiency is reduced when sea and river water temperature increases, or when river flow decreases. In the latter case, efficiency reduction comes from an increase in ambient air temperature and/or relative humidity. Generally, the efficiency of thermal power generation is reduced with higher air temperatures (Šen et al., 2018; Coffel and Mankin, 2021).

For completeness, it is also worth mentioning other minor forms of power production that either are less sensitive to weather variables such as geothermal (14 GW of installed capacity in 2020) or are at an early stage of commercialization as in the case of marine power (tidal and wave power being the main ones, with an overall installed capacity of over 500 MW in 2020) (IRENA, 2021; REN21, 2021). In addition, bioenergy, which involves the use of biological materials[12] for energy purposes, accounted for an estimated 11.6%, or 44 EJ, of total final energy consumption in 2019 (REN21, 2021). Although bioenergy is weather sensitive, for simplicity, this form of energy is not explicitly described in this publication. However, most of the material presented (for example, in Chapter 2) also apply to it.

1.2.3 Network challenges

One important consequence of the increased use of variable renewable energy is that energy systems are becoming more resilient by design, thanks to substantially reduced dependency on fossil fuels and digitalization of the network. However, they are also becoming increasingly exposed to the impacts of weather, climate

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[10] https://doi.org/10.3390/en13061372.

[11] http://www.secli-firm.eu; see specifically case studies 2 and 5 under http://www.secli-firm.eu/case-studies.

[12] A wide range of materials can be used for bioenergy, including residues from agriculture and forestry, solid and liquid organic wastes (including municipal solid waste and sewage), and crops grown especially for energy.

Box 1.1. Integrated weather services for offshore wind power production in China

To ensure the safe production of offshore wind power, reduce costs and increase efficiency, Beijing JiuTian Meteorological Technology Co. Ltd has developed a hazard prevention and smart operation system for offshore wind power. The system provides decision support for offshore wind power production, operations and emergency management.

CGN New Energy, a well-known new energy enterprise with a huge offshore wind power reserve, put forward the need to build the system. The company faced challenges to the safety management of operating equipment, ships and staff, as well as the maintenance and appreciation of company assets. Offshore wind power faces severe safety and efficiency challenges due to complex and changeable marine meteorological conditions. Thus, a system emerged to achieve robust marine weather protection, offshore wind power hazard prevention, smart operations and maintenance.

Based on supercomputers, the system integrates various types of meteorological data. These include nowcasting, with local observations for storm warning, seamless ocean–atmosphere coupled mode high-resolution forecast data and atmospheric model ensemble extended forecasts for operation plan making, reanalysis datasets and climatological data, which are often used to extract valuable features for the prediction correction algorithm. It uses artificial intelligence and big data analysis methods, combining meteorological marine forecasting models.

These data are integrated into rich visualization products (see Figure 1.5), such as working window periods, typhoon path and ship operating status, all presented on a web page. Services are constantly adapted to different scenarios and the system's algorithms are continuously adjusted to ensure improvement in forecast accuracy.

Figure 1.5. Hazard prevention and smart operation system for offshore wind power

Source: China Meteorological Administration

The system was successfully delivered at the end of 2020, bringing significant socioeconomic benefits (SEBs) to the user. The economic benefits to CGN New Energy have thus been improved, and the meteorological company has also received economic returns. For example, the system helped increase the power generation time of the CGN Jiangsu Rudong offshore wind farm during the operation and maintenance period by 10 hours per year, and increased annual income by 1.292 million yuan, according to feedback from the user.

At the same time, the system helps protect the lives of workers and achieve carbon neutrality goals. It also helps to increase the annual power generation capacity of New Energy by 7.86 million kWh and reduce CO_2 emissions by about 800 tonnes per year.

variability and climate change. Therefore, the critical role of W&CSs in facilitating the energy transition is becoming increasingly apparent.

Such services include energy-related short-term forecasts such as demand and generation from wind power, solar power and hydropower, on timescales from seconds to a few hours ahead. These are critical for balancing operations (many wholesale markets are moving towards short settlement time frames of the order of minutes). They also include longer term forecasts from days to several months for system maintenance and resource management. Moreover, these services provide information about the evolution of climate parameters, in terms of average variations and extremes, for long-term (multidecadal) planning.

1.2.3.1 Network operations

The increasing share of renewables will result in more decentralized generation, spread over wider territories, and much more variable than centralized generation systems. These features impose additional constraints on the dynamics of networks that will have to compensate for the variable generation from renewables, to meet demand in an instantaneous manner. In addition, unlike traditional synchronous generators, wind and solar PV plants without batteries cannot provide system inertia, and their advanced frequency and voltage service features are often limited in use due to current regulatory, institutional, technical and data constraints.

Anticipating variable generation from renewables is therefore critical for system stability. This reinforces the need to continuously improve wind and solar forecast accuracy. Innovation with grid forming technologies and power electronics can help tackle this challenge, but even then, the timely knowledge of the actual generation and its short-term forecast remain crucial (for example, see Box 1.1).

In addition to improvements in forecast quality, it is also essential to improve real-time estimation of the actual generation, especially for solar PV power. This situation is made even more complex due to the widespread use of grid-connected rooftop PV panel installations. In most cases, rooftop PV panels are not metered in real time, and hence the corresponding generation is not known accurately. Moreover, the characteristics, orientation, shading and so forth of rooftop PV panels vary considerably, and it is therefore extremely difficult to model production with high accuracy.[13]

Satellite information such as the SODA[14] products can alleviate this lack of data as they provide a wide coverage, even if satellite data and their processing have an inherent delay. Once timely data are collected, either from local weather stations or from high-resolution satellite imagery combined with artificial intelligence, it is possible to improve the real-time estimation of PV generation (Chen and Troccoli, 2016; Prasad and Kay, 2021[15]).

Power cables are generally operated using either annual or seasonal transit capacity (ampacity) values, which have been determined from climatological data. These climatological values need to be applied/considered for long-term planning, but improved weather forecasts would also provide some opportunity to adapt the transit capacity of power lines in near real time. Transmission capacity is determined by the line temperature, which is a function of ambient temperature, wind speed and direction, solar radiation and current intensity.

More power can transit the lines when the wind speed is high and air temperature is low. Under these conditions, more power from wind farms, for instance, can be transmitted, thus avoiding curtailment if the climatological ampacity is reached. This practice is known as dynamic line rating (DLR). Its development is subject to the availability of high spatial resolution data and forecasts, mainly for wind speed, air temperature and solar radiation. Another issue with power cables, particularly at relatively high latitudes, is freezing rain and the resulting heavy load of ice accumulating on overhead transmission lines, which can cause collapse of the electricity supply for large regions (CLIM4ENERGY, 2017).

1.2.3.2 Long-term planning

Distribution (low- to medium-voltage) and transmission (high-voltage) power networks are generally long-lasting infrastructures (order of decades). Their lifespan depends on the type of asset, whether they are overhead or underground lines, power stations and substations, pylons and so on. For instance, high-voltage power lines are typically built to last for ca. 80 years.

Existing infrastructure has been dimensioned and built based on climatological information such as air temperature and wind speed, which determine the maximum current intensity that can transit in the wires (ampacity), or the probabilistic estimation of extremes so that assets are not at risk for instance of a 100 year return period of flooding. Engineering practices account for comfortable margins; yet, these may not

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[13] A workaround is to attempt an accurate prediction for a small representative area and then upscale the results by multiplying the power output in that area by the amount of PVs installed in that region. However, such an estimation still carries a considerable level of uncertainty.

[14] www.soda-pro.com.

[15] http://dx.doi.org/10.1127/metz/2016/0725; https://doi.org/10.3390/en14185865.

be sufficient in the near future considering observed and anticipated climate change. New approaches need to be developed to consider the expected climate evolution.

Such approaches are a scientific and technical problem. The necessary information must be highly local, which is not typically readily available as it requires tailor-made downscaling of climate projections. To define priorities among the different options for network reinforcement or replacement, it is also necessary to provide information on the rate of change of the different meteorological variables over time. The goal is then to determine which assets are most at risk for a given time window, and which ones can be operated longer without upgrading. For new infrastructure, the current practice is to estimate the climatic conditions under which it will operate through its lifetime. But future options may consider building assets with a shorter expected lifetime and either renovating them or even replacing them more often, if this is estimated to be a more economical option – for instance because uncertainties in the long-term climate are too high and/or severe extremes are expected to be more frequent.

There is also a normalization and logistical problem, as the whole value chain from the materials providers, to network developers and operators, to regulatory authorities must conform to new standards. There is no established standard that takes climate change into consideration in dimensioning and building rules of electrical materials. It is only by collaborating and sensitizing the producers of materials that their manufacturing can be adapted to different climate conditions.

1.2.4 Energy efficiency challenges

While energy efficiency results from technological improvement and innovation, often achieved in response to changes in policy and regulatory frameworks (including standards), changes in consumption will come mainly through individual and collective behavioural changes and adaptation of technologies. Behavioural changes include deliberate decisions to limit personal energy use (for example, turning off lights or setting thermostats lower in winter and higher in summer), and also choices about the source of energy being used (for example, proactively purchasing green electricity) and the way energy is used (for example, charging electric cars when electricity is more abundant).

Technology can contribute to efficiency changes via the application of demand response programmes. These provide an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting electricity usage during peak periods in response to time-based rates or other forms of financial incentives, via deployment of smart grid technologies such as “smart meters”.[16] Specifically, in the context of smart grid technology, weather forecasting plays a critical role, for instance with the scheduling of power resources (for example, see Box 1.2).

Even if every person has a role to play, individual contributions can account only for a relatively low share of the necessary effort. For France, for instance, carbone 4 (2019) estimates that a maximum of 25% of emissions reductions can be achieved by individuals. This means that considerable efforts to reduce emissions must also come from governments, local authorities and businesses.

1.2.5 System reliability and design challenges

The increased generation variability that comes with an increased deployment of wind and solar power may require an expansion in the interconnection between neighbouring power balancing areas. As weather regimes vary spatially (typically from tens to hundreds of kilometres), neighbouring regions can experience different wind and solar radiation conditions (Drücke et al., 2021).

Geographical dispersion of wind and solar power plants to improve the balance of renewable generation will therefore become increasingly important. System stability will thus benefit from the development of interconnections among balancing areas. Building long-distance high-voltage lines has a significant cost;

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[16] A smart meter is an electronic device that records information such as consumption of electric energy, voltage levels, current and power factor. Smart meters communicate the information to the consumer for greater clarity of consumption behaviour, and electricity suppliers for system monitoring and customer billing.

Box 1.2. Smart Energy Online – an energy saving service using location-specific weather forecast information in Hong Kong, China

The Smart Energy Online platform (CLP, n.d.),* an initiative by CLP Power Ltd, in Hong Kong, China, enables business users to take informed energy saving actions. The platform incorporates smart meter and weather data to provide energy consumption forecasts, which facilitate customer energy saving actions and promote decarbonization. It allows business customers to access their load profiles, monitor their energy consumption and manage their energy demand in accordance with meteorological conditions.

The platform was developed by understanding user needs, co-production and collaboration between the Hong Kong Observatory (HKO) and CLP. It allows customers to visualize their energy demand profile. Based on the load profile display, customers are informed of the anticipated time of peak demand and can plan for any operational changes to better manage their energy usage. Customers can compare their energy consumption with their historical profile to access energy use and projections.

The platform also allows users to pre-set their consumption level, triggering an alert when the pre-set consumption level is exceeded. Subsequent versions of the platform have improved the accuracy and allowed automatic incorporation of regional weather forecast data. This has enabled demand forecasting on an hourly basis, with a forecast period of 9 days. This forecast function allows customers to prepare well in advance for taking necessary energy saving actions, thus helping them to operate their homes and facilities more efficiently and cost-effectively.

The energy consumption forecast enables business users and property managers to better understand their energy consumption profiles and plan for energy saving measures to reduce power consumption and peak loading, especially during hot weather conditions. The functions of the platform are especially useful for users with large air-conditioning loads, such as hotels, shopping centres, office blocks and factories. Some users managed to save up to 6% of their electricity consumption (Cheung et al., 2016), without any capital investment.

Enhanced features, such as customizable data display by type of customer account, energy data and different timescales, enable customers to review their electricity consumption at a glance. This information can lead to improved energy operations and result in more economical savings and comfort for customers. The CO_2 emissions dashboard on the platform also provides emissions data across customer premises, which helps them measure the GHG emissions of their business, set decarbonization targets and track progress on climate action.

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* https://www.clp.com.hk/en/business/low-carbon-solutions/energy-management/smart-energy-online.

therefore, accurate information about present and future continental-scale weather and climate patterns is critical in the dimensioning of power networks, and the siting of renewable production plants.

Energy generators may experience competition with other sectors in the use of resources. This is the case in the water sector, as water is used for hydropower generation and thermal power generation cooling, but it is also critical for agriculture (for example, irrigation), domestic use (for example, drinking water), recreation (for example, tourism and fishing), flood control measures and management of ecosystem services.

Climate change is already manifesting itself into significant impacts on the water cycle, and it is anticipated these will be even more prominent in the future. Water availability may decrease in places, due to more intense and longer droughts, but more frequent flash flooding could create challenges too. It is therefore apparent that information on water resource availability, weeks to months to decades ahead, needs to be an integral component of energy operations and planning.

Electricity production or grid-related innovation areas that will require meteorological information include batteries for storage (for example, peak shaving or load shifting (Energylink, 2021[17]), digitalization of the network, and development of new technologies such as new wind power generators (for example, floating offshore wind systems or airborne wind energy systems) (Cherubini et al., 2015; Watson et al., 2019; Weber et al., 2021) or solar power generators (for example, bifacial PVs[18]). The first two areas are explored in more detail next.

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[17] https://goenergylink.com/blog/load-shifting-and-peak-shaving/.

[18] The use of bifacial PVs is a rapidly growing technology that can improve electricity production by utilizing light irradiation from both sides of the panel (Jouttijärvi et al., 2022). See also https://www.pv-magazine.com/2020/08/19/bifacial-modules-the-challenges-and-advantages.

Battery storage will improve the stability of the network and the availability of power over time frames from seconds to hours (and potentially longer). As the lifetime of a battery depends on the number of charge and discharge cycles that a battery completes and the depth of discharge,[19] using weather forecasts to manage battery operations will provide significant cost savings. Moreover, as battery performance and degradation depend on temperature (Leng et al., 2015; Ma et al., 2018) (similar to the performance of PV panels, but in a much more complex way, due to the chemical reactions that occur inside a battery), meteorological information can help extend battery lifetime, for instance by limiting use when weather conditions are predicted to be outside of the battery's recommended operating range.

Digital technologies are making energy systems around the world more connected, intelligent, efficient, reliable and sustainable. Advances in data, analytics and connectivity are enabling a range of new digital applications such as smart appliances and shared mobility. Digital data and analytics can reduce power system costs in at least four ways by reducing operations and maintenance costs, improving power plant and network efficiency, reducing unplanned outages and downtime, and extending the operational lifetime of assets (IEA, 2017). Under increased use of renewables in the electricity system, the integration of W&CSs within digital technologies will therefore assist in all these four areas.

W&CSs are therefore crucial for the energy sector, particularly as the sector transforms into a new system compatible with the net zero emissions target. Forecast quality is, and will remain, an area of improvement, as requirements for forecasts are refined and also expanded. While forecast quality can be improved through the use of scientific approaches such as probabilistic forecasts, using meteorological probabilities is something that needs to be accounted for in any energy system operation and planning, in a similar way as engineering, technology and finance have their own operating ranges. Ultimately, meteorological probabilities are important inherent factors to be considered in any decision-making, which naturally also involves subjective considerations.

The quality of forecasts will be discussed in considerable detail, together with the main characteristics of the production and availability of forecasts, in Chapter 2 in terms of meteorology and Chapter 3 in terms of energy.

1.3 Integrated weather and climate services towards net zero transformation

W&CSs rely on the production and delivery of relevant, credible and usable information. The energy industry, with its long-standing and varied needs for these services, has strong experience of using weather services, and to a lesser extent climate services,[20] with the latter being a more recent endeavour.

However, under the backdrop of a changing climate and the energy transition, new and revised approaches for W&CSs are required. In addition, the weather and climate enterprise is continually evolving and improving through, for instance, the increasing resolution of Earth system models and the use of machine learning/augmented intelligence approaches. At the same time, it is also important that the burgeoning area of climate services learns from the more mature weather services industry, in terms of, for example, user interactions, to potentially leapfrog development. The following chapters detail the technical, social and business requirements of W&CSs such as stakeholder engagement.

While the relevance of W&CSs for the energy sector has been discussed, the meaning of the word "integrated" (as per the section title) needs some explanation. As the energy systems become increasingly dependent on weather variations, it is apparent that the information flow from weather and climate data and forecasts needs to be properly incorporated into the decision-support systems. Such systems may already use weather and climate information in some cases. However, in general, they will need to be updated or redesigned to also account for new energy technologies and to properly embed new ways to manage energy demand and generation, while properly integrating the weather and climate information feed.

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[19] For lithium-ion batteries, which are the most common technology used, as they exhibit high energy efficiency, long cycle life and relatively high energy density; see, for example, Crawford et al. (2018) and Chen et al. (2020).

[20] Specifically in terms of forecasting from a month ahead and beyond.

1.3.1 Meaning of weather and climate services

Despite the concept of "service" being relatively recent in the climate community, a few decades younger than for weather services, the two "services" essentially share the same objective, and hence definition, which can be enunciated in a synthetic form as (Troccoli, 2018):

> A (weather and climate) service is a set of actions aimed at helping its beneficiaries make the best use of tailored information so as to improve their "business".

The reason "business" is in inverted commas is to indicate that W&CSs are not commercial endeavours only. Indeed, W&CSs are crucial also in public use, through, for instance, early warning systems that can help save lives, anticipate lack of electricity supply and so forth.

While there is some level of uncertainty on the real size of the W&CS market, be it for commercial or public purposes, it is rapidly increasing in size (see Chapter 5 for estimates). Such a trend is partly attributable to a renewed interest in climate variability and extremes (possibly triggered by a clustering of extreme weather events) and partly due to changes in legislation and regulation, also related to the Task Force on Climate-related Financial Disclosures (TCFD[21]). Chapter 5 discusses the business of W&CSs in detail.

1.3.2 Comparing weather services and climate services

Despite the close similarities between weather services and climate services, it is useful to note some important distinctions between them, leaving aside their intrinsic distinction according to which weather services essentially deal with forecasts of up to a few weeks in advance, and climate services deal with forecasts and projections from a few weeks to decades.

In this context, it is important to clarify the role of historical information – be it observations (in situ and/or satellite derived), physical models or combinations of the two (typically reanalyses). While it is customary to associate historical data with climate services, mainly due to their coverage over climatic timescales, these data are useful in weather services too, as they assist for instance with the identification and computation of statistics of anomalous events to provide a baseline for weather forecasts. For this reason, historical information is here regarded as a common denominator between weather services and climate services.

The main differences between weather services and climate services (Troccoli, 2018) are the following:

- Weather services are considerably more mature than climate services; the former have been around since at least the 1980s (Pettifer, 2015) and the latter started to be developed in a consistent way during the 2000s.

- Weather services are based on information (for example, forecasts) that is more accurate (shorter lead time) and verifiable (lifespan is shorter, in line with lead time) compared to climate services (for example, seasonal climate forecasts).

- Data (including forecasts) policy for weather services can be different, and more restrictive, than for climate services.[22]

- Weather services are more time critical: they rely on real-time measurement availability and international exchange, and typically have specified regular delivery times (for example, hourly or daily at 0600 Coordinated Universal Time (UTC)). Thus, weather services are more dependent on the 365/24/7 operation of information technology (IT) infrastructure (high-performance computers, servers, networks and so on). Climate services also require computational systems to be operational for some of the production (such as for the running of seasonal climate forecasts). However, small delays of a day or more in their delivery

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[21] https://www.fsb-tcfd.org.

[22] While there are common data policies on common data sharing, data policies for weather forecasts differ substantially in say the United States of America (free sharing) and Europe (data are charged for). For further discussion, see Harrison and Troccoli (2010), WMO (2015a) (https://library.wmo.int/doc_num.php?explnum_id=3314) and Chapter 5 in this publication.

are less consequential, whereas a delayed weather forecasts could put lives at risk due to, for example, unexpected power cuts to life-saving equipment.

1.3.3 Weather and climate services supporting net zero energy transition

From the perspective of an energy sector user (such as a grid operator), there are several areas served by W&CSs (see also Figure 1.6):

- Characterization of past weather/climate events using **historical data**. This is perhaps the most important element, as it provides a baseline, or first-order approximation, of the current risks and opportunities and is thus key to managing energy production and distribution (especially considering the increasing fraction of renewables in the energy mix and the changing patterns in energy consumption).

- **Nowcasting/short-term weather forecasts** for load balancing by maximizing the usable component of the generated power (for example, by optimizing power generation temporally and spatially or by reducing curtailment through use of DLR).

- **Sub-seasonal to seasonal (S2S) climate forecasting** for maintenance of infrastructure and resource and risk management purposes (for example, to ensure sufficient water reserves are available for hydropower production) (for example, see Box 1.3).

- **Decadal climate forecasting**[23] for multi-year resource risk management; these forecasts effectively extend the seasonal forecast range to typically 10 years ahead, thus allowing a longer risk assessment horizon.

- **Multidecadal climate projection** for infrastructure risk assessment, planning and design purposes. This includes providing authoritative data on possible evolution of the climate considering different emissions scenarios, including those aligned with policies. Projections related to policy targets are naturally critical as they inform planning and support system design including understanding the implications of unlikely but impactful events.

As a way of assessing current capabilities and gaps of national W&CS providers – the National Meteorological and Hydrological Services (NMHSs) – and have a view about service provision for the energy sector, the WMO Study Group on Integrated Energy Services (SG-ENE) conducted a survey in 2022. In total, 87 NMHSs replied to the survey (as of 15 July 2022), of which 85 responded to a multiple-choice question asking to identify the most important factors for enabling the uptake of W&CSs for net zero energy transition.

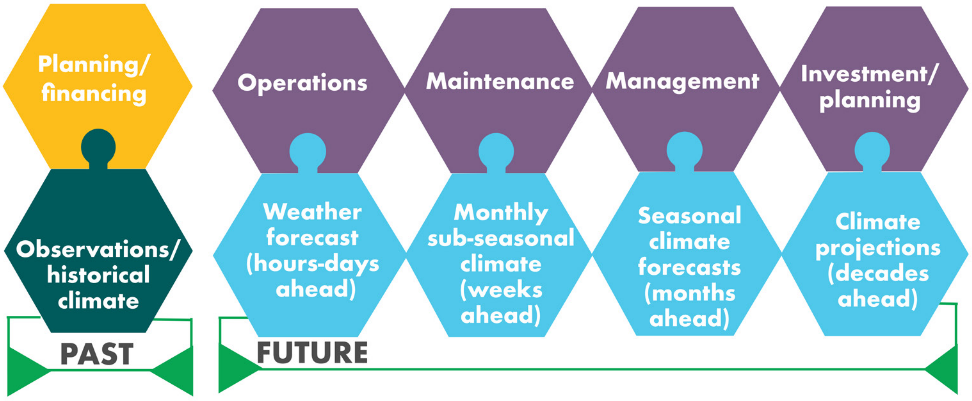

Figure 1.6. Weather and climate data: (bottom row) historical over the past, and forecasts/projections over the future, and (top row) their typical use in the energy sector

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[23] This is the latest scientific development in terms of forecasting. It differs from (multidecadal) climate projections mainly in terms of the way the initial conditions of the climate are defined, with decadal forecasting starting from a better description of the state of the climate.

Box 1.3. Dry winters in northern Italy and energy generation in Italy (case study of the SECLI-FIRM project)

The European Union H2020 SECLI-FIRM project (http://www.secli-firm.eu) aimed to demonstrate how improving and using long-term seasonal climate forecasts can add practical and economic value to decision-making processes and outcomes, in the energy and water sectors. This was achieved though case studies co-designed by industrial and research partners.

The main objective of this case study is to illustrate the benefits of designing adequate decision-support products to identify winter conditions in the Alps and Apennines that affect the power system. The ultimate goal is to improve the way power companies like Enel and Alperia can effectively manage the risks associated with extreme climatic events. Underlying questions addressed by this case study include the following: how can hydropower production management be optimized, and, more broadly, how well can gas price be predicted in low hydroelectric power production and changing demand net of total renewables?

This case study focuses on seasonal forecasts of precipitation and hydrological balance. Seasonal forecasts of precipitation and snowpack were used to forecast hydroelectric production. Due to a prolonged drought with an extremely dry autumn and mild temperatures, the end of 2015 and the beginning of 2016 were characterized on one hand by a low level of power and gas demand and on the other hand by a deficit in hydro supply production (see Figure 1.7). During the first 3 months of 2016, the hydroelectric production (red line) was almost half of the energy produced during the same period of 2015 (red ellipse). It was even lower than the minimum of the 5 year range. There was a similar situation in the period of October to December 2016 (green circle). The combined effects of low demand and hydro deficit led to an increasing Italian spark spread level (the difference between power prices and gas prices).

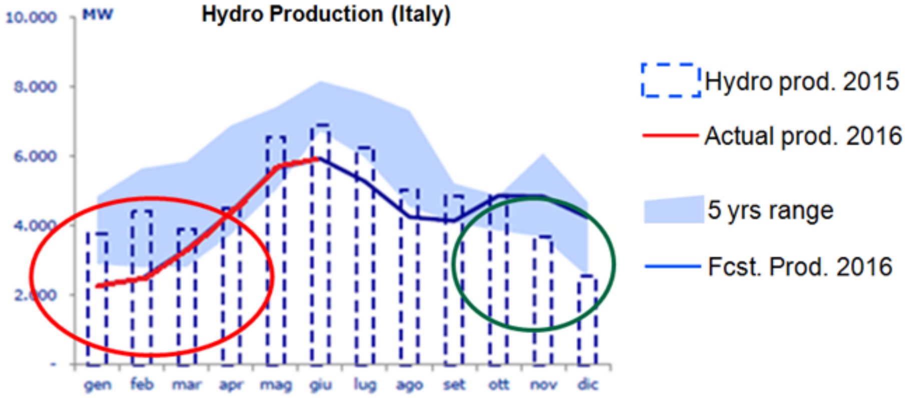

Figure 1.7. Hydropower production in Italy during 2015 and 2016 compared to a 5 year average

Source: SECLI-FIRM (2021a)

The European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal forecast system and the combination of four models (from ECMWF, Météo France, the Met Office and the German Weather Service (Deutscher Wetterdienst, DWD)) were compared with ERA5 climatology and actual values. The study was performed at different initialization months before the target period (1, 3 and 5 months) and separately for the Alpine and Apennine areas. The seasonal forecasts were compared with a base case scenario (computed using climatology as the input) and a "perfect forecast" scenario (using the real value as the input of the decision-making tree). To evaluate the added value of seasonal forecasts inside Enel's economic assessment, a performance indicator was defined and calculated for each initialization and each solution.

Overall, the indicator performances in the fourth quarter of 2015 shows a slight improvement, but not significant in amplitude, with the use of seasonal forecasts. This behaviour reflects some of the limitations of seasonal climate forecasts, even when these are tailored. It is important to remember that seasonal forecasts are probabilistic in nature; as such, they should not be evaluated on individual events. Nonetheless, the results of this, and similar, case studies indicate that while seasonal forecast models are not able to accurately reproduce extreme events, investing in the use of these models is something that is being pursued by energy companies like Enel.

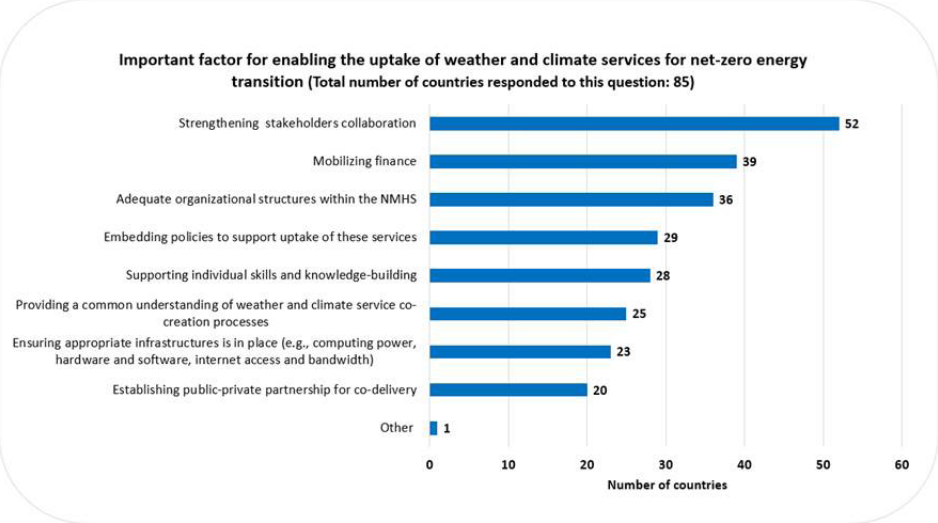

Figure 1.8. Analysis of the responses from NMHSs of the survey question: "Select the three most important factors to enable uptake of W&CS for net-zero energy transition"

As shown in Figure 1.8, strengthening stakeholder collaboration is considered the most important factor by 52 countries (uniformly distributed geographically among the six WMO regions), and also in relation to other factors such as mobilizing finance and adequate organizational structures within NMHSs.

Overall, there is a strong need to develop collaborative approaches among weather, climate and energy, which are still too fragmented. Additional multidisciplinary projects, including effective and well-supported networks, are needed. These should be embedded within long-term collaboration frameworks, to overcome the issue of the limited lifespan of a project and corresponding (intense) collaborations within them.

The lack of sustainable collaboration is exacerbated because there are still critical disconnects between the W&CS community on the one side, and energy system modelling on the other side, even if some efforts in this direction are under way. This is due to the increasing recognition that weather and climate data should

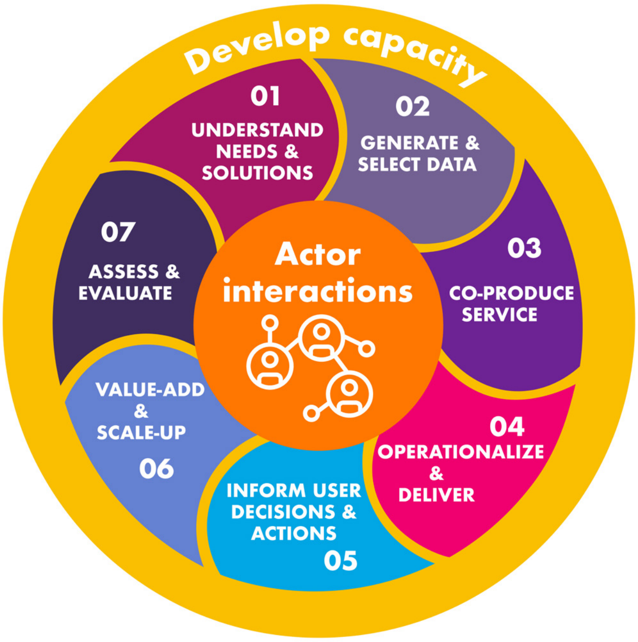

Figure 1.9. Framework for co-developing integrated W&CSs

play a more important role in energy modelling (see, for example, the newly established European Forum for Energy and Climate Transition network[24]).

1.4 Framework for co-development of weather and climate services for the net zero energy transition

This publication provides an updated framework for conceptualizing the W&CS value chain, building on the framework previously developed by WMO and the Global Framework for Climate Services (GFCS). This framework combines elements of the co-development approaches (Carter et al., 2019[25]), as outlined in Figure 1.9. It is applicable to the energy industry and can readily be adapted to other sectors. While the framework provides an ideal co-development process, not all steps are necessarily taken by the same actor, nor do they necessarily occur sequentially, or in a rapid succession. The different stages of the framework are outlined below, also with reference to the relevant chapters.

Actor interactions: These are at the heart of the W&CS co-creation process. It is possible to distinguish among knowledge producers (for example, NMHSs), intermediaries (for example, W&CS providers) and users (for example, grid operators) that represent the three broad groups of actors involved in this process. As discussed in Chapter 4, these actors can interact at various levels of context-specific engagement.

Understanding user needs and solutions: This includes understanding context, building partnerships, identifying common ground and co-exploring needs. The reliability of weather and climate information and solutions has improved greatly in recent years, complemented by advancements in information gathering and dissemination technologies (Daron et al., 2015). However, it is important to ensure this information reflects what users need. Singh et al. (2016) argue that the disconnection between users and producers of weather and climate information is a factor that influences the uptake and use of the solutions (Findlater et al., 2021). To bridge this gap, product development approaches that focus on end users, such as user-centred (or human-centred) design and design thinking approaches can play an important role in building relationships with users and creating common ground, as well as fostering ownership of solutions.

Solutions development teams are often faced with multiple user requirements that can emanate from a multitude of sources and involve various departments within an organization, such as management, sales, marketing, engineering/technical and legal departments, as well as other decision makers and users. Stakeholder involvement is therefore important for understanding user requirements to enable consideration of all aspects of service co-development. It plays a critical role in product uptake, especially when users (or stakeholders) buy in and take ownership of the product development cycle. Some of the methods that are considered useful in building partnerships to establish common ground with various stakeholders to understand their needs include field studies, surveys, interviews, focus groups, needs analysis and group task analysis (Courage and Baxter, 2005; Baxter et al., 2015), as discussed in more detail in Chapter 4.

Data generation and selection: The starting point for the development of new services is the systematic collection and analysis of user requirements. The outputs of this initial phase can then be used to inform either the selection of available data or the generation of new data, or both (see Chapters 2 and 3). A critical step in the selection or generation of data is to ensure they are fit for purpose and address existing gaps and/or the necessary procedures to transform them into user-relevant information.

Well-established international cooperation on weather and climate through programmes by WMO, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA) and the Network of European Meteorological Services, among others, and the effort made by some institutions (for example, the European Commission via the Copernicus programme), has made it possible for a large amount of relevant data – observational and model based – to be accessible.

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[24] https://www.efect.eu.

[25] https://futureclimateafrica.org/coproduction-manual.

In some cases, such as NOAA and Copernicus, data are free of charge (see Chapter 5). This constitutes a fertile ground over which W&CSs can be developed (see, for example, the new WMO unified data policy (WMO, 2022a[26]), also discussed in Chapter 5). However, there is still a considerable amount of data provided at a (considerable) charge, thus creating a barrier to entry to new W&CS providers. While the standard use of these data requires an expert skill set and knowledge to better account for all the uncertainties and limitations, making the data public has generated a set of "unorthodox" usages of the data, some of which may result in useful and innovative tools. Finding the right balance between expert knowledge and the rapidly growing market of sectoral applications is now a key challenge, particularly of the climate service sector.

While in many circumstances the existing data are sufficient to meet user requirements, there are also requirements that cannot be fully met by the available resources. Documenting these gaps and the associated user aspirations and feeding those into research and development agendas is key to ensuring user-relevant evolution of the service provision. However, it is also important to acknowledge that some requirements can be met through pragmatic solutions rather than research projects. In other words, the best science is not always the answer to such requirements, even if this creates some tension between the search for precision by scientists and the need for timely solutions by the industry.

Data generation can be divided into two distinct phases: (i) generation of the fundamental weather and climate data that underpin the sectoral services, generally produced by government/research organizations, and (ii) generation of products and indicators and more generally weather and climate information tailored to the needs of the energy sector users. It is important to maintain full visibility of the first of these two phases, as many of the services the industry relies upon would be unviable, challenging or even impossible to establish if it were not for the large, mostly public investment, that goes into the generation of the weather and climate data in the first place.

Service co-production: This may include co-design of a project or initiative and co-development of the solutions to be applied. This process, as discussed in Chapter 4, allows user needs and knowledge producer capacities to be considered, taking into account the ability and interest of intermediaries in participating and facilitating this process.

Operationalization and delivery: A robust and real-time information production workflow is critical to providing a timely and effective service, so it can be used, for instance, to manage predicted extreme events and major disruptions to the grid. The first step to delivering the operationalization and delivery phase is to capture user expectations in terms of data usage (frequency and volume), time availability, mode of transfer and so forth. Data volumes vary considerably, depending on the use of output like spatial gridded data rather than a few selected locations, or of ensemble members rather than just the mean of the ensemble.

Typical elements of the operationalization and delivery workflow of a service are:

- **Production:** This includes the automated chain of computations, from data retrieval (also accounting for future known datasets updates, delays in data availability or lack thereof), to data processing and quality control checks (including, for example, size of files and range of data). A robust data management plan (DMP) is critical for an effective production chain.

- **Availability and reliability:** The following aspects need to be considered: (i) use of a secure protocol (for example, Secure File Transfer Protocol), (ii) user-friendly data queries and (iii) limited time delay from production to data availability. Typically, the service should be available over an agreed time (for example, 24/7 or during standard office hours), and downtimes limited to a small percentage of the available time (for example, scheduled outages should occur for 0.5% of the time at most).

- **Maintainability and data recovery:** All the service data should be backed up in case of the need to retrieve them within a short time frame. If the data were not available due to an unforeseen downtime, data should be provided through alternative, previously agreed, modalities.

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[26] https://library.wmo.int/doc_num.php?explnum_id=11256.

- **User support:** This includes having a dedicated team able to: (i) respond to user queries, (ii) maintain up-to-date and accurate documentation and (iii) rapidly fix technical issues when they arise.

Given its nature, the operationalization and delivery component of the service need to be closely monitored. Depending also on the size and complexity of the service, the monitoring should be done with input from different experts such as software developers, system administrators and technical/scientific officers.

User decisions and actions: Utilizing the information provided by the service, also based on semi-automated decision-making processes (for example, based on decision trees) and support tools (for example, interactive visualization platforms), enables users to properly embed weather and/or climate data into their decision-making. Input from experts remains a critical part of the service, even when using automated tools.

Adding value and scaling up: Assessing a value, be it economic, social or environmental, ensures the outcome of a service is understood and appreciated. Assigning a value is critical for communicating the benefit of the service, and potentially for scaling it up to other geographies and/or sectors and/or typology of users (for example, scientific literate or non-technical managers). The scalability of W&CSs may rely on innovative business models and partnerships among public, private and non-governmental organizations (NGOs). Chapter 5 discusses this in more detail.

Assessing and evaluating services: Setting benchmarks and key performance indicators (KPIs) is critical to ensuring effective and successful services. In this context, evaluation can be understood as having several layers: (i) meteorological/climatological evaluation, which compares the results of weather and climate models with available meteorological observations; (ii) evaluation of energy-related service components, where W&CS outputs (for example, wind power resource assessment and energy production forecasts) are compared against actual energy data; (iii) socioeconomic assessment, where the value of dedicated W&CSs is estimated for a given case study, or to a sector as a whole; and (iv) performance of the delivery of the service, including user support.

The evaluation of W&CSs can include process and results evaluation. As discussed in Chapter 4, process evaluation may include scoping, implementation and stakeholder engagement. Results evaluation may include outputs, outcomes and impacts. Chapter 5 provides a framework for assessment of SEBs. This includes a range of economic, social, climate, environmental and health benefits.

Developing capacity: As illustrated in Figure 1.9, capacity development takes place across all stages of the co-creation process. As discussed in Chapter 6, this may include the individual, procedural, infrastructural and organizational spheres of capacity and targeted activities to build these.

The framework presented above lays the foundation for the remainder of this publication. Chapter 2 continues by discussing the underlying information production of W&CSs, namely weather and climate data. Chapter 3 discusses energy conversion models, using the weather and climate data introduced in Chapter 2, to meet industry needs. Chapter 4 then looks into co-production approaches, while Chapter 5 looks at enabling uptake of W&CSs through realizing SEBs, harnessing business models, identifying key policies, and creating partnerships and collaborations. Chapter 6 discusses capacity development. Finally, Chapter 7 provides concluding remarks and recommendations.

2. PRODUCTION OF WEATHER AND CLIMATE INFORMATION

2.1 Introduction

The production of weather and climate information (in the form of data, visualizations and briefs) that underpins the services for the energy sector (and indeed for other sectors too) is ultimately based on the simulation or observations of the Earth system (or relevant components, depending on the specific problem). Observing and simulating the Earth system involves extremely complex technology, which has been developing over many decades, with huge and long-term investments and national/international efforts and collaborations. This remains the case even when just the atmospheric component is simulated, which is necessary, for example, in the prediction of wind power up to several days ahead.

Figure 2.1 shows an appreciation of the complexity of the Earth system, with its many interacting components of different media that evolve on different time and spatial scales. To continue with the above example, to predict wind power at a specific location a few days ahead, it is necessary to simulate the physics of the atmosphere in a highly detailed manner, and in a wide region around the location of interest. This is because the wind at one location generally depends on the air motion, as well as all other atmospheric phenomena (such as radiative exchanges), up to hundreds of kilometres away over a timescale of a few days.

Development of weather and climate models has been guided by the search for answers to specific questions or decisions, such as "Will it be safe to fly our commercial plane carrying 300 people from London to New York?" Observation campaigns, theoretical studies and modelling developments started in the first half of the twentieth century with questions and decisions as targets, alongside a thirst for academic knowledge. Since then, the weather and climate industry has grown enormously as scientists and users have realized that many more questions could be addressed, as is the case for the energy industry itself. Consequently, W&CSs can now start to address questions such as "Can we estimate the electricity demand for my country in a few months?"

The science and technology underpinning W&CSs are extremely complex. Therefore, the descriptions in this chapter can only scratch the surface of the vast knowledge acquired. Nonetheless, in this chapter, a selection has been made that should allow a scientifically literate reader to gain an understanding of the main elements required and used for weather and climate data production.

Specifically, the chapter starts with an overview of the main features of the physics of the Earth system (atmosphere, ocean, land surface, ice sheets and so forth), to get an appreciation of the reasons why modelling and forecasting of the Earth system is possible. A brief description of available observations, especially of variables relevant to the energy sector, is presented next. Observations are the main reference in the science and technology developments, as they allow testing of the hypotheses, the constraining of models and improvement of service products. Some of the foundations of modelling and forecasting are discussed next.

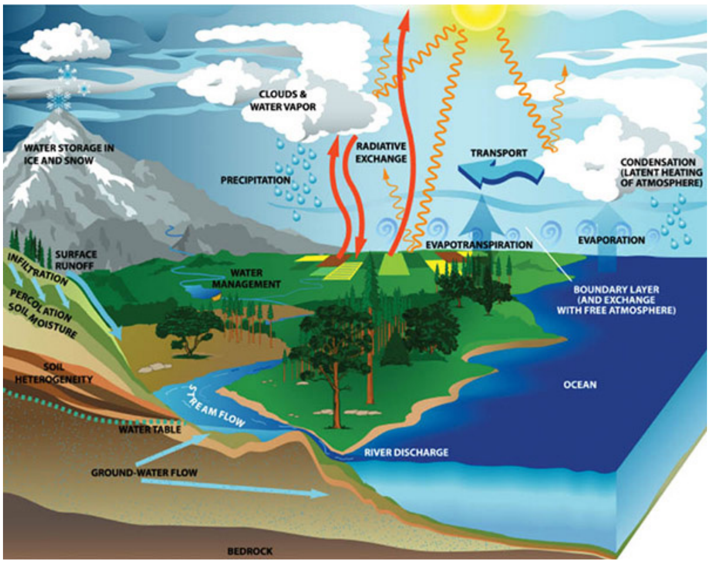

Figure 2.1. Main components of the Earth system with representation of some of their key physical processes

Note: Some components such as sea ice are not represented.
Source: NOAA (2014)[27]

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[27] https://research.noaa.gov/News/Scientist-Profile/ArtMID/536/ArticleID/1209/NOAA-launches-research-on-next-generation-of-high-performance-weather-climate-models.

Forecasting also involves a combination of observations and models via a process called data assimilation. Rigorous data management needs to be implemented, to produce robust weather and climate data workflows for the delivery of service products. This is the reason that data management is introduced alongside the modelling and forecasting. Schematically, these elements can be represented as in Figure 2.2. The chapter concludes with the presentation of a selection of upcoming developments in the area of weather and climate information for the energy sector.

It is worth noting that while some references are made in this chapter to specific uses of weather and climate information for the energy sector, the focus here is on the meteorological aspect of the services. Chapter 3 presents the conversion of meteorological data into typical energy indicators.

2.2 The science underpinning weather and climate information

In the energy sector, there is a need for information about several hydrological and meteorological variables – typically temperature, precipitation, wind speed and direction, solar radiation and relative humidity – over a wide range of time and spatial scales. Various methodological approaches exist for providing such information; these have been developed for decades in general meteorological applications. Weather and climate data relevant to the energy sector and beyond are produced by a combination of a large network of observations, sophisticated numerical models of the atmosphere and other components of the Earth system, and postprocessing techniques that range from simple statistical adjustments to complex machine learning models.

These three technological elements – observations, Earth system models and postprocessing techniques – are presented in the following. While an attempt is made to keep the descriptions of the three elements separate, overlaps between their presentations is inevitable as they are often combined to achieve better products than when used in isolation (as in the case of data assimilation).

Before delving into the technology of weather and climate information, it is beneficial to have some understanding of the science behind the creation of this information and why it is possible to attempt predictions as far as several months/years ahead. As implied by Figure 2.2, science is central in the production of weather and climate information. The science of the Earth system, which is needed to simulate to a large extent to obtain weather and climate data, is also highly complex. Only some key aspects of the science are therefore covered here.

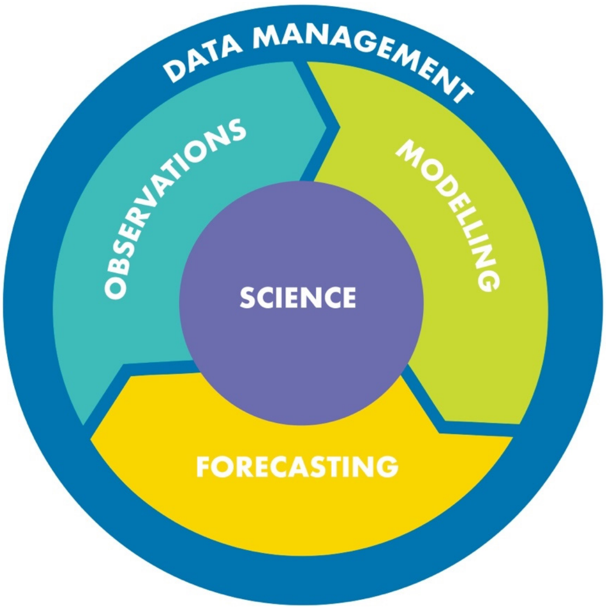

Figure 2.2. Components for the production of weather and climate information

Observational data indicate that the Earth's climate fluctuates over a wide range of timescales. For instance, the North Atlantic and Pacific Oceans are characterized by variations on decadal to interdecadal scales, which reflect large-scale changes in sea-surface temperature (SST) and ocean heat storage. These low-frequency variations interact with the atmosphere, and ultimately affect and modulate meteorological variables such as precipitation and temperature over land, hurricane variability in the Atlantic Ocean and monsoon intensity, as well as the spring–summer climate variability in Europe and the United States of America.

Overall, the chaotic nature of the climate system, which ultimately arises from the turbulent phenomena in the Earth system's fluids (air and water), is such that the ability to predict weather beyond a theoretical threshold will always be limited. This threshold is estimated to be about 2 weeks, but it is dependent on the experimental set-up, including the resolution of models used to test this predictability hypothesis. However, there are parts of the Earth system, including the land (and rivers and lakes), the oceans and the cryosphere, that are characterized by higher density and heat capacity than air, and therefore evolve more slowly than the atmosphere. It is this slower motion that provides the "memory" to extend the time-horizon of predictions to well beyond the 2 week theoretical limit. That is why sub-seasonal (weeks ahead), seasonal (months ahead) and decadal (years ahead) forecasts are possible.

Soil moisture is among the slowest-evolving land-state variable, and its anomalies may impart a considerable fraction of predictability in mid latitudes at S2S timescales. Spring soil moisture conditions influence the probability of occurrence of phenomena such as summer heatwaves. It has been proven that the contribution of spring land surface conditions is crucial to anticipate temperature anomalies and boost summer forecast accuracy.

The coupling between the atmosphere and ocean is generally strong, particularly in the equatorial region, where the El Niño Southern Oscillation (ENSO) originates. ENSO is a highly pronounced interannual signal, second only to the seasonal cycle. It provides a strong source of predictability, and therefore relatively accurate seasonal forecasts, especially at low latitudes. However, in the extra-tropics, only a fraction of climate variability may be ascribed to the ENSO teleconnection. This is why Earth system models produce mixed results when simulating the dynamics of mid- and high-latitude regions, especially when they are far from the tropical Pacific Ocean as in the case of Europe (Zebiak and Cane, 1987; Stone et al., 1996; Johnson et al., 2020).

The dynamics of sea ice in the Arctic Sea also convey S2S predictability through persistence or advection of sea-ice anomalies and their interactions with the ocean and atmosphere. It has also been demonstrated that a proper representation of sea ice yields a more accurate seasonal prediction of the autumn sea ice, which can now be represented even at a regional scale. As a consequence, such proper representation improves forecasts of the northern hemisphere winter climate, as well as large-scale features such as the East Asian winter monsoon.

Global predictability at the decadal timescale has been recently associated with other components of the Earth system. In particular, the initial state of the land surface, sea ice (its extent and thickness), stratospheric conditions and aerosols have been proposed to affect predictability at long timescales. The Antarctic ozone layer could provide a source for predictability for the southern hemisphere.

By considering other external (to the Earth system) factors such as human-induced GHG concentrations in the atmosphere and oceans or the solar cycle, it is possible to extend the prediction time-horizon (also called lead time) even beyond the multiannual timescale and therefore produce climate change projections over the next several decades. In this case, projections (in contrast to predictions) are also referred to as a boundary-value problem, because the mere knowledge of the initial conditions is not sufficient to properly simulate the time evolution of the Earth system. These boundary conditions typically start to influence the climate predictions a few years into the model integration, and can then become more important than the initial conditions as the integration time increases.

In summary, given the multiple interactions occurring in the Earth system, it is therefore critical to use fully coupled atmospheric–ocean models, complemented by an interactive land surface (and its hydrology), sea ice and stratosphere to produce the most accurate simulations and predictions. Weather and climate predictions are an initial-value problem, where the system predictability is associated with the initial state of the atmosphere and the atmosphere's lower and upper boundaries: the ocean, land surface, sea ice and stratosphere.[28] The relative role of these components depends on the prediction lead time. The atmosphere state is crucial for weather forecasts. The land, stratosphere, sea ice and ocean conditions are increasingly important for S2S to decadal predictions, together with ocean circulation, sea-ice evolution (the slowest components of the Earth system), GHGs and the solar cycle, for climate projections (Figure 2.3).

2.3 Observations and climate monitoring

This section discusses various methods used to observe the Earth's atmosphere, with a focus on fields relevant to the energy–meteorology community, mainly near-surface wind speeds, solar radiation, temperature and precipitation. The global observation network provides meteorological information about the state of the atmosphere from various types of ground-based and space-based instruments. Figure 2.4 gives examples of these instruments, including those used for ground-based, marine, aircraft, radar, upper-air and satellite observations. Such data are useful as initial conditions for creating weather forecasts, for monitoring the climate and for understanding vulnerabilities to climate (such as the assessment of dry periods to enhance the resilience of hydropower production). These data are also useful for model assessment and adjustment.

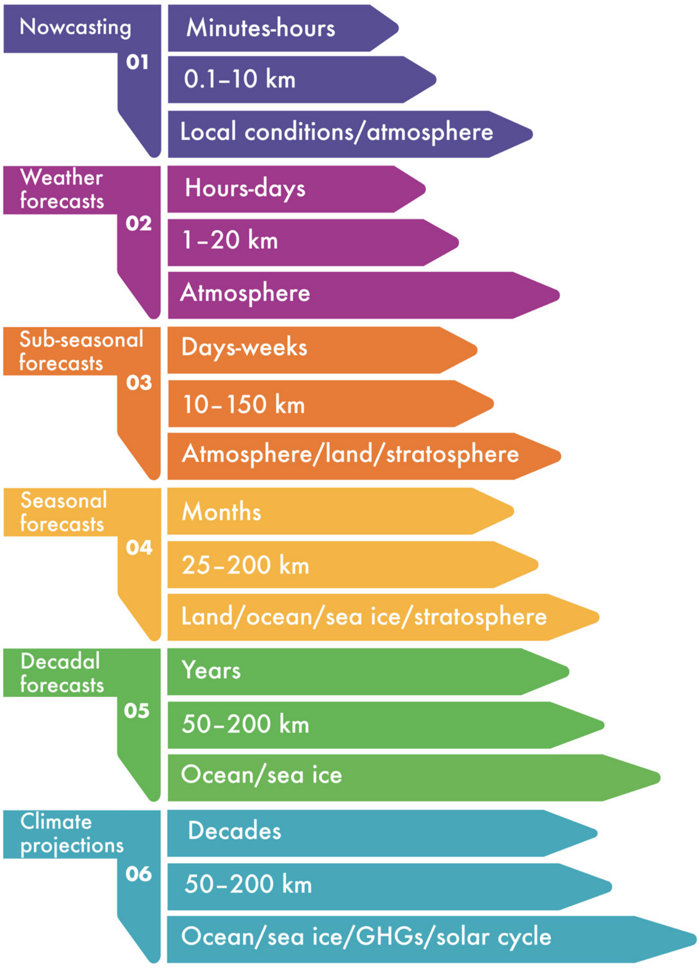

Figure 2.3. Main features for different forecasting lead times, from nowcasting to climate projections (numbered from 01 (top) to 06 (bottom))

Note: For each lead time, the three bars represent temporal lead times, spatial scales and source of predictability.

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[28] While potentially important for climate evolution, volcanic eruptions are generally not considered in climate predictions as they are largely unpredictable.

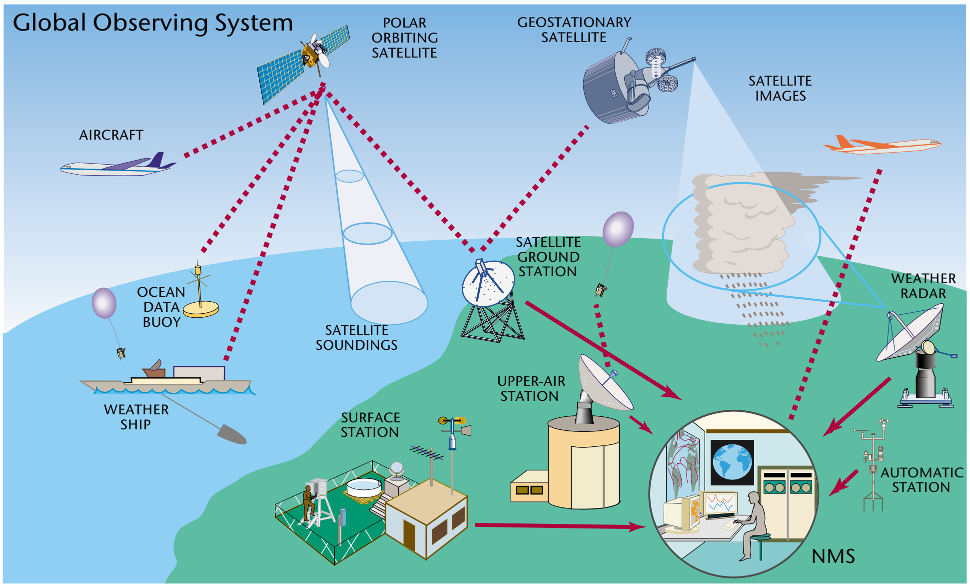

Figure 2.4. Global Observing System

Note: NMS = National Meteorological Service.
Source: WMO (2022a)[29]

2.3.1 *Ground-based observations*

Ground-based meteorological observations are the traditional and generally most accurate way to measure Earth system variables. They measure physical variables such as temperature, pressure, wind and precipitation. Nowadays, ground-based observations are a small fraction of the total number of observations available, as they are dwarfed in amount by satellite-derived data. However, since they provide a direct measure of physical variables, they constitute the best source of information or "truth". These observations are used for various purposes such as to calibrate satellite-derived data, to initialize weather forecast models, to train statistical models for predictions of for example solar power forecasts, and/or to compute statistics (such as long-term trends and extreme variations).

However, if the instrumentation is not well sited or maintained, the quality of the data collected could be of poor quality to the extent that they might need to be discarded. For instance, in the case of wind speed data, it is not unusual to encounter issues such as sudden steps or ramps (up or down or both) and steep overall trends (perhaps due to urbanization or vegetation changes rather than driven by the climate).[30]

In 2010, WMO defined a classification of the environment of measurement sites to determine their representativeness on a small scale, based on the influence of the surrounding environment.[31] Thus, a Class 1 site is considered a reference site of a relatively large area (a few tens of square kilometres), while a Class 5 site is a site where nearby obstacles create an inappropriate environment for collecting meteorological measurements. Even a Class 5 site may still be used for particular applications, especially if long-term (several years or longer) consistency is not a requirement (for example, for short-term (minutes to days ahead) forecasts), as long as the instrument is accurate enough.

There are over 11 000 surface-based weather stations making observations at least every 3 hours (WMO, 2022b[32]). However, global coverage is not uniform, with a significant bias towards the northern hemisphere. The land area also contains significantly more observations than the oceans, where ships and ocean buoys

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[29] https://public.wmo.int/en/programmes/global-observing-system.

[30] For example, to study climatological wind speed trends, Troccoli et al. (2012) had to discard around three quarters of the original stations due to failure to pass quality control procedures.

[31] https://community.wmo.int/activity-areas/imop/cimo-guide.

[32] https://public.wmo.int/en/programmes/global-observing-system.

provide much of the data. Observations of wind and temperature profiles are routinely made by commercial aircraft during ascent and descent, and are therefore plentiful around airports.

Some of the observation instruments of relevance to energy applications include: anemometers (for wind speed and direction at a specified height), lidars (for the vertical wind speed), psychrometers (for air humidity), pyranometers (for global solar radiation), pyrheliometers (for direct solar radiation), spectroradiometers (for the solar radiation spectrum), ceilometers (for the height of clouds and amount of sky covered), sky cameras (for visual imaging of the sky surrounding the camera) and psychrometers (for the hygrometric state, or air humidity, of the atmosphere).

Ground air temperature is the measurement of temperature typically at a height above the ground between 1.25 m and 2 m. This value is always measured in a weather shelter designed to protect the thermometer from solar radiation, thermal radiation from the ground and sky, and possible precipitation. This shelter must be located on open ground, with natural soil representative of the region. As far as possible, the shelter should be at a temperature close to that of the air; it is therefore white in colour. It must protect the sensor from radiation and allow free air circulation. To achieve this, cups or louvres are employed, even though the set-up is not always sufficiently satisfactory. Thus, under conditions of high solar radiation and poor ventilation (<1 m s^{-1}), errors exceeding 1 °C are possible.

The main difficulty in measuring precipitation is the correct capture of precipitation by a defined surface. In the absence of wind, the water particles fall vertically. However, in the presence of wind, the air streams are deformed by the rain gauge itself, so that vertical drafts are created depending on the shape of the rain gauge. This results in a capture failure that depends on wind speed and rain gauge shape. The simplest way to measure precipitation is by means of rain gauges which are graduated containers that collect water and typically require manual reading. For automatic measurements, the most common rain gauges use tipping buckets, placed under a collection cone, which switch alternately when filled. There are also optical rain gauges: a light beam is emitted to a detector that analyses the signal drops associated with the passage of particles falling into the beam. Another type of rain gauge, which is being widely implemented, uses a weighing type precipitation sensor, in which the weight of the water collected is measured as a function of time and converted to rainfall depth.

Weather radars have been used to detect clouds and precipitation and calculate rainfall rates since the 1950s. Doppler radars are used extensively as part of national and regional networks. These can be particularly useful for short-range forecasting of severe weather phenomena. Doppler radars measure wind and estimate rainfall amounts.

The hygrometric state of the atmosphere can be measured by a psychrometer. This is a device composed of two thermometers: the first measures the temperature of the dry air and the second measures the temperature of a wet thermometer using a wick dipped in a water tank. Evaporation cools the wet thermometer and is more intense when the air is dry.[33]

Wind speed observations are mainly derived from weather station observations, typically at 10 m height (the international standard). For some locations, wind towers have been established to obtain wind speeds at multiple levels (up to about 100 m), relevant for wind power generation. However, these wind towers are a small fraction of the 10 m wind measurements. Therefore, while observations of the upper atmosphere are also provided from radiosondes (weather balloons launched into the atmosphere), methods to extrapolate the 10 m wind to higher levels, at different heights not far from the surface (up to about 150 m), are often used. The simplest method is by means of the wind shear or α coefficient, which is used to estimate the vertical wind profile and relies on atmospheric stability and terrain type.

The α coefficient is defined as:

$$\alpha = \frac{\text{In } v_2 - \text{In } v_1}{\text{In } h_2 - \text{In } h_1},$$

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[33] https://www.encyclopedie-environnement.org/en/air-en/ground-weather-observations-what-is-measured-and-what-is-done-with-it.

where ln is the natural logarithm function, v_2 and v_1 are the wind speeds at the target height (for example, 100 m) and 10 m respectively, and h_2 and h_1 are those two heights. The standard value of the α coefficient is 1/7 (ca. 0.143), which provides a rough global estimate. In practice the α coefficient varies in time (for example, with the diurnal cycle and seasonal cycle) and in space (terrain/sea features and conditions); therefore more precise estimates should be adopted whenever possible. One option is, for example, to take the ratio between the wind at 10 m and that at, say, 100 m from a global weather model output for each grid point, time of day and month.

For wind resource assessment, ground station observations are often complemented by modelling products typically using high-resolution weather prediction models that downscale global reanalysis (use global reanalysis as initial and lateral boundary conditions) or use additional observations to provide regional reanalysis (see discussion below about reanalyses).

Among ground observations, solar radiation is possibly the most complex, not least because there are several radiation components: total radiation, scattered radiation, direct radiation and reflected radiation. While ground stations are mostly used as auxiliary or calibration instruments in solar power assessment and forecasting, given they provide the best local reference, there are few high-quality measurements globally (typically a few tens of stations per country at most). Fortunately, developments in satellite remote-sensing technology have allowed marked augmentation of the availability of accurate solar radiation data.

Sunshine duration, defined at the tenth session of the Commission for Instruments and Methods of Observation (WMO, 1989, Recommendation 16) as the period during which direct solar irradiance exceeds a threshold value of 120 W m^{-2}, has been measured since 1880. Several methods can be used for measuring it (WMO, 2020a[34]):

- A pyranometric method using a pyranometer combined with an electronic device
- A burn method using a Campbell–Stokes sunshine recorder
- A contrast method using a specially designed multisensor detector combined with an electronic discriminator and time counter
- A scanning method using one-sensor receivers equipped with a special scanning device and combined with a time-counting device

Solar radiation observations are measured from the ground using two main instruments: (i) a pyranometer, which measures the global component of solar radiation on a horizontal plane, using a thermopile between the receiving surface of a black body and the body of the device, and (ii) a pyrheliometer, which measures the direct solar radiation on a plane normal to the incoming direction of the radiation, and also uses a thermopile, but continuously oriented in the direction of the Sun, within a narrow angle (a few degrees).

Shaded pyranometers are used for measuring the diffuse solar radiation, namely the global radiation minus the direct component, by essentially blocking the direct radiation. In addition, pyrgeometers measure thermal radiation from the sky, where the thermopile is protected by a dish that is opaque to solar radiation and transparent to infrared radiation. This measurement is useful for example to estimate the heat reaching PV panels, given their temperature-related efficiency, when temperature sensors mounted on the panels themselves are not available.

2.3.2 Satellite-derived observations

Dedicated weather satellites have collected climate-related atmospheric observations since the beginning of the 1960s, with the first successful launch by NASA. By the late 1970s, a considerable increase in satellite missions and amount of data collected led to these data being properly utilized to constrain and initialize prediction models. Measurements have most commonly been of atmospheric temperature, but nowadays also include many other variables such as wind speed, solar radiation, cloud properties, precipitation, humidity and soil moisture.

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[34] https://library.wmo.int/index.php?lvl=notice_display&id=19673.

Earth observation satellites occupy different types of orbits. They can operate at a low altitude (several hundred kilometres above the surface) or at a high altitude at thousands of kilometres. Lower-orbiting satellites move faster than the speed at which the Earth is rotating and circle the globe multiple times each day. A satellite in a low orbit is suited for monitoring climate conditions at various locations or at given locations at different times. Its closer proximity to the Earth's surface makes it easier to produce high-resolution images.

Satellites in geostationary orbits are positioned at an altitude of about 36 000 km, which keeps the satellite over a fixed longitude at the Equator and therefore allows permanent observation of the same region of the Earth with high temporal resolution. The series of European Meteosat satellites is an example of such geostationary satellites, as well as the Japanese Himawari series. They permanently observe Europe and Africa in the case of Meteosat, and Japan, East Asia and the Western Pacific region in the case of Himawari, allowing for derivation of long-term datasets of specific parameters.

There are many different types of satellites. The first launched in the late 1960s and lasted for a couple of years only. Then, the next lasted maybe about 7 years, emphasizing the long continuation of satellites (for example, the NASA A-Train of satellites shown in Figure 2.5). A global ground station dataset over the entire time period is needed to cross-calibrate the observations from the satellites. However, this is impossible to achieve, as, over time, the measurement errors of satellite sensors increase. Through quality management, the data must be continually evaluated and corrected to ensure consistent high-quality data.

Multidecadal continuous data series are crucial to develop reliable and accurate records for meteorological services. Most satellites are expected to function for less than 10 years, although many of them operate beyond a decade. Therefore, satellites are launched regularly for follow-up missions, but designing new and improved satellites requires substantial investments and can take decades. The quality and resolution of modern satellite images are significantly improved compared to early images from the 1960s. The satellite data are sensitive to the adjustments that scientists make, and more sensitive than the calibration of surface data.

Using knowledge of radiative transfer processes, the data collected from meteorological satellites can be used to infer multiple observations about the Earth's atmosphere. These include the brightness of the layers of air near the surface, atmospheric temperature and wind speed, as well as the location, height and type of clouds. For example, the Aeolus satellite carries an atmospheric laser doppler instrument that probes the lowermost 30 km of the atmosphere. It provides important information on the vertical structure of aerosol, clouds and wind speeds in the troposphere. These meteorological fields can be calculated with various degrees of accuracy.

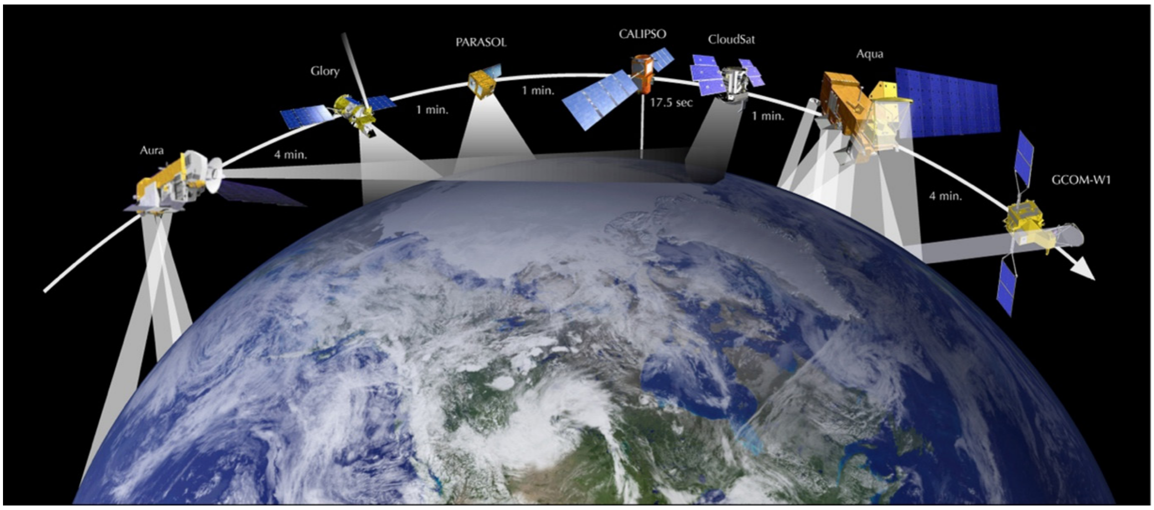

Figure 2.5. The NASA A-Train of satellites, so called as they orbit the Earth one behind the other on the same track

Source: NASA (2009)[35]

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[35] https://www.nasa.gov/mission_pages/hurricanes/features/atrain.html.

Software now enables meteorologists to select any portion of a satellite image and determine the temperature to within 1 °C of what would be obtained by surface measurements, which are themselves affected by uncertainties. Accordingly, an appropriate error bar needs to be assigned to the satellite temperature estimate thus derived. However, the same level of accuracy cannot be achieved for variables such as precipitation.

Direct vertical profile measurements of wind fields are highly needed for improvements of numerical weather and climate prediction models, and are crucial for accurate wind power forecasts. Station-based upper-air observations are widely used, but the balloons used to measure the wind profile are launched only a few times per day, and predominantly from the northern hemisphere. Wind profile information over the oceans, in the tropics, in the southern hemisphere and in remote regions is largely missing. Surface winds over the ocean can be obtained from satellite observations because the wind generates waves that modify the emissivity and backscattering properties of the sea surface.

An application where satellite observations are playing an important role is connected to water resources management, which relies on accurate precipitation measurements to monitor the freshwater resources necessary for human activities. This includes water for public consumption, irrigation, sanitation, mining, livestock and hydropower. Global observations of precipitation from satellites allow for a better understanding and prediction of changes in freshwater supply.

Images from geostationary satellites are widely used to obtain hourly estimates of surface irradiance. An example of such a dataset is the SARAH-2.1 dataset (Surface Solar Radiation Data Set – Heliosat) (Pfeifroth et al., 2019), produced by the European Organisation for the Exploitation of Meteorological Satellites Satellite Application Facility on Climate Monitoring. It is a satellite-based climate data record of the solar surface irradiance and the surface direct irradiance (horizontal and normal components, respectively), the sunshine duration, spectral information and the effective cloud albedo derived from satellite observations. The data are available from 1983 to 2017 and cover the region ±65° longitude and ±65° latitude and thereby provide long-term irradiance information for Africa and Europe. The products are available as monthly and daily means, and (partly) as 30 minute instantaneous data with a spatial resolution of 0.05° × 0.05°. Such satellite-based radiation datasets are the basis for web-based platforms that allow users to directly access site-specific information for PV applications, such as the PV Geographical Information System of the European Commission's Joint Research Centre (JRC).[36]

2.3.3 Reanalysis products and applications

Global reanalyses represent one of the most popular products among users of climate data, and have been widely used within the energy sector. The regular and gap-free global spatio-temporal coverage and the consistent quality are two sought-after characteristics of these reconstructions of the climate. Global reanalyses are produced by blending the global observational network and an NWP model to produce the best estimate of the state of the atmosphere at each point in time. This is done through a technique called data assimilation, which is designed to optimally combine the data coming from a vast array of observations with the data of weather, or even Earth system, models. It is apparent from this description that reanalyses are not direct observations of the Earth system. Indeed, the regular gap-free coverage is achieved by use of an NWP, which provides physical consistency between variables, while filling gaps and also extending the signal from observations beyond the "measurement site" (whether in situ or from a satellite). Thus, while reanalyses are not direct observations, they are often considered under the "observations" category as done here.

NWP models are improving with new model development, and enhancements are added to the system at each new cycle (typically several months apart). The changing nature of the NWP model and its biases make weather predictions unsuitable to characterize the climate of a region or see changes over time. By freezing the model on a specific set-up and re-running the simulation over the historical period, as done in reanalyses, it is possible to address some of these limitations. Reanalyses are then run over the historical period using all data available for that time.

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[36] https://ec.europa.eu/jrc/en/pvgis.

One of the advantages of running the simulations years after the event occurred is that reanalyses can also use much more data, including those that did not make it into a weather prediction at the time because they arrived later than the cut-off time. Another key benefit is the availability of a consistent set of fields for all meteorological variables at many vertical heights. While global reanalyses have been steadily increasing in resolution, with ERA5 (Hersbach et al., 2020) now in the range of 30 km, some energy applications require a finer granularity of data. Although the new generation of reanalyses, which is now in preparation, is expected to push the resolution further, this will not necessarily meet the needs of all users.

Several solutions already exist to downscale and regionalize reanalysis data with statistical and dynamical tools (for example, UERRA (C3S, 2019[37])). Reanalyses have been widely used for energy applications as they provide a reasonable proxy for observations, even in data-sparse regions. Applications range from the assessment of renewable energy resources (operational energy dataset (C3S, 2022[38])), to the mapping of weather hazards for critical infrastructures (operational windstorm service for the insurance sector (C3S, n.d.a[39])).

Reanalysis products are often used as an alternative to station-based observations or satellite-derived data. However, the accuracy of data for some meteorological fields can be quite low. For example, estimates of solar radiation and surface wind speeds, or also precipitation, can contain large biases. Care must be taken when using these data, particularly for areas where observation coverage is normally lower (for example, low latitudes), even if data are provided as continuous (gap free), seemingly of uniform quality, records. Yet, the overall quality of these reanalysis datasets is continually improving.[40]

The benefit of using very high-resolution modelling for wind resource estimates is well established. A growing number of atlases have been produced in recent years. These include (partly) publicly available atlases as in the case of the Global Wind Atlas (with a spatial resolution of ca. 3 km^2, only overall statistics are publicly available, whereas time series are provided at a cost) or commercially available atlases using up to about 100 m grid spacing. However, even in these high-resolution products, there can be large errors in surface variable simulations, especially over complex terrain, which is particularly challenging in wind resource assessment and prediction over mountainous regions. Caution is advised when taking an “off-the-shelf” gridded meteorological product, and any potential biases should be assessed before using for specific applications.

2.4 Weather and climate modelling and forecasting

2.4.1 Background

Numerical models for climate and weather forecasting are, in essence, discretized versions of the physical equations that govern the evolution of the Earth system (atmosphere, ocean, cryosphere, land surface, vegetation and external radiative forcing, including anthropogenic forcing). The equations stem from the physical principles of conservation of mass, energy and momentum. Such models range from simplified versions that can run on a home computer to much more complex versions that can run only on some of the world’s most powerful high-performance supercomputers.

There is therefore a high variety of numerical weather and climate forecast (or prediction[41]) models, with varying levels of description of the physics, and which differ in the spatial and temporal resolutions, geographical coverage and integration or forecast lead time. For instance, among the most complex global models are the weather forecasts produced daily by operational centres such as NOAA or ECMWF. In addition, there are about a dozen centres around the world that produce global weather forecasts.

Some of the models also produce sub-seasonal forecasts (out to a few weeks, see Figures 1.6 and 2.3). There are a few more global producing centres (GPCs) for seasonal forecasts; in addition to the operational centres

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[37] https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-uerra-europe-soil-levels?tab=overview.

[38] https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-energy-derived-reanalysis?tab=form.

[39] https://climate.copernicus.eu/operational-windstorm-service-insurance-sector.

[40] https://reanalyses.org.

[41] Although subtly distinct, prediction and forecast are used here interchangeably.

for weather forecasts, some research centres run them too as the set-up and requirements are less stringent than for weather forecasts. For seasonal forecasts, fewer observations to handle their initialization via data assimilation are needed (because atmospheric observations are less critical as their "memory" is lost after a couple of weeks), and updates can be less frequent (typically once a month). For climate projections, there are many more producing centres (a few tens), as these do not need to be produced operationally and do not require initialization given that the external forcings or boundary conditions are much more important.

Weather forecasts, available on horizontal grids of as low as 10 km on the global scale, have reached such a high quality that people can now consider sensibly, say, the predicted probability distribution of temperatures for a specific location at a 10 day lead time. Precipitation, wind speed and solar radiation forecasts are generally not of the same quality as those for temperature since, by their nature, these variables tend to be considerably more variable than temperature spatially and temporally, which makes them more difficult to predict. Weather and climate models are characterized by a given spatial resolution, represented by grid boxes, which determines the range of atmospheric, land and oceanic processes that can be resolved directly by the model (see Figure 2.6).

2.4.2 Physical process parametrization

The subgrid-scale processes that are unresolved need to be included via so-called parametrizations. Parametrizations of physical processes are simplified relationships described by empirical submodels that involve parameters calibrated against observations and experiments. These processes include turbulence, convection and gravity wave drag, some aspects of the water cycle and cloud formation – essentially all processes whose characteristic length scales are smaller than the model grid spacing, and which the model cannot simulate. Which parametrizations are included in a given model largely depends on the model's temporal and spatial resolution (see Figure 2.7). For instance, convective systems (cumulus clouds) have a length scale of the order of 1 km, while current NWP global models typically have a grid spacing of the order of 10 km.

Therefore, current global models are unable to directly resolve convective processes, and a convection parametrization scheme is required for this type of model (however, resolutions of global models increase regularly in time, thus far with a halving time of ca. 8 years). In contrast, limited area models, which simulate smaller regions using global models to define their boundary conditions, can have much higher spatial resolutions, of the order of 1 km or less. These types of models might not need a convection parametrization

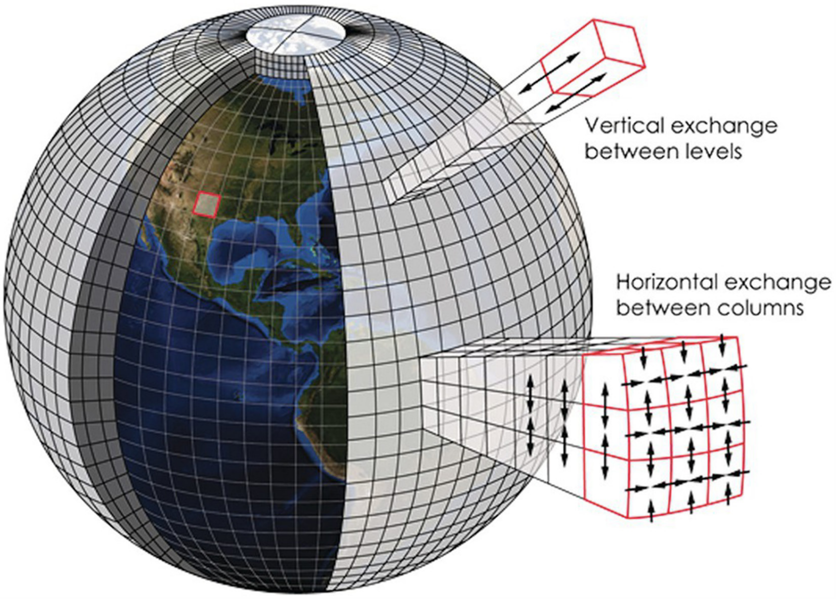

Figure 2.6. Discretization in grid boxes of the Earth system as typically described by a weather and climate prediction model

Source: Copyright 2026 American Geosciences Institute and used with their permission

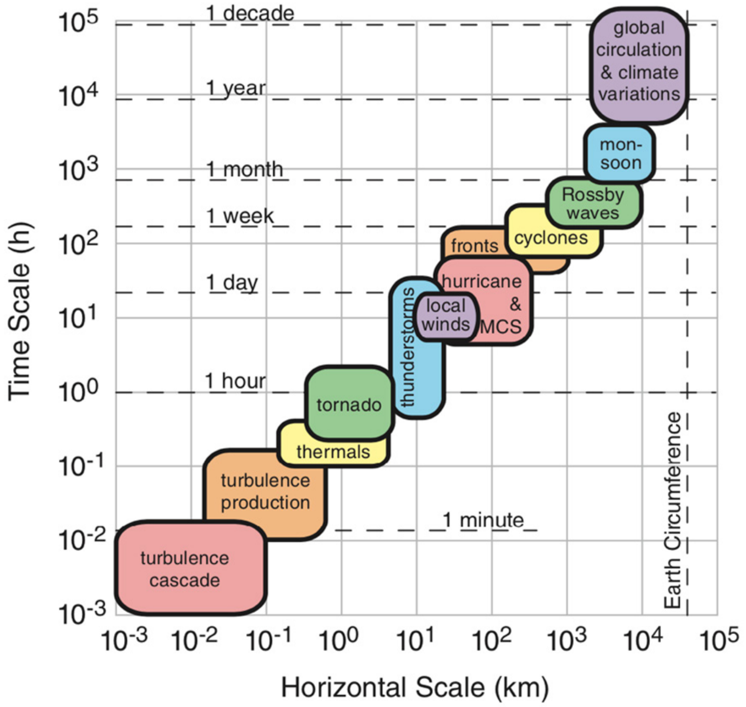

Figure 2.7. Time duration versus spatial size of key weather and climate phenomena

Note: MCS = mesoscale convective system.
Source: Stull (2017)

scheme. However, they would still need a parametrized description of turbulent processes, which are responsible for the exchanges of heat, momentum and mass between the atmosphere and the land or sea surface, as these involve a cascade of energy, ultimately reaching the molecular scale. These scales are not resolved by any atmospheric model and will always need to be parametrized.

While the limited spatial resolution of the models artificially reduces the number of degrees of freedom of the geophysical flows, parametrizations are considered a large source of uncertainty and model error in numerical models. Development of new parametrizations and improvement of current ones have been active areas of research. Such research includes the use of machine learning to model these parametrizations.

2.4.3 Model initialization and uncertainties

To produce accurate weather, but also seasonal or decadal climate forecasts, numerical models must be initialized from the best approximation to the actual initial conditions based on observations. This is done by a process called data assimilation, which mathematically combines observations with the model state of the Earth system towards the closest possible approximation of reality.

One of the main constraints for model development has always been the availability of computational resources. As computing systems progress, numerical models become more complex and their resolution is enhanced. A few decades back, climate and weather forecast models were treated differently as their purposes and the relevant processes that each one attempted to simulate acted on different timescales.

As computational resources improve, weather prediction and climate models are converging to the point that many forecasting centres around the world are moving towards a so-called seamless approach. For this approach, essentially the same model components are used for all time-horizons from a few hours to more than a century. However, while the model components may be the same, the actual way in which the model is run, its resolution, initialization and so forth vary considerably depending on the timescale. This is because, for instance, it would be too computationally expensive to keep the same spatial resolution used for weather forecasts for seasonal climate forecasts, let alone for climate projections.

The atmosphere (and the Earth system as a whole) is a non-linear system exhibiting sensitivity to initial conditions, which means that small differences in the initial state may lead to large differences in a future state. This is usually illustrated by the so-called "butterfly effect" in which a hypothetical butterfly flapping its wings over say the Atlantic could lead to a change in the path of a hurricane.

Modern forecasting systems based on NWP models use ensemble forecasts to quantify uncertainty in the forecast. Ensemble forecasts consist of a collection of forecasts each initialized from slightly different, albeit consistent, initial conditions to produce a range of possible outcomes (Sweeney et al., 2019). The way in which the ensemble is generated, and therefore its ensuing evolution including its spread, generally varies from one producing forecast centre to another.

Numerical model integrations are subject to uncertainties arising from initial-condition errors and model errors, due to incomplete description of the relevant physics laws. Bias correction is therefore normally required to correct for known systematic errors before the output can be used for applications, including energy. Many different bias-correction techniques have been developed depending on application and data availability. These techniques range from simple correction of the mean to sophisticated statistical methods. However, there is no perfect technique, and there will always be residual errors that need to be quantified and considered when using numerical model output for the estimation of weather-dependent energy variables.

Weather and climate predictions are sensitive to the initial state of the Earth system, as well as to model physics and external forcings. Due to the limitations in data coverage, particularly in the case of ocean observations, and deficiencies in data assimilation techniques, uncertainties on the initial conditions can be large. It is essential to estimate them as accurately as possible to represent the initial state. Moreover, as previously discussed, many physical processes cannot be resolved explicitly due to insufficient spatial resolution or extreme complexity. Therefore, the accuracy of specific parametrizations (surface fluxes, radiative transfer, convection and so forth) is crucial.

A practical way to account for the uncertainty associated with the initial conditions and model errors is the use of a forecast ensemble, obtained by: (i) perturbing the initial state of one or more of the climate components (land, atmosphere and ocean) and/or (ii) stochastically perturbing the physical parameters of the model. The concept of having an ensemble of forecasts was first introduced in weather prediction. However, in sub-seasonal to decadal prediction, the rationale behind the use of ensembles is slightly different in the sense that the weather statistics over a given future period (probabilistic predictions) will be considered rather than predicting the exact state of the atmosphere at any given time (deterministic prediction).

Particularly in the extra-tropics, the chaotic atmospheric variability can mask any predictable component of climate variability, and thus even for a perfect model, any individual forecast is not sufficient for determining the predictable signal. Averaging across a large ensemble eliminates significantly the inherently unpredictable noise and so allows the predictable signal to be detected.

Conceptually, for a sufficiently large ensemble, the ensemble mean anomaly represents the predictable component that supposedly is common in all realizations and masked by the superimposed chaotic noise, even if the ensemble mean itself may not be an actual physical state, given it is the result of the mean of many different possible physical states. In addition, tailored statistical postprocessing of climate indices from model outputs can improve greatly the poor skill related to the signal-to-noise ratio.

The way in which climate forecasts are initialized may generate different outcomes. Two main approaches have historically dealt with model biases in initialized climate forecasts: full-field initialization (same as for weather forecasts) and anomaly initialization. In full-field initialization, the model is constrained to be close to observations during the assimilation process, allowing a drift back to the model attractor that re-establishes the bias, which is then diagnosed and corrected by postprocessing the model output. In anomaly initialization, the model is constrained by observed anomalies and deviates from its preferred climatology only by the observed variability. In theory, the forecasts do not drift, and biases may be easily removed based on the difference between the model and observations.

While full-field initialization is definitely more skilful for the seasonal timescale, differences between the two approaches are generally not significant in the multiannual range. However, a refinement of the anomaly

Box 2.1. A short-range solar radiation forecasting product in Southern Africa

The European Union Horizon 2020 project, Transforming Water, Weather, and Climate Information through in situ Observations for Geo-Services in Africa,* offers short-term prediction of the amount of solar radiation reaching the surface by extrapolating cloud movements and daily cloud formation patterns.

The short-range solar radiation forecasting product can be used to support the establishment and management of solar power systems, including the development of solar minigrids. The product delivers two functionalities: the mapping part, which depicts a prognostic map of the solar radiation (forecasts), providing spatial extent, and the analytical part, which depicts a graphical display (spot graphs) of the solar radiation variation (Figure 2.8) over 3 days for specific sites.

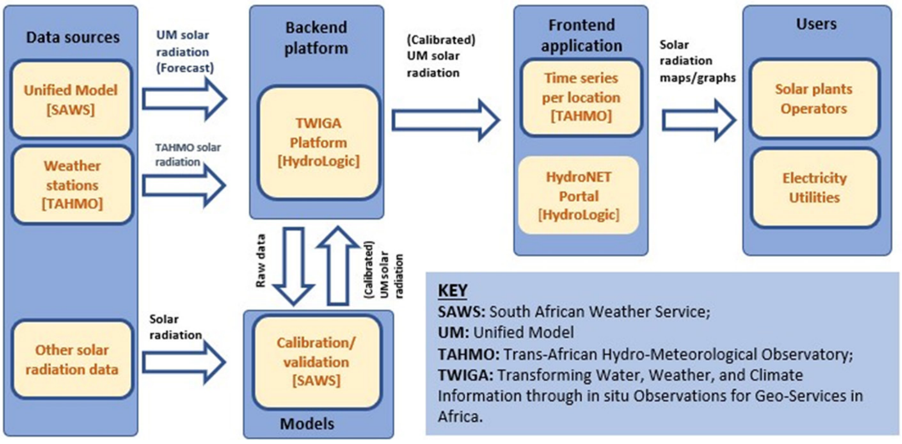

Figure 2.8. Operation and data flows

Source: SAWS

The platform is available to various stakeholders, such as research institutions, communities, municipalities and solar energy companies. A range of users have adopted it, including a solar company, which uses the short-range solar irradiation forecast product as a value added service. The solar company, Solar Works, provides users of solar energy systems with power generation forecasts for 1–3 days ahead. It provides information to a wide range of solar home systems – from small systems for lighting and mobile-charging capability to bigger systems that power televisions, refrigerators, ventilators, sound systems and sewing machines.

Solar radiation forecasts are provided by the South African Weather Service (SAWS). SAWS runs a high-resolution Unified Model for South and Southern Africa, which provides solar radiation output data that are integrated into the HydroNet Platform. To validate the product, forecast data are validated against SAWS observation data.

There are about 2 500 individuals benefiting from the service in Mozambique. The solar company designs and markets high-quality solar solutions for lighting and provides related products to off-grid households and small businesses in rural and peri-urban areas. Benefits include improved planning of energy system operations, demand management and climate change mitigation by transitioning to clean energy sources. The product also provides SEBs, such as increased health and well-being through the use of clean energy, increased access to electricity and energy security, creation of jobs and income-generation opportunities, and capacity-building of community members who receive training to maintain the solar systems.

With regard to long-term benefits, surveys carried out by the company highlight there is potential for the short-range solar radiation forecasting product to support the establishment of solar home systems that will serve an additional 50 000 households in Mozambique.

There are good prospects for providing similar products in other African countries that have low energy access rates, such as Malawi. Future work on the product will focus on, among other things, addressing current challenges with the spatial resolution at which the data are provided to make them available at 10 × 10 km^2 resolution, as required by some users, and extending the forecast to 5 days. The product is open for use by stakeholders such as small companies, microgrid operators, utilities and municipalities as long as they subscribe to the platform.

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[*] https://website.twiga-h2020.eu/; https://www.hydrologic.com/the-twiga-information-service-infrastructure/.

initialization approach has shown to significantly improve the multi-year prediction of some regional features, such as sea-ice volume.

2.4.4 Nowcasting

Nowcasting involves predicting weather conditions at a relatively small spatial scale (hundreds of metres to tens of kilometres) out to lead times of several hours ahead (see Figure 2.3). It has many applications, and plays an important role in grid integration and renewable energy forecasting. According to the format of the forecast products and the application scenarios, nowcasting can be divided into two types: station based and model grid based.

For station-based nowcasting, the main methods are extrapolation (based on historical time series) and calibration (based on numerical weather forecasts) (for example, see Box 2.1). Extrapolation is based on historical time series. The time series approach is a method of forecasting a future period through a historical period. The basic time series methods are the consistency, moving average and auto regressive moving average methods. With the rise of sequence-to-sequence applications in artificial intelligence, techniques like this are also applied to nowcasting time series extrapolation, such as the Long Short-Term Memory, Gated Recurrent Units and the boost algorithm.

Due to the time continuum, wind speed forecasts can be used as time series forecasts, and have achieved good results in practical applications. As for solar power forecasts, since solar radiation is closely related to meteorological and astronomical conditions such as quarter, cloudiness, water vapour, aerosols, and day and night (which cause variability in PV power output, especially in the short term), the accuracy cannot be guaranteed by extrapolation alone, and calibration based on astronomical elements needs to be applied.

However, nowcasting of solar power is greatly improved through the use of dedicated instruments such as sky cameras or imagers. The camera images have a higher resolution than satellite images, and offer grid operators and PV plant operators accurate forecasts up to 15 minutes ahead. The spatial and temporal resolution and the range depend on the cloud situation and the time of day. A cloud camera can record an area of about 10 × 10 km^2. Multiple cameras, providing triangulation, have also been deployed to extend the forecast lead time.

Figure 2.9 shows an example of a sky camera application. With the purpose of forecasting solar irradiance and power for controlling equipment on electrical grids, a combination of image calibration with a machine learning model (artificial neural network) has been applied to different typologies of clouds: high cirrus, cumulus and cloud advection. Stratifying the behaviour of solar irradiance forecasting based on these cloud types allows provision of the most appropriate forecast depending on sky conditions (West et al., 2014).

With calibration based on numerical weather forecasts, the calibration takes weather forecast output as the initial field, which is then combined with additional information such as topography, subsurface, time, climatology or astronomy to revise the target site by statistical methods or artificial intelligence.

Artificial intelligence methods include the Support Vector Machine, ensemble methods such as Random Forest or eXtreme Gradient Boosting, hybrid models such as empirical decomposition-sample entropy and extreme learning machine combination, and neural network methods based on fuzzy rough set and improved clustering. These methods can be applied to wind energy and short-range solar power forecasting. For the power grid, the main methods are extrapolation based on grid observation and analysis data with NWP coupled with statistical calibration of real-time observations.

Extrapolation based on grid observation and analysis data is performed by collecting observations and analysis data, such as from satellites and radar, and analysis products based on weather stations, and using extrapolation tools such as the optical flow method, or artificial intelligence methods such as ConvLSTM (a recurrent neural network for spatio-temporal prediction that has convolutional structures) and TrajGRU (based on subnetworks to generate a location-variant recurrence structure) to extrapolate the required prediction variables.

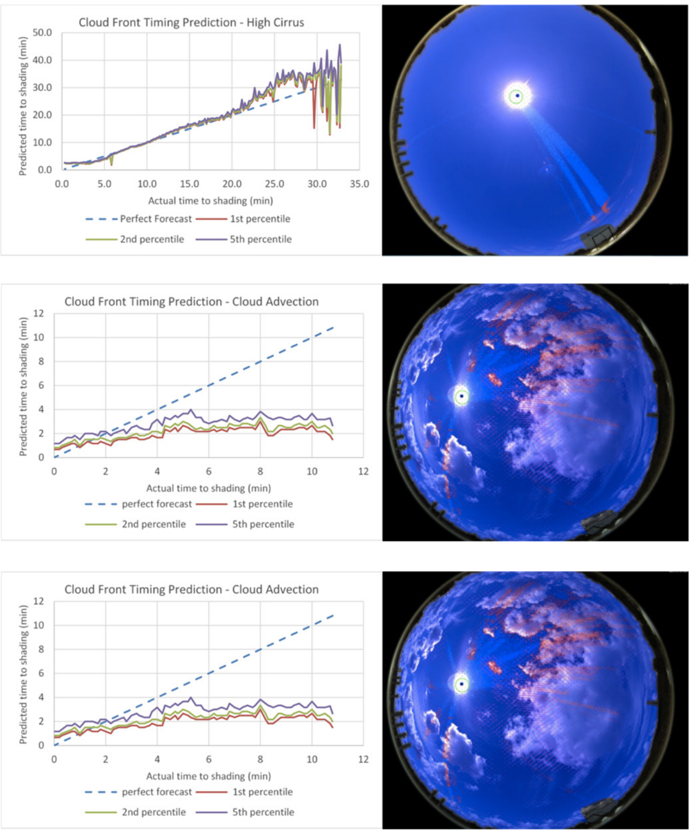

Figure 2.9. Performance of a machine learning model for irradiance forecasting based on three different cloud types

Source: S. West, Commonwealth Scientific and Industrial Research Organisation, personal communication

For short-range prediction of meteorological variables, such as those important to optimizing renewable energy integration, of the order of several hours, machine learning methods can often outperform the physical NWP models on average, particularly if real-time observations are available. Depending on the problem, the advantage over NWP lasts of the order of 4–10 hours. The skill of the machine learning models drops off with lead time due to the loss of memory from the time of the observation because of sensitivity to initial conditions.

2.4.5 Weather forecasts

Weather prediction systems are numerical systems that provide forecasted realizations of weather evolution. Numerical weather forecasting systems can be discussed or grouped based on the following different aspects:

- According to forecast horizons, NWP systems can be divided into very short-range forecasting (up to a few hours), short-range forecasting (a few hours to a few days) and medium-range forecasting (a few days up to 2 weeks).

- According to the region for which the forecast is being made, NWP systems can be divided into global modelling systems (grid spacing about 10 km and more) for medium-range forecasting and limited area modelling systems (grid spacing typically 1–10 km) for short-range and very short-range forecasting.

- According to the approach to forecast uncertainty, NWP systems can be divided into deterministic and ensemble systems.

Generally, there are two main requirements for successful NWP. The first one stems from the goal of weather prediction systems, which is to forecast weather in a given time and day, unlike seasonal or climate simulations, which typically simulate means or anomalies over a longer period. This requires knowledge of the weather at the current moment, that is the time when the model forecast is being initialized ("initial-value problem"). In other words, to know the weather in the next few days, it is necessary to know the weather right now. Therefore, an important aspect of NWP systems is a data assimilation procedure that blends observations with model data to provide optimal analysis or model description of the initial state of the atmosphere. Most frequent data assimilation set-ups nowadays include advanced methods such as variational data assimilation.

Despite the challenges associated with the assimilation of satellite data, one of the great successes in moving to a variational framework for assimilation has been the improvements in forecasts directly attributable to the improved extraction of information in satellite radiances. Figure 2.10 shows a convincing demonstration of this, depicting the improvements in southern hemisphere forecast skill at ECMWF. As ground-based observations are much sparser in the southern hemisphere, the duplication of the northern hemisphere skill by forecasts for the southern hemisphere is due almost entirely to the improvements made in incorporating satellite data into the assimilation.

Figure 2.10 also demonstrates how the forecast skill has been increasing over time. For instance, the forecast skill at day 7 lead time (green lines) is about the same as the skill at day 3 (blue lines) about 40 years ago. It is based on this and similar estimates that weather forecasts are said to have been improving by 1 day in lead time per decade.

Regardless of the type of NWP model system, the common requirement for 365/24/7 operational service is implementation of the system on a dedicated supercomputer. This allows satisfaction of the time criticality of the weather forecasting process, which is to provide timely and reliable NWP.

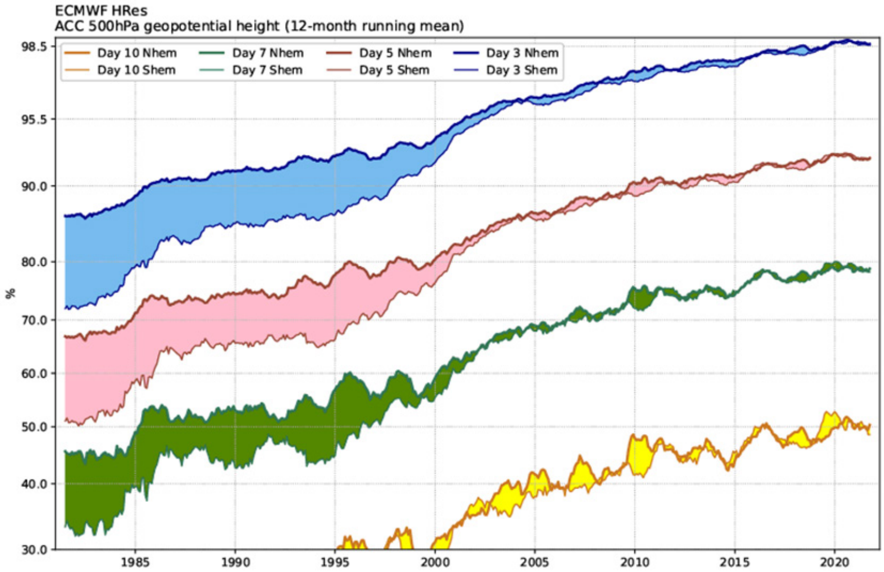

Figure 2.10. Improvement in the anomaly correlation skill score in the ECMWF forecast system over the past 40+ years

Notes: Improvement is shown for various forecast lead times: 3, 5, 7 and 10 days; the upper curve for each lead time shows skill in the northern hemisphere, while the lower curve shows skill in the southern hemisphere. Nhem = northern hemisphere; Shem = southern hemisphere.
Source: ECMWF (n.d.a)[42]

In practical applications, the entire process of producing numerical forecasts is technically composed of several fully automated steps. Also, the limited area (or regional) modelling systems depend on global model systems, as the latter provide model data required for the so-called lateral boundary conditions for the former,

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[42] https://charts.ecmwf.int/products/plwww_m_hr_ccaf_adrian_ts.

as well as initial conditions for the limited area systems that do not have their own data assimilation system. The technical steps for the set-up of a typical NWP model, including limited area models, are:

- **Collection of observational data:** Advanced systems use observational data extensively, such as SYNOP, SHIP, satellite, radar, aeroplane and airport data.

- **Quality control of observational data:** As these data will be blended in the process of data assimilation with model fields to produce the best possible state of the atmosphere, different data treatments and data rejections need to be applied to ensure the best results.

- **Data assimilation:** Blending of different sources of information from observations and models to provide the best possible initial state of the atmosphere is now typically performed with the use of variational data assimilation procedures. In the case of ensemble data assimilation, several equally likely initial states are produced.

- **Preparation of lateral boundary conditions from the global model:** Lateral boundary conditions are a necessary requirement of limited area model implementations. In the case of limited area modelling systems without data assimilation, the global model also provides the so-called initial conditions.

- **Model integration:** Model solutions are advancing step by step in time using an underlying numerical scheme. In the case of ensemble forecasting, ensemble of model integrations is implemented, which may have different initial states and/or may differ in model formulation, for example using stochastic perturbations in physical parametrizations.

- **Postprocessing (calibration):** After model integration is done, results are optimized or localized with observational data. In its simplest form, this step includes mean bias adjustment, but in more advanced forms, postprocessing improves also other properties of the forecast, either deterministic or ensemble.

- **Production of products:** Depending on user requirements, whether for transmission system operators (TSOs), energy market bidders or individual power plant managers, there are different needs for products (for example, tables, maps and graphs), which are regularly reviewed.

- **Access of forecasts:** After the forecast production is finished, data and products are made available for user access. Typical access methods include ftp (File Transfer Protocol), web, Web Map Services and other web applications.

- **Archiving:** Model forecasts are typically archived for a given amount of time to allow assessment of the model quality over long periods of time (months or years) and to serve as a source of data in case there is a need to reuse the historical forecasts.

- **Model verification:** Online (and offline) verification is an essential component of model development, which is used to track the real-time model performance and model deficiencies, as well as to assess the model reliability. Depending on the observations available for verification, evaluation can include graphical comparison, time series comparison, moment-based statistics, spectral evaluation and spatial verification.

- **Monitoring:** Automated monitoring and notification systems need to be implemented to track potential issues in the execution of the process. In addition, monitoring may be used to assess statistics of the delivery, especially in contracted services.

In the case of operational weather forecast centres, the entire process is fully automated, executed and regularly repeated on a supercomputer. For very short-range forecasting, advanced systems are typically refreshed hourly, while short- and medium-range forecasts (up to a 10 day lead time) are typically refreshed every 6–12 hours. Most advanced forecasting systems have a backup chain of operations to ensure product delivery, even in cases of major technical difficulties with the primary operational system. Such systems provide nearly absolute resilience of the weather forecasting chain and are essential in cases of force majeure events. For example, back up of the ALADIN-HR NWP system of the Croatian Meteorological and Hydrological

Service (Državni hidrometeorološki zavod, DHMZ), which was hosted on ECMWF infrastructure, proved essential to ensure regular service delivery after an earthquake in March 2020 that severely damaged DHMZ headquarters (described in ECMWF, 2020[43]).

In principle, weather forecasts provide predictions for very short lead times, such as hours. However, the computation time and the delay in obtaining the data due to retrievals and other possible technical matters mean that, in practice, forecasts are typically available a few hours into the actual lead time. Nonetheless, it is important to assess the relative quality of forecasts from different sources at these short timescales. A comparison of the performance of the different approaches as a function of lead time has shown that (Figure 2.11):

- For forecast horizons of 1 hour ahead, persistence of ground-measured clear-sky index values performs similar to the satellite-based Cloud Motion Vector (CMV) approach.
- For about 1–4 hours ahead, the satellite-based CMV approach outperforms ground-based persistence and ECMWF-based forecasts.
- Beyond 5 hours ahead, ECMWF-based forecasts are the best choice when referring to single model forecasts.
- The forecasts combining all three models show a significant improvement compared to ECMWF and CMV single model forecasts.
- Forecast errors of the German mean values are considerably smaller than for single site forecasts. However, the effect of spatial averaging is not the same for all methods; for example, the improvement obtained with the combined approach is much more pronounced for regional forecasts than for single site forecasts.

A conclusion from this comparison is that solar power forecasting at lead times longer than a few hours should inlcude one (or more) NEW-based forecasts.

2.4.6 *Sub-seasonal forecasts*

Sub-seasonal prediction systems generally target forecasts for the next 60 days (ca. 8 weeks, see Figure 2.7). This timescale sits between weather prediction (up to 15 days) and seasonal prediction. Sources of predictability and skill for sub-seasonal prediction reside in the low-frequency modes of coupled variability, for

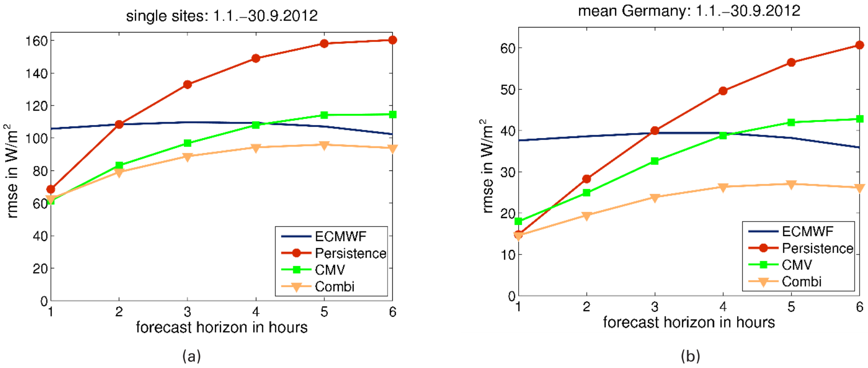

Figure 2.11. Root mean square error (rmse) of ECMWF-based, satellite-based CMVs and combined forecasts in comparison to persistence as a function of the forecast horizon: (a) single sites and (b) German mean

Note: For the ECMWF-based forecast, the 1200 UTC run of the previous day is evaluated independent of the forecast horizon and variations of the root mean square error with the forecast horizon are due to the horizon-dependent datasets.
Source: Lorenz et al. (2014)

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[43] https://www.ecmwf.int/en/newsletter/164/editorial/meeting-challenge.

example, the Madden–Julian Oscillation and slowly evolving components of the Earth system, such as SST, soil moisture, sea ice and vegetation.

Sub-seasonal prediction systems are usually coupled ocean–atmosphere general circulation models (GCMs), but some operational sub-seasonal forecasting systems are still atmosphere only. To capture the forecast uncertainty, use of ensemble predictions is a common practice, and allows for formulation and communication of forecasts in a probabilistic framework.

It is also well known that biases in long-range predictions can be substantial. Therefore, real-time model forecasts need to be corrected in an attempt to remove the influence of forecast biases and to improve their prediction skill. To facilitate this, the real-time forecasts are accompanied by an extensive set of hindcasts (also referred to as reforecasts) over a historical period. For example, the real-time sub-seasonal forecast system at ECMWF is accompanied by hindcasts over the previous 20 years. To maintain consistency with the real-time forecasts, hindcasts are generated using the same system as used for the real-time forecasts. The availability of hindcasts allows estimation of the skill of the forecast systems, correction for biases in real-time forecasts and calibration of real-time forecasts to increase forecast reliability.

The prediction systems participating in the joint World Weather Research Programme (WWRP)–World Climate Research Programme (WCRP) S2S Prediction Project provide a good overview of the current generation of sub-seasonal prediction systems. The primary goal of the S2S project is to collect forecast and hindcast data from operational and research centres and make them available to the research community to improve understanding of the various aspects of sub-seasonal variability and to explore development of new forecast products (together with an estimate of their skill).

There are 12 sub-seasonal prediction systems that provide their forecast data to the S2S project database hosted by ECMWF (ECMWF, 2016[44]). A survey of the characteristics of the sub-seasonal forecast systems reveals the following general features:

- The horizontal resolution varies between 30 km and 200 km
- The typical hindcast period is around 20 years
- The forecast frequency varies from an ensemble of daily forecasts to an ensemble of forecasts done on a few selected days of the week
- The ensemble size of forecasts that run daily tends to be smaller (~4) than those that are run less frequently (~20–50)
- The forecast range varies from 30 days to 60 days

The S2S project database does not disseminate real-time forecast data. The availability of the latest forecast is 3 weeks behind; it is therefore not suited for generation of real-time products. However, this dataset has been used widely for research purposes to quantify the skill and predictability of various aspects of sub-seasonal variability, for example, to assess sensitivity in forecasting and simulate sub-seasonal variability on forecast system characteristics such as forecast model resolution or ensemble size.

2.4.7 Seasonal forecasts

Seasonal climate forecasts fall between two different time-horizons: weather forecasting and climate projections. They share with NWP the difficulty of initializing the simulations with a realistic state of the atmosphere and the need to periodically verify different aspects of their quality, while additionally are burdened by uncertainties in feedback processes that also play a central role in constraining climate projections. In addition, seasonal predictions have to deal with the challenge of initializing all the components of the climate system (ocean, sea ice and land surface).

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[44] https://confluence.ecmwf.int/display/S2S/Description.

Dynamical seasonal forecast predictions assume that large-scale and long-lasting anomalies will convey predictive skill. Depending on the forecast time-horizon, different drivers/predictors may play a role in the correct forecast of certain anomalies or extremes. Seasonal forecasting began in the 1950s using statistical or empirical techniques, when the relationships between large-scale atmospheric variability and ocean temperature anomalies were first identified at the seasonal timescale. In the 1980s, seasonal prediction was based on lag correlations with observed upper atmosphere geopotential height anomalies or analogues. In the following decades, statistical forecasts have often identified relationships between weather patterns and ocean anomalies, relying on linear regressions or variations such as canonical correlations.

At around the same time, complex dynamical models have allowed unprecedented, detailed investigations of the climate system, with a much-improved understanding of the dynamical evolution of the main components of the Earth system, including their interaction. Such an understanding has translated into the ability to produce usable and useful operational seasonal predictions on the global scale. More recently, significant forecast skill improvement of variables such as temperature and precipitation has been conveyed by sophisticated machine learning algorithms, whose development has raised a renovated interest in statistical approaches.

Statistical and dynamical methods are employed to produce seasonal predictions, although mixed methodologies are also used, as they can enhance the accuracy of either. In the case of dynamical prediction, the initial conditions are usually obtained through data assimilation, aimed at obtaining an optimal estimate of the state of the climate system at the start of the forecast.

This procedure allows capture, in the best possible way, of ocean anomalies associated with ENSO events and other ocean variability, soil moisture, snow and ice cover to enhance the quality of the forecasts. Unfortunately, less information is available about the state of the ocean, the sea ice, snow and land than about the atmosphere, and often the predictions are penalized by a lack of understanding of the relevant physical processes and the interactions among the subsystems.

Owing to many different reasons, such as the initial-condition uncertainty, model inadequacy and lack of appropriate computational resources, the ability to make predictions on timescales longer than about 2 weeks in the same way as is done for weather forecasts reduces considerably. However, by averaging physical variables over a larger area (50–100 km) and a longer averaging period (a month or a season; cf. Figure 2.3), the signal from the forecasts starts to emerge. In other words, to be able to extract potentially useful information, the longer the lead time, the larger the averaging time and the larger the spatial area needs to be to extract a useful signal from the forecast.

WMO coordinates organizations involved in the production of meteorological products including seasonal climate forecasts, and is therefore an excellent starting point in the search for seasonal forecast sources. One of the WMO coordination activities is related to the Global Producing Centres for Long-Range Forecasts[45] (GPCLRFs). Through the WMO designation process, GPCLRFs adhere to certain well-defined standards, aiding the consistency and usability of: (i) fixed forecast production cycles, (ii) standard sets of forecast products and (iii) WMO-defined verification standards (for retrospective forecasts).

At a minimum, the following items are required from GPCLRFs:

- Predictions for averages, accumulations or frequencies over 1 month periods or longer (typically, anomaly in 3 month averaged quantities is the standard format for seasonal forecasts, and forecasts are usually expressed probabilistically)
- Lead time: between 0 and 4 months
- Issue frequency: monthly or at least quarterly
- Delivery: graphical images on GPCLRF website and/or digital data for download

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[45] https://community.wmo.int/global-producing-centres-long-range-forecasts.

- Variables: 2 m temperature, precipitation, SST, mean sea-level pressure, 500 hPa height, 850 hPa temperature
- Long-term forecast skill assessments, using measures defined by the Standard Verification System for Long-Range Forecasts

WMO has also defined a comprehensive set of standard verification measures, and has officially designated 14 GPCLRFs.

One of the main sources of information and a wealth of seasonal forecast data is the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (C3S, n.d.b; see also ECMWF, 2021, n.d.b[46]). C3S provides a consistent dataset, with eight state-of-the-art seasonal forecasting systems, which make their output available according to well-established conventions. Some of the C3S features are: (i) access approval on registration and download of the application programming interface (API) access key and (ii) open access for commercial use, as well as for research purposes. Through the API access, CDS provides access to historical and real-time seasonal forecast data from 1993 to present, with the following common features:

- Multimodel seasonal forecast data have a temporal resolution of 6 hours for the outputs, while the update frequency is monthly
- Multimodel seasonal forecast atmospheric monthly means have a monthly output temporal resolution
- Ensemble members vary over time, with recent increases to a maximum of 51
- There is a standard 1° × 1° spatial resolution, though this can be specified pre-download
- Lead times are typically 6 months
- Tailored outputs are available on request
- Spatial/temporal subsetting is available pre-download
- Output variable selection is available pre-download
- Formatting options (pre-download) for delivery in Network Common Data Form 4 (NetCDF4) or Gridded Binary 2 (GRIB2) data formats are available

Another important source of seasonal forecast data is the North American Multi-Model Ensemble (NMME), which began in February 2011 and became an experimental real-time system in August 2011. NMME provides historical (and real-time) seasonal forecast data of eight models (two of them are currently in common with C3S CDS). These models provide less data than those in C3S CDS, but have a key advantage in that they are made available in a timelier way: around day 8 of each month compared to day 13 for C3S.

The Korean Meteorological Administration also hosts global seasonal forecast information through the WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble.[47] This portal contains background information about the 14 GPCLRFs, as well as plots of some common variables such as multimodel statistics.

Seasonal climate forecasts are inevitably affected by biases. These biases therefore need to be accounted for before seasonal forecasts are used. Bias correction, as well as forecast skill assessment, must be based on past performance. Many runs of the coupled model need to be performed to build a sufficient sample, which provides the statistical moments (mean and variance) upon which the a posteriori correction is based.

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[46] https://cds.climate.copernicus.eu/; see also https://confluence.ecmwf.int/display/COPSRV/Copernicus+Climate+Change+Service+-+C3S; http://apps.ecmwf.int/data-catalogues/c3s-seasonal/?class=c3.

[47] https://www.wmolc.org/.

A set of reforecasts (or equivalently back integrations or retrospective forecasts or even hindcasts), run over a past period, constitute the sample. The length of the period is dictated by a mix of practical and statistical considerations. From a statistical viewpoint, the sample should contain as many interannual modes of variability (for example, ENSO) cycles as possible. Moreover, due to the pronounced seasonality in model errors as well as in model performance, statistics have to be generated separately for each month of the year. Normally, several ensemble members are run for each start date (coupled general circulation models (CGCMs) are currently typically run on the first of each month).

Seasonal forecast output is possibly the most complex meteorological forecasting product. It is based on an ensemble and requires reforecasts for calibration, both of which are not straightforward concepts. A way to condense the information conveyed by seasonal forecasts is through the use of climagrams. These directly compare into a single plot the forecasts (as monthly averages) with the forecast model's own climatology distribution and the observed climatology distribution (Figure 2.12). Specifically, a climagram allows visualization of the value of the forecast, its direction (that is, whether it tends to be above or below its own climatology), and how strong the forecast signal is (as measured by the distance between the forecast, purple boxes, and its climate, grey boxes, also in the context of the observed climatology, orange and yellow distributions). Retrospectively, it is also possible to include the actual observed climate (red dots). As can be seen in this case, the forecast seems remarkably good, with the red dot within the purple boxes for all 6 monthly lead times. However, given the probabilistic nature of the forecast, it is not possible to draw strong conclusions about the accuracy of the forecast, even for a seemingly good forecast like the one shown.

As with all dynamical weather and climate forecast systems, seasonal forecasts are bound to have uncertainties due to their parametrization of physical processes as well as inaccuracies in their methods of solving some physical processes. This, combined with uncertainties in observed and analysed initial conditions and the chaotic nature of weather and to some degree, seasonal climate variations, tends to lead to inaccuracy.

To account for this, combining the ensembles from the independent skilful seasonal forecast systems into a multimodel ensemble has proven to be a reliable method to improve the skill of these forecasts. The reason is that the widening of the ensemble spread achieved by including different models helps mitigate the overconfidence of individual forecast systems.

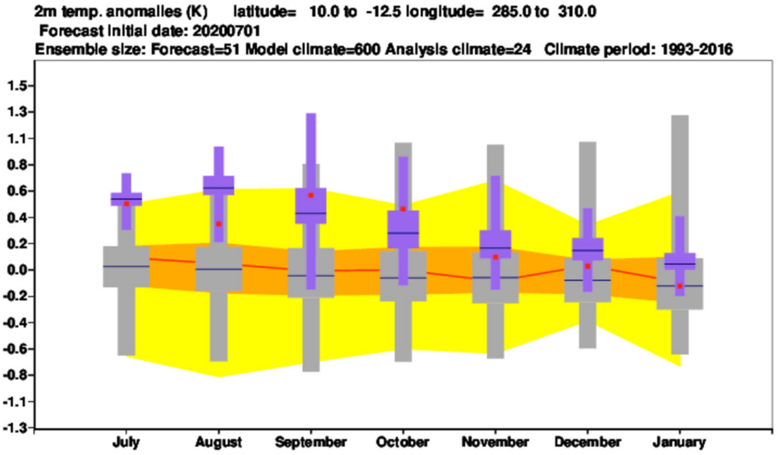

Figure 2.12. Representation of a seasonal forecast using a so-called climagram

Note: This figure shows the distribution as monthly means of the seasonal forecast (purple), the model climate based on past forecasts (grey) and the historical climatology (orange and yellow distributions). Red dots indicate observed values. The values shown are averaged over a 25° × 25° domain, centred in the northern part of South America.
Source: ECMWF (n.d.c)[48]

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[48] https://charts.ecmwf.int/products/seasonal_system5_climagrams_2mt?base_time= 202007010000&index_type=Carribean%20Amazon%20basin.

Furthermore, error cancellation between models may also help in minimizing the error of the mean of the multimodel ensemble compared with the individual models. It has also been proven that combining more independent models with different physical representations of atmospheric and ocean processes results in a higher accuracy of forecasts.

Seasonal climate forecasts require the use of a probabilistic approach, as opposed to a deterministic (one realization) approach. Key to the probabilistic approach is the generation of an ensemble of forecast realizations of the same real climate. The aim of ensemble generation is to mimic the effect of errors due to the uncertainty in the initial conditions and model deficiencies. Both sources of errors increase in magnitude with forecasting lead time. It is therefore critical to account for them in some way.

Thus, seasonal forecasting systems are always available as a set of ensemble members. The number of members varies from system to system. Typically, there are fewer members for hindcasts (for any particular start time) than for forecasts (also for any start time), and they can vary in number from as low as four to a few tens in the case of hindcasts and from about 10 to more than 50 for forecasts. However, care must be taken to suitably account for uncertainty when considering individual ensemble members. These must be treated as indicating a plausible scenario rather than a prediction per se. This explains why it is necessary to generate many such plausible scenarios so as to sample an appropriate range of likely outcomes.

Since, by design, all ensemble members are equally likely, the forecast provides a distribution of outcomes, given by the spread in the ensemble members, rather than a single deterministic answer. However, to simplify initial forecast assessments, these are often performed taking the ensemble mean as the reference (or most likely representation of reality) and practically treated as a deterministic forecast. Increasingly, users are learning how to exploit the power of the information provided by the ensemble, in a probabilistic manner.

2.4.8 Decadal forecasts

Prolonged droughts in south-west United States, increased hurricane activity in the tropical Atlantic, extreme events such as the recent massive American, European and Russian heatwaves, and the need to adapt to time-evolving climate change have raised concern among policymakers and decision makers about the possibility of predicting the climate evolution in the near term (up to 10 years, referred to as the decadal timescale). Impacts resulting from these conditions have significant socioeconomic and environmental implications.

Since the first studies carried out about 15 years ago, the field of decadal prediction has grown, and it is now well established that observation-based initialization of CGCM simulations can significantly enhance predictive capacity on timescales from a year to a decade in advance. The prediction of climate at such timescales is considered as a combined initial- and boundary-value problem; therefore, the outlook is sensitive to initial conditions and external forcing. Decadal predictions have an important advantage compared to climate projections. Their skill can be assessed by performing retrospective forecasts (or hindcasts) of the historical period to compare against subsequent observations.

Fully coupled initialized hindcast ensembles are run over the historical period, and then verified against observations and compared to uninitialized, free-running simulations to determine overall skill and the benefits of initialization. The enormous computational cost of performing decadal prediction experiments has been a significant impediment to progress in this field. For example, the Decadal Climate Prediction Project Tier 1 is based on a set of 10 member ensembles initialized once a year since 1960, integrated for 10 years.

The considerable cost of such experiments makes it difficult to systematically evaluate the sensitivity to arbitrary configuration choices. Such choices include the ensemble size, the method of ensemble generation, the number of start dates per year, the initialization method and the number of initialized components, in addition to the ocean, and the model resolution.

Several studies have tried to address the relevance of one or more of these aspects. Various authors have analysed the importance of the ensemble size. The standard 10 member ensemble is probably insufficient for many fields and regions of interest, but is generally considered adequate for practical reasons. Ensemble sizes smaller than 10 are strongly discouraged, especially in regions with low signal-to-noise ratios. A weak signal may be revealed only by using large forecast ensembles in the presence of strong, unpredictable variability. Consistent skill improvement is found by increasing the number of members to 16 or 20, especially for longer forecast ranges.

The advantages of initialized decadal predictions compared to uninitialized projections are widespread over a number of oceanic and atmospheric indices. This is because initialization allows the climate predictability arising from internal variability to be exploited. This enhanced skill is not limited to the first years of integration, but is extended to up to 10 years, while the global warming signal takes over the memory imparted by the initial climate state. A large part of the SST skill is due to the long-term linear trend, even in the first 5 year average of prediction. However, when the trend is removed, the anomaly correlation coefficient remains high and significant over vast portions of the North Atlantic and North Pacific Oceans.

Initialization also leads to a significant improvement in prediction of the West African Monsoon, which is mediated by latitudinal shifts in the tropical convection, and helps with representation of the atmospheric anomalies related to the occurrence of blocking in the Euro-Atlantic. This consequently affects the storm track and the frequency and intensity of extreme weather events over Europe. Therefore, skilfully predicting the decadal fluctuations of blocking frequency and the North Atlantic Oscillation (NAO) may be used in statistical predictions of years ahead climate anomalies.

The C3S programme has developed a demonstrator service aimed at providing sector-specific decadal prediction products (C3S, n.d.c [49]). In particular, one of the prototypes focused on hydropower generation, to provide users with decadal predictions of precipitation aggregated over three river catchments. By using decadal predictions of NAO, a synthetic forecast of rainfall was produced and proved successful with respect to a long-term hindcast, allowing generation of indicators crucial for determining water inflow to dams and expected energy production.

2.4.9 Climate projections

Climate projections aim to predict future climatologies, that is, the statistics of weather, the state of the ocean, the cryosphere, vegetation and atmospheric chemical composition. They are based on several assumptions about human evolution (population, economy, land use, land management, technologies and climate policies) and understanding of the Earth system's response to this evolution.

Projections are considered as a mainly boundary-value problem, where climate responds to external drivers. The principle is different from that of weather or seasonal climate forecasts, which are mainly an initial-value problem and whose aim is to provide a detailed representation of the state of the atmosphere at particular points or ranges in space and time (Vautard, 2018).

Global climate projections are simulations of the climate system performed with GCMs that represent physical processes in the atmosphere, ocean and cryosphere and on the land surface. These models cover the entire world, and use information about the external influences on the system. Climate projections are usually initialized from an equilibrium state in a period when human influence is assumed to be minor relative to external natural forcing (solar and volcanic), namely in the middle of the nineteenth century. Starting from an equilibrium state, they allow the simulation to slowly adjust to new states as boundary conditions such as GHG concentrations in the atmosphere are modified in line with observed values.

Consequently, climate projections are meant to represent possible trajectories of the weather, and the probability distribution functions of these fluctuations, rather than precise states. This is because models have biases that are difficult to fully control, owing to the accumulation of approximations, which are due to low-resolution and insufficiently well-represented physical or biogeochemical processes such as convection or land–atmosphere interactions. In models, all these processes are in a balance that is typically shifted compared to in the real world.

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[49] https://climate.copernicus.eu/sectoral-applications-decadal-predictions.

Climate projections also aim at explaining the evolution of past climate, from the instrumental period to paleoclimatic periods. A correct simulation of past periods, including the last century, millennium and beyond, provides some confidence in the model's ability to simulate climate change, even though comparison with paleo observations often faces numerous scientific challenges.

Global climate projections (or simulations) have been generated by multiple independent climate research centres in an effort coordinated by WCRP and assessed by IPCC. Climate projections are run under the Climate Model Intercomparison Project (CMIP), which was established in 1995 by WCRP to provide climate scientists with a database of CGCM simulations. The CMIP process involves institutions (such as national meteorological centres or research institutes) from around the world running their climate models with an agreed set of input parameters (forcings). The modelling centres produce a set of standardized outputs. When combined, these produce a multimodel dataset that is shared internationally between modelling centres and the results are compared (ECMWF, 2022[50]).

Analysis of CMIP data allows for:

- An improved understanding of the climate, including its variability and change
- An improved understanding of the societal and environmental implications of climate change in terms of impacts, adaptation and vulnerability
- Informing the IPCC reports

Comparison of different climate models allows for:

- Determining why similarly forced models produce a range of responses
- Evaluating how realistic the different models are in simulating the recent past
- Examining climate predictability

The sixth phase of CMIP (CMIP6) consists of 134 models from 53 modelling centres (Eyring et al., 2016; Durack, 2020). The aim of CMIP6 was to address three main questions:

- How does the Earth system respond to forcing?
- What are the origins and consequences of systematic model biases?
- How can future climate changes be assessed given internal climate variability, predictability and uncertainties in scenarios?

With CMIP6, a new set of GHG emissions scenarios were defined. The new scenarios, which represent different possible socioeconomic futures, are based on a matrix that uses Shared Socioeconomic Pathways (SSPs) and forcing levels of Representative Concentration Pathways (RCPs) as axes (O'Neill et al., 2017).

The conceptual framework for the design and use of SSPs is based on a description of the future evolution of key aspects of society that would together imply a range of challenges for mitigating and adapting to climate change. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses. These narratives are then combined with RCPs to produce specific values of the future trajectories of the emissions that constitute the main anthropogenic driver in climate projection simulations.

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[50] https://confluence.ecmwf.int/display/CKB/CMIP6%3A+Global+climate+projections.

The CMIP6 data archive is distributed through the Earth System Grid Federation (ESGF), although many national centres have either a full or partial copy of the data. A quality controlled subset of CMIP6 data is also made available through C3S CDS.

Climate projections can be used for a wide range of services for the energy sector, including for planning and risk assessment. As an example, using a set of CMIP models displays consistent expected increases in annual mean streamflow for high-latitude regions (northern North America and northern Asia), and large parts of the tropics (central Africa and southern Asia). For 25% of the global land surface area, increases in annual mean streamflow for the 2050s are consistent among all 10 CMIP models. Consistent decreases in streamflow are projected for the United States, southern and central Europe, south-east Asia and southern parts of South America, Africa and Australia (8% of the global surface area for the 2050s) (Figure 2.13).

One study showed the impacts of climate change on electricity transmission and distribution infrastructure (including power poles and transformers) of the United States (Fant et al., 2020). Using GCMs under two GHG emissions scenarios, it has been estimated that the total infrastructure costs are projected to rise considerably, with annual climate change expenditures increasing by as much as 25%. The results demonstrate that climate impacts will likely be substantial, also considering that this analysis captures only a portion of the total potential impacts (Figures 2.14 and 2.15).

2.4.10 Climate model downscaling

Global circulation models used for seasonal and decadal forecasts, as well as for projections, have a relatively coarse spatial resolution, in the range 50–200 km. This makes their use for local applications challenging as users normally would like to have information at the scale of a site (for example, a solar power plant). However, it is important to note that even if the model grid were to considerably increase, due to predictability limits and model biases, the actual accuracy of the forecast or projection would not necessarily improve.

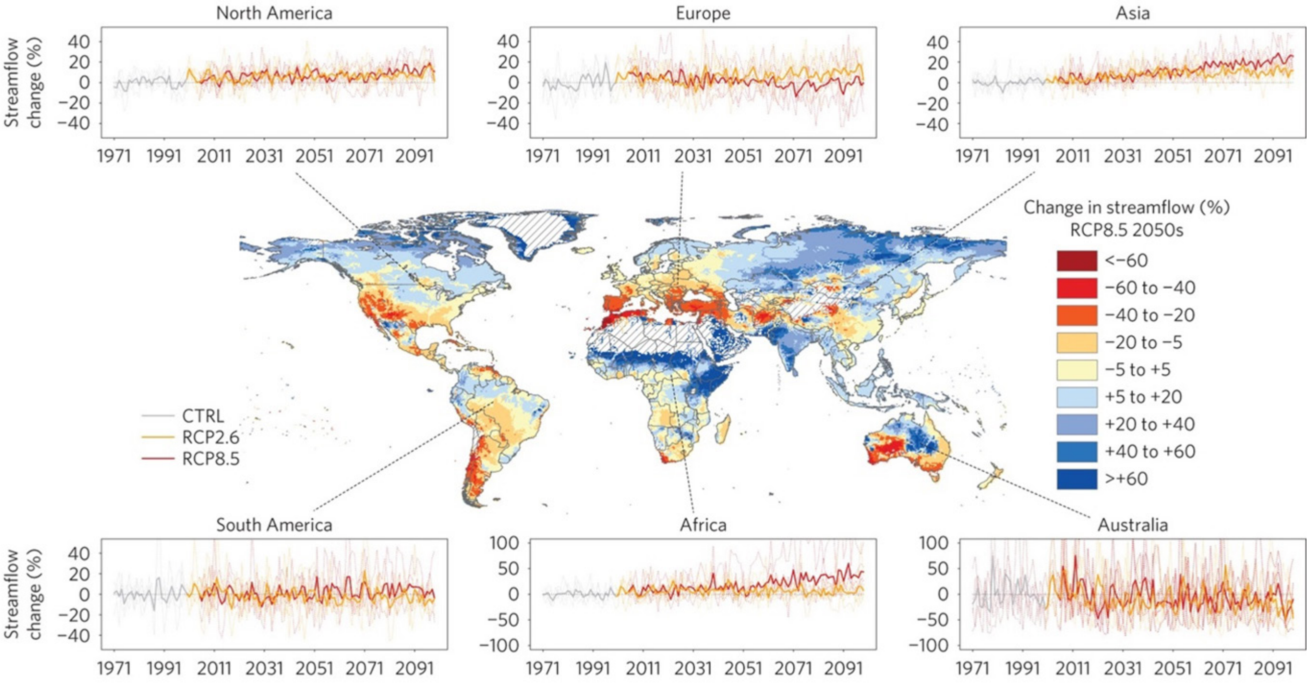


Figure 2.13. Impacts of climate change on annual mean streamflow

Note: The figure shows maps of changes in streamflow for RCP8.5 for 2040–2069 (2050s) relative to the control period 1971–2000. Trends in changes for 1971–2099 are presented based on the GCM ensemble mean results (thick lines) and for the five individual GCMs separately (thin dotted lines) for RCP2.6 (orange) and RCP8.5 (red). Trends per continent were assessed by calculating mean values in streamflow and water temperature over all continent grid cells. Future changes were then calculated relative to the control period 1971–2000.

Source: van Vliet et al. (2016)

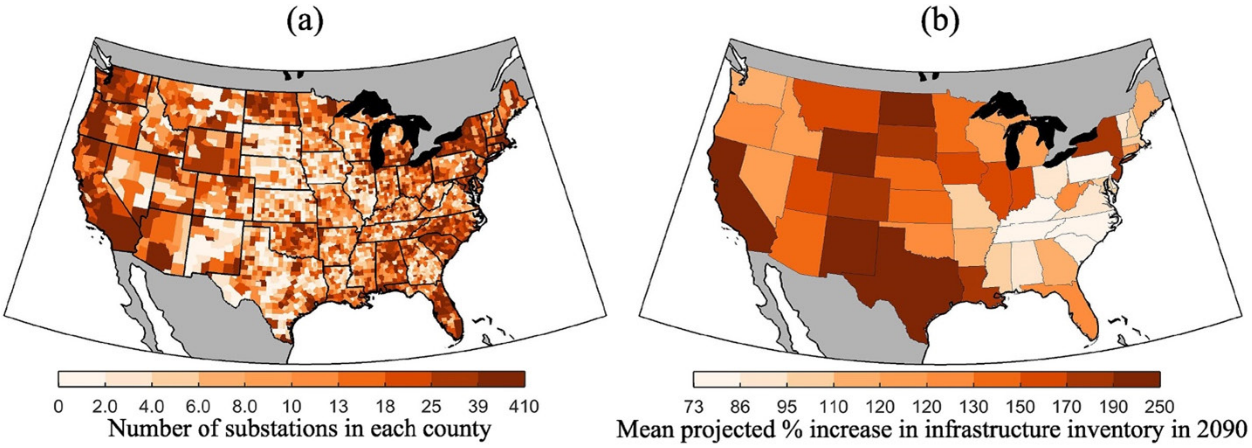
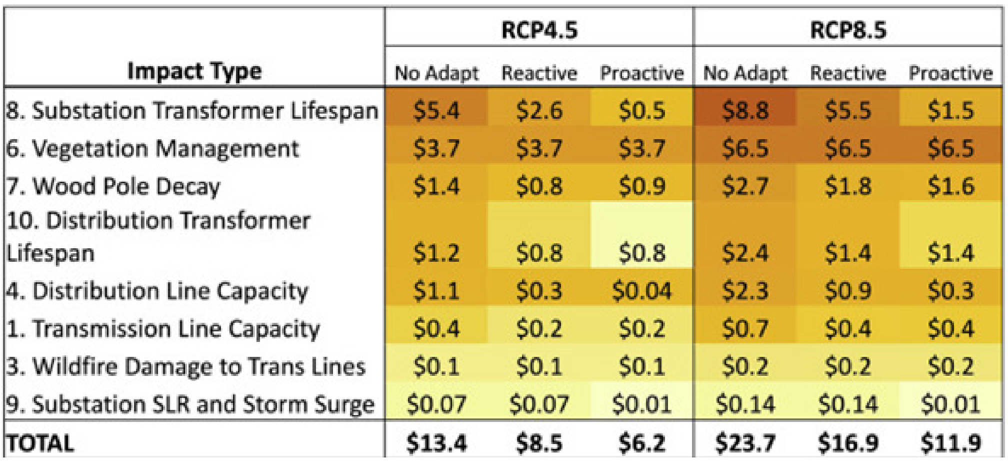


Figure 2.14. (a) Number of substations at the county level and (b) projected average increase in infrastructure inventory (in percentage increase) in 2090 as compared to in 2015 for RCP8.5, mean of all five GCMs, in the United States

Source: Fant et al. (2020)[51]



Impact Type	RCP4.5			RCP8.5		
	No Adapt	Reactive	Proactive	No Adapt	Reactive	Proactive
8. Substation Transformer Lifespan	$5.4	$2.6	$0.5	$8.8	$5.5	$1.5
6. Vegetation Management	$3.7	$3.7	$3.7	$6.5	$6.5	$6.5
7. Wood Pole Decay	$1.4	$0.8	$0.9	$2.7	$1.8	$1.6
10. Distribution Transformer Lifespan	$1.2	$0.8	$0.8	$2.4	$1.4	$1.4
4. Distribution Line Capacity	$1.1	$0.3	$0.04	$2.3	$0.9	$0.3
1. Transmission Line Capacity	$0.4	$0.2	$0.2	$0.7	$0.4	$0.4
3. Wildfire Damage to Trans Lines	$0.1	$0.1	$0.1	$0.2	$0.2	$0.2
9. Substation SLR and Storm Surge	$0.07	$0.07	$0.01	$0.14	$0.14	$0.01
TOTAL	$13.4	$8.5	$6.2	$23.7	$16.9	$11.9

Figure 2.15. Annual average climate change costs (billion US$ 2017/year) projected during the 2080–2099 period under the two emissions scenarios, three adaptation strategies and nine impact categories, averaged across the five GCMs, in the United States

Note: SLR = sea-level rise.
Source: Fant et al. (2020)

Other ways to increase the resolution therefore need to be sought. Such an increase in resolution, with the purpose to produce more useful and relevant data for specific applications, is achieved through a process called downscaling. There are two main approaches to downscaling climate model outputs: statistical and dynamical. Moreover, downscaling can be applied to either the spatial or the temporal dimension, or to both at the same time (as typically done with dynamical downscaling).

Dynamical downscaling refers to the use of high-resolution regional simulations to dynamically simulate the effects of large-scale climate processes to regional or local scales of interest. These downscaling models, usually called regional climate models (RCMs), are often atmospheric-only models, forced by SSTs and lateral boundary values of temperature, humidity and wind prescribed from global climate models.

RCMs typically adopt the same physical formulation of the global models, but given their resolution, they are able to better resolve local features than global models, and should, in principle, also better reproduce the local climate. The formulation of RCMs is computationally intensive, so they are normally run for selected

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[51] https://doi.org/10.1016/j.energy.2020.116899.

regions and at varying spatial resolutions. These can range from 10 km to 50 km, depending on the chosen domain. The Coordinated Regional Downscaling Experiment (CORDEX) organizes a large set of regional models (Giorgi et al., 2009; Vautard, 2018).

With statistical downscaling, a statistical relationship is developed between the historical observed climate data (local observations and/or gridded reanalysis data) and the output of the climate model for the same historical period. The relationship is then used to develop the future climate data. As with all statistical approaches, the results of the statistical downscaling become better with higher quality and longer duration of historical climate data. A vast range of statistical downscaling methods are available.

Some common methods for spatial downscaling are:

- **Delta Method (DeltaSD)**: A simple widely used method that assumes changes occur over larger, regional scales and that relationships among climate variables will remain the same in future scenarios (Pourmokhtarian et al., 2016).

- **Equi-distant Quantile Mapping Method**: This is a modified version of the quantile mapping technique to account for shifts in time with bias correction specifically for monthly GCM outputs (Li et al., 2010).

- **Piecewise Asynchronous Regression Method:** Similar to the Equi-distant Quantile Mapping Method, this method utilizes bias-correction techniques, but it also addresses the random irregularities from sampling variables by fitting a series of lines to the point data in order to smooth out the small-scale noise (Lanzate et al., 2019).

- **Cumulative Distribution Function transform (CDFt)**: The CDFt approach links the local-scale cumulative distribution function (CDF) of the variable of interest to the associated large-scale CDF through a quantile–quantile approach performed between the future large- and local-scale CDFs, and not between present CDFs as in the classical quantile–quantile method (Michelangeli et al., 2009; Vrac et al., 2012, 2016).

Temporal downscaling also utilizes a wide range of approaches from simple linear interpolations to machine learning simulations. A typical target is to produce an hourly time series starting from 3 or 6 or even 24 hourly climate model outputs. Hourly time series are, for instance, critical for electricity grid studies. An example of a relatively simple approach is spline interpolation, which is a special type of piecewise polynomial function. Because the interpolation error can be minimized even when employing low-degree polynomials for the spline, spline interpolation is frequently favoured over polynomial interpolation.[52]

From a practical point of view, it is worth noting that while downscaling can be done either dynamically or statistically, the latter is more accessible to a wide range of service providers as it is computationally much less demanding than the former.

2.4.11 The country-focused Climate Services Information System

Climate services can be organized and delivered in several ways, based on national priorities and mandates. For delivering climate information effectively to all countries worldwide, it is imperative that appropriate operational institutional mechanisms are in place to generate, exchange and disseminate information nationally, regionally and globally.

As defined in the GFCS implementation plan (WMO, 2014a[53]), the Climate Services Information System (CSIS)[54] describes such a mechanism comprising physical infrastructures of institutes and centres, and computer/

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[52] Instead of fitting a single, high-degree polynomial to all of the values in the time series at once, spline interpolation fits low-degree polynomials to small subsets of them, such as fitting nine cubic polynomials between each pair of 10 points instead of a single degree-10 polynomial to all of them (Perperoglou et al., 2019).

[53] https://library.wmo.int/?lvl=notice_display&id=20047#.Y9gYSHbMKUk.

[54] https://gfcs.wmo.int/CSIS.

information capabilities that, together with professional human resources, develops, generates and distributes a wide range of information products to support decision-making processes (Allis et al., 2019[55]).

The implementation strategy of CSIS is based on a three-tier structure of collaborating institutions that collectively consolidate existing climate data, products, tools and research findings, and establish an operational system encompassing core products in the areas of: (i) climate data rescue, management and mining, (ii) climate analysis and monitoring, (iii) climate prediction, (iv) climate projection and (v) tailoring information to specific user needs. These functions are undertaken through a global–regional–national system of interlinked producers and providers of climate information (Hewitt et al., 2020)[56] (Figure 2.16).

There are already several entities and functions involved in implementing the CSIS. These include the constituents of the WMO Global Data-processing and Forecasting System:

- WMO GPCLRFs and GPCs for annual to decadal climate prediction provide global-scale operational climate predictions from 1 month to 2 years, and from years to a decade, including verification information.
- WMO Regional Climate Centres (RCCs) are centres of excellence that create regional products in support of regional and national activities. They serve as CSIS stewards at the regional level, facilitating climate data services and conducting regional and in-country training activities.
- NMHSs own and operate most of the infrastructure needed for providing the weather, climate, water and related environmental services for the protection of life and property.
- Regional Climate Outlook Forums bring together national, regional and international climate experts to produce regional climate outlooks based on inputs from NMHSs, regional institutions, RCCs and GPCs.
- National Climate Outlook Forums are the same as Regional Climate Outlook Forums, but at the national level, bringing national providers and users of climate services together.

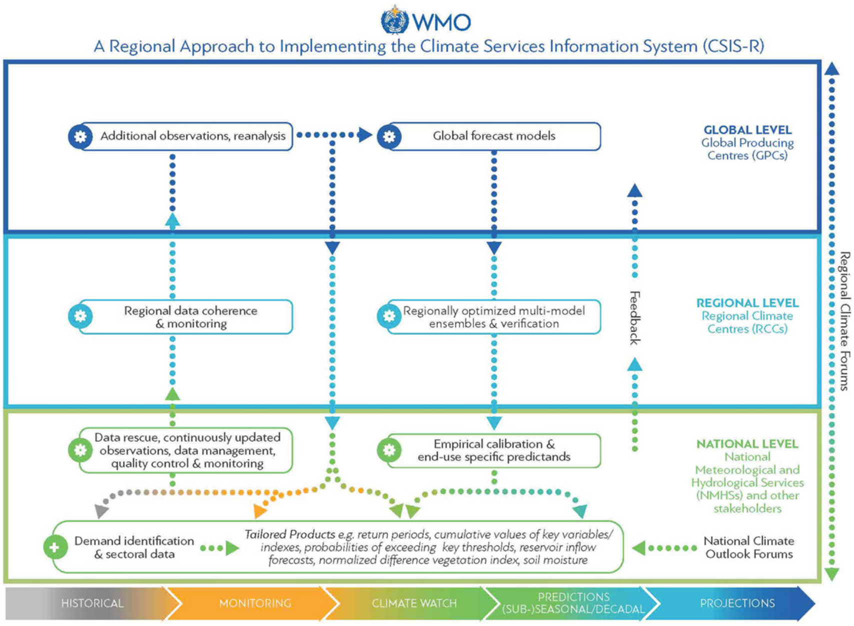

Figure 2.16. CSIS operationalization with special emphasis on a regional approach in support of country-level service delivery

Source: Allis et al. (2019)

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[55] https://library.wmo.int/doc_num.php?explnum_id=5843%#page=52.

[56] https://doi.org/10.1175/BAMS-D-18-0211.1.

To promote best practices around the world for climate data management, monitoring, prediction, projection and user-tailored climate information, WMO is developing a Climate Services Toolkit (CST) – a suite of guidance, data, software tools, training resources and examples (case studies) for enabling climate services. CST includes products, tools, models and data from RCCs and GPCLRFs.

2.5 Data availability and management

2.5.1 Data availability

One of the challenges faced in the transition towards a climate smarter society is how to rapidly scale up the ability to process efficiently a huge volume of data and extract the most interesting elements. Considering that the typical size of a global reanalysis, for example, is of the order of 10 petabytes (10^{15} bytes), these data cannot simply be moved around before processing. It has become a necessity to develop solutions to process the data close to the data and reduce the size of data download. This has further implications since, to be useful, the data need to be standardized, interoperable, traceable to the original source and quality controlled. Some global climate programmes, such as C3S, have addressed this challenge by developing data store conventions compliant with the Findability, Accessibility, Interoperability and Reusability principles.[57]

C3S CDS provides access to quality controlled data about the past (in situ and satellite climate variables and reanalyses), the present (near-real-time reanalyses) and the future (seasonal predictions and projections) climate of the planet. Such an extensive set of mutually interoperable datasets jointly with a set of applications and tools that can be applied to them have attracted a large number of users (100 000+ in October 2021). The service also provides examples of how the data can be used for specific applications including energy, as well as for user support, training material and courses.

2.5.2 Data management

Given the complexity of W&CS technology and the enormous amount of data involved, DMPs are essential to ensure operational systems can run efficiently and without (major) interruptions. Typically, the foundation components of a DMP are:

- Basic project information (name, funding body, budget, duration and partners).
- Data management policies and guidelines, including access and data sharing. Issues to be covered include controlling access to the data, permissions, charges and timing.
- Data, metadata and documentation. Issues to be covered include domain, resolution, subregions and reference periods, list of variables, description of variables, file-name conventions, file structure and format, quality assurance, lineage, link to related datasets, title, summary and keywords, author(s), project name and date of creation, and rights/licence.
- Data standards, interoperability and processing. Issues to be covered include use of standards for data format and processing methods; a common format for climate data is NetCDF, which follows the Climate and Forecasts (CF) convention.[58]
- Storage, security, backups and long-term preservation of data. Issues to be covered include location, media, transmission, method, regularity, responsibility, permissions, restrictions, encryption and archive location.
- Finance (costs of short- and long-term storage).
- DMP revisions (responsibility and timing).

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[57] https://www.go-fair.org/fair-principles.

[58] http://cfconventions.org; http://cfconventions.org/Data/cf-standard-names/37/build/cf-standard-name-table.html; http://www.unidata.ucar.edu/software/netcdf/workshops/2008/netcdf4/Nc4DataModel.html; http://www.unidata.ucar.edu/software/.

Some of these components are expanded on below, to provide an indication of how a DMP should be populated in practice. It is also useful to be aware, and ideally follow, international directives such as the European Union INSPIRE Directive (2007/2/EC) (European Commission JRC, 2007[59]).

In terms of data elements, W&CSs should include the main characteristics of the data to be provided, such as:

- Domain, resolution, subregions and reference periods
- List of variables
- Description of variables
- File-name
- File structure and format
- Quality assurance
- Title, summary and keywords
- Author(s), project name and date of creation
- Rights/licence
- Lineage
- Link to related datasets

Specifically regarding file-name and file structure conventions, it is instructive to see how these are set and implemented for a huge, distributed repository like the ESGF platform. Specifically, ESGF[60] climate data comply with the Data Reference Syntax (DRS) as described in the following.

DRS includes file naming conventions and metadata as NetCDF attributes. Data files must comply with the NetCDF format, according to the CF convention. Each file may contain only one output field (target variable) from a single simulation. The entire time series of a target variable can be distributed over several files covering continuous time period slices. The DRS element values consist of the characters a–z, A–Z, 0–9 and "-"(hyphen). No other character is allowed. The terms in brackets following the DRS element names in the list below indicate whether the values are prescribed ("single value"), must be taken from a fixed list of values or can be chosen freely. Most elements must have the same value as a mandatory NetCDF attribute. The elements are:

- **Activity** (single value) has to have a common value, for example "CMIP".

- **EnsembleMember** (regex formatted) identifies the ensemble member of the CMIP experiment that produced the forcing data, for example r1i1p1. Invariant fields (frequency = fx) may have the value r0i0p0 or that of the corresponding GCM EnsembleMember attribute.

- **ExperimentName** (enumerated list) is either evaluation or the value of the CMIP experiment of the data used (for example, rcp45).

- **Domain** (enumerated list) is the name assigned to each of the available regions.

- **GCMModelName** (enumerated list) is an identifier of the driving data. The name consists of an institute identifier and a model identifier. For runs driven by CMIP model data, these are the associated CMIP institute and the CMIP model. The two parts of the name are separated by a "-" (hyphen).

- **Institution** (enumerated list) is an identifier for the institution responsible for the scientific aspects of CMIP simulations (configuration, experiments and so forth).

- **Product** (single value) has to have the value output.

- **Frequency** (enumerated list) is the output frequency indicator: 3hr = 3 hourly, 6hr = 6 hourly, day = daily, mon = monthly, sem = seasonal and fx = invariant fields.

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[59] http://inspire.ec.europa.eu/documents/Metadata/MD_IR_and_ISO_20131029.pdf.

[60] https://esgf.llnl.gov.

- **StartTime and EndTime** (build rule) indicate the timespan of the file content. The format is YYYY[MM[DD[HH[MM]]]], that is, the year is represented by four digits, while the month, day, hour and minutes are represented by exactly two digits, if they are present at all.

- **VariableName** (enumerated list) is the name of the target variable in the NetCDF files.

- **Bcname** (enumerated list) is an identifier for the applied bias-correction method that includes a combination of acronyms for the institute and the bias-correction method, separated by "-" (hyphen).

- **OBSname** (enumerated list) is an acronym for the observation/reanalysis datasets used as reference data for bias adjustment.

- **REFperiod** (build rules) is the reference or calibration period in YYYY–YYYY format (for example, 1971–2000 or 1981–2010).

2.5.2.1 Metadata

Another key aspect of a DMP is metadata definition. Metadata are descriptors that allow the content of a data file to be uniquely defined. An example of a metadata list is provided here for ease of use:

> *Variable name*
> *1 General*
> *1.1 Description*
> How this variable is computed and what it represents for the three periods considered: historical, weather forecast, seasonal forecasts, decadal forecast and projections.
> *1.2 Reference date*
> Date of data publication/revision/creation in format dd/mm/yyyy.
> *1.3 Variable type*
> Observation/model output/derived/other (specify).
> *1.4 Unit*
> Unit of measure of variable and whether it is absolute or a relative change (for example, projection minus present day).
> *1.5 URL*
> Link to an appropriate portal.
> *1.6 Data format*
> Downloadable data in, for example, CSV (comma-separated values) format.
> *1.7 Keywords*
> For example, temperature or air.
> *1.8 Contact*
> Name and email address of person providing the data.
>
> *2 Dataset coverage*
> *2.1 Geographic area*
> Coordinates of the region and location. Provide latitude/longitude boundaries and coordinates. In the case of irregular areas, for example country, the reference name should be used (typically using NUTS2 (Nomenclature of Territorial Units for Statistics 2) conventions).
> *2.2 Spatial resolution*
> Grid resolution or point representation.
> *2.3 Temporal resolution*
> Annual/monthly/seasonal/daily/hourly. Time series/long-term averages/single sample.
> *2.4 Time period*
> Start and end dates.
> *2.5 Data creator and licensing*
> Name and email address of the owner/creator of the data and permission to use the data.
>
> *3 Usage*
> *3.1 Licence conditions*

Specify conditions or else state "none".
3.2 Citation(s)
List of relevant references.

4 Lineage statement
4.1 Original data source
Brief description of process history of dataset (for example, postprocessing of original "raw" data). Also information on process, technique, quality, uncertainty, exposure and management. Note if official/legal dataset.
4.2 Linked datasets
Datasets that are "linked" to this one (for example, datasets that have been used to compute an index).

2.5.2.2 Making data interoperable

Interoperability describes the extent to which systems and devices can exchange data and interpret the shared data. For two systems to be interoperable, they must be able to exchange data and subsequently present those data so they can be understood by a user regardless of their physical architecture and operating systems.

Interoperability can be achieved through the use of open standards (for example, International Organization for Standardization, World Wide Web Consortium or Open Geospatial Consortium standards) and the use of open-source software. This allows development of downstream services based on the output produced by a specific W&CS. For instance, OPeNDAP (Open-source Project for a Network Data Access Protocol) is one such standard. It supports the DAP2 (Data Access Protocol 2) protocol that provides a discipline-neutral means of requesting and providing data across the World Wide Web. The goal is to allow users of the service to immediately access whatever data they require in a form they can use, while using applications they already possess and are familiar with.

2.6 Future energy sector needs for weather and climate information

W&CSs will continue to play an important role due to the greater uptake of renewables within electricity markets around the world and the increasing importance of energy efficiency and demand flexibility. A key concern for future markets is how to ensure continuity of supply and also ensure the energy system is resilient under all types of weather conditions, particularly extremes. This is why W&CSs will become even more critical in the future.

There is a dramatic increase in the use of renewables globally; for example, wind and solar power increased from 1.7% of the share of world electricity generation in 2010 to 10.1% in 2021 (IEA, 2021a). Furthermore, many regions are planning to decarbonize their energy systems in the coming decades even further; for example, the European Union and the United States are aiming to reach net zero emissions by 2050.

An energy system with a high penetration of renewable energies is directly linked to meteorological conditions: snow, rain and temperature for hydropower; wind speed and direction for wind power; and solar radiation and temperature for solar power. This tight relationship means that to be efficient and secure, energy systems should maximize the use of any possible source of information about past and future weather and climate. Moreover, extreme weather events affect energy infrastructure (for example, electricity networks), and their impacts on end users can be exacerbated by the increasing interconnectivity of systems, due to energy transmission infrastructure and sector coupling.

Energy systems are becoming more flexible and efficient, but at the same time more complex. This complexity sometimes translates into an increase in vulnerability to unpredictable and extreme events. Climate services have proved their effectiveness in using the available weather and climate information to mitigate the impacts of extreme events, in many sectors including energy.

The energy system as a whole is a sector vulnerable to climate variability, whether looking at the present supply/demand match or the impact of weather extremes on conventional and renewable resources. Looking to the future, renewable energy is seen as a form of energy that can support mitigating some of the changes to the climate; however, these changes in climate will also affect demand and, more importantly, supply. While a lot of work has already been done on resource assessment, data analysis and forecasting for renewable technologies, the energy sector is only just starting to realize the importance a changing climate may have on renewable resources.

There is also growing interest from industry and financiers as to what the climate impact will be, as that will determine the overall level of risk associated with financing and investing in new energy resources, particularly those more dependent on weather and climate. In these early stages, it is important to identify what work is currently being done in this space, including what models and assumptions are used, and to also work out where the field should be heading into the future.

As countries realize greater investment is needed in transitioning the energy sector to net zero emissions, it is necessary to look forwards to see how this transition will occur. In addition, any risks due to climate change that could impede this transition must be mitigated. Climate services will be needed in this respect where investors, insurance groups, and owners and operators of large-scale developments would use climate forecasts as ways to determine if planned investments will still be profitable in the future based on outputs from climate models. These outputs will be used as risk management tools. Numerous studies have used various climate outputs and emissions scenarios based on the IPCC climate projections (CMIP6, CORDEX simulations, NARCliM to name a few). These studies identify how renewable resources will change in the future based on these scenarios (for example, Cronin et al., 2018).

Improving the quality of weather and climate data leads generally to an improvement in the corresponding services. One of the vital components of a service is the data used to inform and support a specific decision-making process. The increasing need for more reliable and specific climate services is driving an improvement in how the data underlying a service are generated and how different sources of data are managed to maximize their value. Climate models are one source of information underpinning climate services. Any improvement in reliability or resolution of a model may result in more valuable or detailed downstream applications, due to the data provided by the model and translated into actionable information.

The link between computing power and weather and climate model development is bidirectional. On the one hand, the availability of more computing power and more sophisticated technologies can enable new developments that were unfeasible in the past. On the other hand, the need to improve the quality of the models can create new needs of increasing computing power and more efficient technologies. In the last few decades, there has been an increase in the resolution and quality of climate models, with a consequent improvement in the downstream applications, including climate services.

Satellites, radars, observational weather stations and numerical models are producing more data than ever before, for which storage, management and processing of so-called “big data” require expensive infrastructure. Another challenge is that data volumes are becoming so large that it is impractical to download the data fast enough to meet operational requirements.

Two main infrastructure elements play a role in increasing the performance of weather and climate prediction and services: the observational ecosystem that provides the input data and the IT ecosystem including communication, computers and storage, with all internal and external interfaces. Computing and data must always be considered together since more sophisticated prediction systems create more diverse and more voluminous output data.

“Big data” (also “unstructured data”) is a widely used term and usually refers to new technical solutions to deal with massive amounts of data (volume) that are being created and/or moved frequently (velocity), where the nature of the data can be different (variety) and the trustworthiness is source dependent (veracity). The amount of data produced daily by large centres will be of the order of a few petabytes by the end of this decade. The main reasons are the limited bandwidth of the Internet and the complexity of using the data provided.

New postprocessing algorithms to derive user-relevant information from big data may be one way to overcome the data deluge and barriers to access. In addition, cloud technologies have matured in recent years and will be a trend over the next decade; they are now available everywhere and offer a wide variety of functions. They support the so-called “bringing the data to the user” paradigm.

The bandwidth issue can be solved by providing the output of numerical models and big observational data in cloud data storage. This will enable users from a weather enterprise to run their own numerical models and sophisticated applications on the cloud, which may open new business opportunities. As another advantage of this approach, data centre and computational resources development, maintenance and support are shifted to the cloud services provider, which reduces the costs significantly (see, for example, WMO, 2021a[61]).

This opens another area of collaboration and partnership among sectors, energy included, as big data companies will continue to provide cloud services. Many NMHSs and other public sector agencies will gain long-term efficiency by using these services. However, the transfer of responsibility for data handling to those service providers should be based on strong and reliable relationships with guarantees for protection of data and continuity of service over long periods.

Data are becoming central in climate services for multiple reasons. First, more data are becoming available due to improvement in computation power and development of more efficient and effective data mining and analysis software (including big data frameworks). Second, W&CSs are tackling more and more complex challenges, increasing the need for multidisciplinary approaches and more sophisticated workflows. Generally, more sophisticated workflows rely on effective data exchange/analysis protocols to be more efficient.

As discussed in this chapter, there are numerous forecasting methods, with additional ones emerging. These range from improving statistical techniques, satellite and sky imagery, NWP models and probabilistic forecasts and utilizing other tools such as lidar. However, the area that is seeing the biggest advances is machine learning. Ultimately, the techniques that will be more quickly taken up will be those that can readily function in real-time energy markets, following close consultations with energy sector users.

One of the key industry requirements, and also one of the key challenges, is the ability to provide a forecast in real time. Much of the literature assesses the performance of forecasts based on well-understood metrics, and against historical periods. Literature in the area of performance in real time and for operational markets is limited. Moving forward with W&CSs, there are a few key questions that need to be considered related to industry requirements:

- Does the value/relevance of the forecast mean the same thing to forecasters and to energy industry users?
- What is the best way to characterize the uncertainty around the forecast, and how best to provide the information in a way that is of use to the energy industry?
- When providing forecasts, are the forecast errors being minimized or are the costs being minimized/profits being maximized?

It will not just be improvements to different forecasting techniques, but also the way in which the large amount of data being collected and processed around the world is being accessed, used and interpreted. Many different types of data repositories, which are collected and collated at varying temporal and spatial resolutions, will need to be expanded and improved, from real-time measurements at renewable plants, to grid and market data at short timescales, to reanalysis and climate projection data. How these data are used, assimilated into models and used for verification purposes will be an area for development.

Numerous academic and commercial entities are working on forecasts for renewable plants (large scale and distributed) and at all forecast horizons. For the open-source codes that exist for meteorological variables and energy forecasts, the community should be aiming for a consensus on forecasting practice.

A proposed guideline for solar forecasting practice indicates that forecasts should be reproducible, operational, probabilistic or physically based, ensemble based and provide skill measures (Yang, 2019). In other words: all code and data should be made publicly accessible whenever possible (particularly when developments are funded by public funds); the forecasts should be tailored to grid forecast requirements; probabilistic

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[61] https://library.wmo.int/doc_num.php?explnum_id=10611.

forecasts should be developed; ensembles should be utilized; and there should be a set of agreed upon metrics for verification.

In terms of forecast guidelines, there is a move towards an increased use of probabilistic-based forecasts. A review on the integration of probabilistic forecasts for power systems sets out a workflow on how to implement these forecasts in an operational setting (Li and Zhang, 2020). Figure 2.17 illustrates the different steps, from the data to the actual types of methods to create a probabilistic forecast, then how uncertainty is represented and how that uncertainty is handled, to the final step of the power system application.

As W&CSs improve their integration in energy industry applications, one of the key challenges is how to best use uncertainty in live market operation. Within each of the steps just mentioned, naturally there are also ways to move forward with improving the physical and non-physical models. Physical models such as Weather Research and Forecasting (WRF)-Solar are adapting to a more tailored forecast for the solar industry. In addition, the WRF-Solar Ensemble Prediction System – an optimized ensemble-based solar forecasting system – is being developed. Such developments will help to improve W&CSs into the future.

Looking further into the future, there will be a greater need for sub-seasonal and seasonal forecasts, as well as for climate or multidecadal predictions. This includes through the blending of output from different models, as multimodel combination has shown to generally enhance the skill of even the best model when taken individually. Section 2.4 overviews these types of forecasts. Continued development is needed, as these longer seasonal forecasts/predictions are important for resource management strategies, plant operators, investors and grid operators. The output from seasonal forecasts will feed into a better understanding of economic returns, planning plant maintenance, and anticipating heating and cooling demand, and also the possibility of extremes.

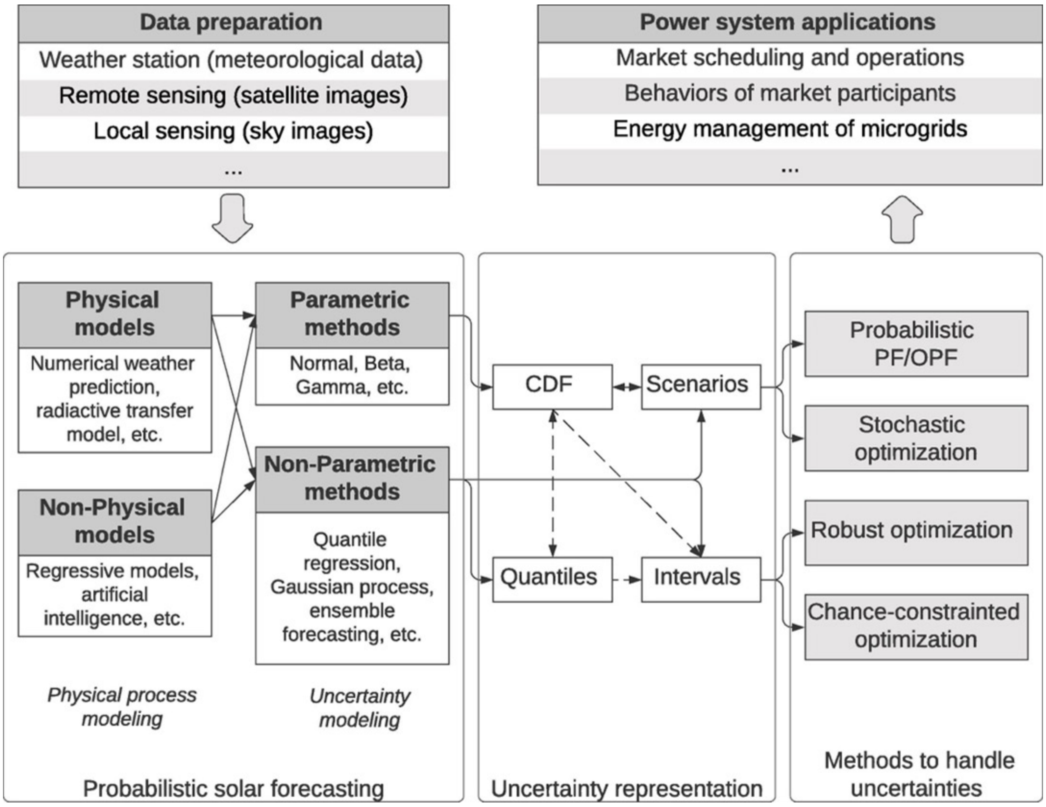

Figure 2.17. Workflow for the use of probabilistic forecasting for solar energy

Note: OPF = optimal power flow; PF = power flow.
Source: Li and Zhang (2020)

A greater understanding of the impact of climate change is an area that needs continued investigation. At these timescales, climate projections describing future scenarios from CMIP models will be used as resource assessment tools. Investors want to ensure they see a return on investment; for example, if a plant is built, will it be profitable over the lifetime it is in operation? Policymakers will use this information to advise on the energy mix, and grid operators will use these projections to better anticipate power grid capacity needs. Importantly, as the models used for seasonal and decadal forecasts as well as for projection have a relatively coarse resolution, downscaling (spatially and temporally) will need to be continually enhanced. And while downscaling can be done either dynamically (with a climate model) or statistically (with statistical approaches of varying levels of complexity), the latter is much more accessible to a wide range of service providers.

There is a huge increase in the number of publications using machine learning, and more broadly artificial intelligence, for forecasting. One of the main reasons for this rapid development is the large amount of data available for weather and climate, which make machine learning, and artificial intelligence, suitable for this type of problem. For instance, the increasing quantity of satellite observations is a key enabler for all the data-intensive solutions based on artificial intelligence. As an example, the Copernicus programme provides 16 TB of data each day based on the Sentinel satellites only. The number of satellites and data streams is increasing steadily, so much so that the term “big Earth data” has started to emerge (Sudmanns et al., 2019).

Machine learning and artificial intelligence can help to explore and improve solutions in an increasingly complex environment. For instance, power systems have been early adopters of solutions based on artificial intelligence with smart grids. Artificial intelligence can also play an important role in monitoring and localization, also driven by the increasing availability of remote-sensing data. An example is the development of machine learning approaches to detect leaks or to identify failures in natural gas pipelines. Artificial intelligence is already widely applied in weather and climate science; however, the rapid development is expected to also improve the provision of effective W&CSs. Indeed, such techniques for W&CSs for the energy sector can be applied to:

- Forecasting of relevant variables (for example, wind speed and direction for wind power, water flow and precipitation for hydropower, and demand)
- Supporting the operational decision-making (for example, dispatch order, market bidding, timing and use of energy storage)
- Improving the monitoring of energy systems
- Improving the efficiency/flexibility and reliability of the system regarding scheduling and planning

A recent trend that might also affect W&CSs is the use of artificial intelligence techniques to improve climate predictions. The improvement can be obtained in multiple ways: by incorporating a process based on machine learning into the atmospheric model; by using a machine learning technique to post for process the model data; or by directly replacing the whole numerical model with a machine learning workflow.

Machine learning can help to combine the information from multiple models, to quantify uncertainty and/or improve the calibration of probabilistic forecasts eventually used by downstream climate services. For example, a novel field is the use of deep learning techniques to replace weather forecasts. This application is recent, yet the community is already wondering when the models based on artificial intelligence will outperform NWP. However, the use of machine learning in weather and climate modelling can increase the complexity of the workflow and the general interpretability of the model (Sønderby et al., 2020; Schultz et al., 2021).

The available technology in support of W&CSs for the energy sector is wide, complex and continually evolving. Such technology hinges on observations and modelling of the Earth system, together with advanced tools such as machine learning techniques. Given the complexity of the technology, it is therefore critical to continue fostering a close engagement between weather and climate experts and energy sector users to implement the most effective and efficient solutions. The next chapter will complement the information presented in this chapter, by showing how weather and climate data can be converted into useful indicators for the energy sector.

3. ENERGY CONVERSION MODELS AND FORECASTING

3.1 Introduction

Weather and climate data can be applied to energy systems in three distinct ways. (i) Historical data can be used at the planning stage to evaluate the expected attributes of a current or future energy system or system component. This may be done at any scale, from evaluating the feasibility of a single project like a wind or solar power plant, or transmission line, to considering the expected weather impacts on the entire system. (ii) Current and near-future data (from minutes to seasons ahead) can be used at the operational stage to manage the energy systems to ensure reliability and/or maximize profits. (iii) Climate projection data can be used at the planning stage to account for the expected impacts of climate change on power generation and/or network infrastructure over decades ahead. However, while research is developing rapidly in this area, practical use of these data is currently limited to applications such as hydropower production assessment. The production of each kind of data is accompanied by specific requirements and constraints.

Analysis and characterization of energy systems for the present-day climate rely on the availability of high-quality datasets of observations or proxies for estimating energy demand and supply. In the wind energy sector, for example, the development of new wind farms is generally dependent upon the characterization of the site, which also includes a statistical analysis of the prevalent winds on site. This statistical analysis relies upon the availability of time series of wind, which ideally should be obtained by measuring the wind on site. However, this process is lengthy as it requires the installation and maintenance of observation stations over a long time to collect a sufficiently long record to assess the statistics. Specifically, long observational time series are needed to accurately estimate the effects of climate on wind power generation, which can be subject to substantial interannual variations. Reanalysis datasets (for example, ERA5) constitute a powerful alternative to long-term observations to assess the variability of site-specific meteorological variables.

The quality of today’s weather forecasts is overall sufficient to meet the needs of the energy industry. However, for instance in the case of power TSOs, errors in the meteorological forecasts become critical with the growing share of renewables in electricity production, as there might be limited scope to provide an alternative power supply in a short time frame. This is particularly the case when high amounts of variable renewable capacity are installed in a small power balancing area.

Therefore, identification of weather situations associated with large forecast errors help NWP model developers to focus on improvement of certain important aspects in the model formulation (including parametrizations) and implement improvements that can assist in such situations. Trying to enhance the balancing area also leads to reduced uncertainty, as does regionally planning generation, especially for renewable generation with weather datasets used in the co-optimization of ideal locations (for example, see Box 3.1).

Table 3.1 shows examples of meteorological conditions that can be associated with large forecast errors. The use of ensemble forecasts will, to some extent, provide information about the forecast uncertainty and a basis for informed decision-making. However, systematic model errors may be identified and reduced by further model development (Sengupta et al., 2021[62]).

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[62] https://iea-pvps.org/key-topics/best-practices-handbook-for-the-collection-and-use-of-solar-resource-data-for-solar-energy-applications-third-edition.

Table 3.1. Examples of critical weather situations for the energy industry identified during dialogues between meteorologists and energy sector users (for example, TSOs and renewable plant operators)

Renewable energy source	*Weather situation*	*Comment*
Solar	Low stratus and fog	Particularly critical if spatially extended Timing for presence and absence of low stratus
	Snow cover and melt on PV panels	
	Small-scale clouds	Convection, or broken clouds, fast changes in the cloud cover
	Mineral dust or other aerosols	For example, advected from deserts and wildfires
Wind	Nocturnal low-level jets	
	Fronts	Gradients, timing and localization
	Icing	On turbines and power lines
	Turbulence in the boundary layer	
	Large gradients (wind ramps)	

Box 3.1. Application of automatic regional weather forecasts in short-term load forecasting (STLF)

STLF is a crucial task in daily power system operation. An accurate STLF result enables power system operators to optimally schedule generating units with adequate generation capacities to meet load demand and maintain the power system in a secure state.

STLF can also facilitate implementation of various demand management programmes that may contribute to deferral of new investments in electricity infrastructure by power companies. Electric load demand varies non-linearly with time, and is influenced by exogenous variables, including weather conditions, the calendar effect, the economy and special events. It is highly challenging for power system operators to predict an accurate short-term load profile.

In this context, CLP Power Hong Kong Ltd collaborates with HKO in utilizing the automatic regional weather forecast (ARWF) to identify suitable parameters and improve the accuracy of load forecasting models (Ho et al., 2021). Figure 3.1 shows the architecture of the STLF model with incorporation of ARWF data.

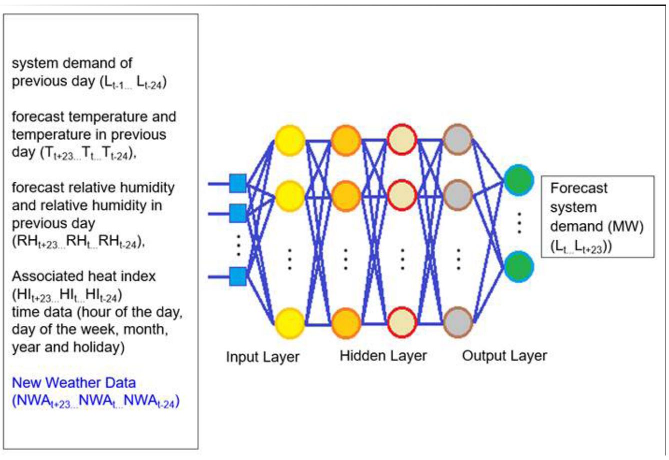

Figure 3.1. Multilayer feedforward neural network of a load forecasting model

Source: Ho et al. (2021)

The incorporation of ARWF data improves the accuracy of load forecasting, particularly in adverse weather, and is a viable approach. The collaboration between CLP and HKO in the STLF project also showcased the benefit of utilizing meteorological data in support of energy sector operations, contributing to energy saving and creating a greener smart city.

Accurate renewable energy forecasting is important for power grid operators and electricity traders to optimize wind power production and minimize the probability of overloading, for example. Similar to typical electric power load forecasting, renewable energy forecasting has a wide range of forecasting timescales from very short-term (several minutes ahead), short-term (day ahead), midterm (week and month ahead) and long-term (sub-seasonal, seasonal or year ahead) temporal scales.

Very short-term forecasting and short-term forecasting are important for stable grid operation and for the day-ahead operational management of reserve power and economic dispatch planning, respectively. In general, NWPs are not available for the very short-term power load forecasting because they require comparatively long model integration times (typically a few hours), even if, in principle, forecasts produced, say, the previous day could also be used. However, on this timescale, statistical methods give sufficiently accurate forecasting information. Except for the very short-term forecasting, NWPs are a useful tool for renewable energy applications:

- They provide renewable energy forecasting especially for short-term forecasting with a combination of other statistical and machine learning methods

- They have been used to estimate renewable energy resources so they provide optimized locations for wind and solar energy farms

- They can be used to estimate environmental effects of massive renewable energy plants

Accurate midterm forecasting and long-term forecasting are critical for power plant maintenance and optimal design of renewable energy farms, respectively. In contrast to STLF, uncertainty in the sub-seasonal and seasonal climate predictions for the mid- and long-term power forecasting makes these data more challenging to use for reliable and efficient operation of renewable energy.

It is worth noting that NWP is affected by errors in near-surface meteorological and terrain conditions. Wind power forecasting is particularly sensitive to wind speed biases because wind power is proportional to the cube of wind speed, so any error is amplified. Thus, wind power forecasting tends to have relatively larger forecasting errors compared to solar power forecasting, due to generally considerable biases in heterogeneous and hilly terrain that NWP cannot resolve.

Furthermore, it is also important to properly evaluate the forecast methods and to be aware of the limitations of NWP-based forecasting, especially by sudden changes in weather such as the passage of small-scale cumulus clouds or a wind ramp pattern. When such highly variable wind and solar radiation conditions occur, errors in renewable energy forecasting can heavily affect the balancing of the power grid, if the likelihood of these errors is not properly accounted for.

To estimate these errors, various statistical measures have been proposed for weather and climate model evaluations. However, they are often not suitable for renewable energy uncertainty estimation from an operational point of view as the target metrics differ (for example, anomaly correlation of a pressure field over an area of hundreds of square kilometres in the meteorological case versus renewable energy production in a balancing area in the case of power). More work needs to be done to develop statistical measures oriented towards renewable energy, to link meteorological forecast uncertainty with power operators and markets. Advanced (web-based) platforms to provide renewable energy forecasting and their uncertainty are currently available only in a limited number of cases.

The starting point for energy forecasting is to construct a conversion energy model that works for present-day conditions, using historical records, going as far back as possible. The same model is then normally applied to various forecast horizons, from days ahead to decades ahead. However, the conversion models have various levels of complexity, depending on the target horizon timescale. For instance, to simulate renewable energy at the decadal or even seasonal forecast timescale, considerable simplifications to the conversion models can be applied compared to those used for minutes or day-ahead forecasts. Such conversion models are presented next.

3.2 Background

Energy conversion models are defined as the models that link meteorological and energy variables. These models can be either statistical or physical, or a combination of both approaches.

Statistical models build relationships between the target variable (predictands) and explanatory variables (predictors), which can be different (climatic, demographic or economic). They allow accurate calibration but require long enough records of the considered variables. They are also dependent on the stationarity of the variables under consideration.

Physical models use a priori knowledge of the links between the target variable and the predictors. They need fewer observations for calibration; nonetheless, they also require observations for validation.

Given the focus of this publication on W&CSs, only the effects of weather and climate variations on energy demand and generation are considered. In this context, energy system components are sensitive to weather and climate. At one end of the spectrum, there is thermal power generation, including nuclear energy. The weather dependency is mainly through the (air and) water temperature used for cooling the power plant. At the other end of the spectrum, wind and solar PV generation are mainly controlled by wind speed, solar radiation and air temperature, even if other factors such as power system failures and maintenance downtime affect the amount of power generated by these technologies. Somewhere in between sits electricity demand with a significant dependency on weather variables, particularly temperature.

However, demand is also driven strongly by several other factors, mainly the hour of the day, the position of the day in the year, and more general ones such as economic productivity, social behaviour and policy. Also in between is hydropower, with run-of-river production more directly dependent on weather and water variability than the reservoir type of production, which is more dependent than pumped hydropower generation.

Conversion models present various levels of complexity, depending mainly on two aspects:

- The addressed timescale (resource assessment, hours to days ahead forecasts, seasonal forecasts, multidecadal long-term planning and so forth)

- The spatial scale of interest (worldwide perspective, regional, national and local levels, and site specific)

For instance, to predict solar power minutes ahead at a specific location, precise information on cloud position, shape and speed, such as observed from sky imagers, must be known. In contrast, if the average solar power production is forecast a few months ahead over a country, it is sufficient to use a relatively simple transfer function linking solar radiation and air temperature (or ideally the temperature of the PV panel) to power.

The following focuses on broad aspects of the conversion models, leaving the details, particularly those required for hours to days ahead location-specific forecasts, to references.

There is a description of how electricity demand is modelled since demand is a critical variable in energy systems analysis and forecasts. The discussion then moves on to modelling renewable energy generation, mainly hydropower, wind power and solar power. Other generation sources such as thermal power generation, particularly the cooling of power plants, are briefly mentioned for completeness.

3.2.1 Electricity demand modelling

The main climate driver of electricity demand is near-surface air temperature, for cooling and heating needs. The thermosensitivity of demand varies significantly from country to country, depending on the nature and characteristics of the appliances and consumer behaviour.

For instance, in Europe (Figure 3.2) in 2019, the estimated average winter thermosensitivity was about 4 000 MW $°C^{-1}$ (a decrease of 1 °C in temperature in winter increases the demand by 4 000 MW). France had

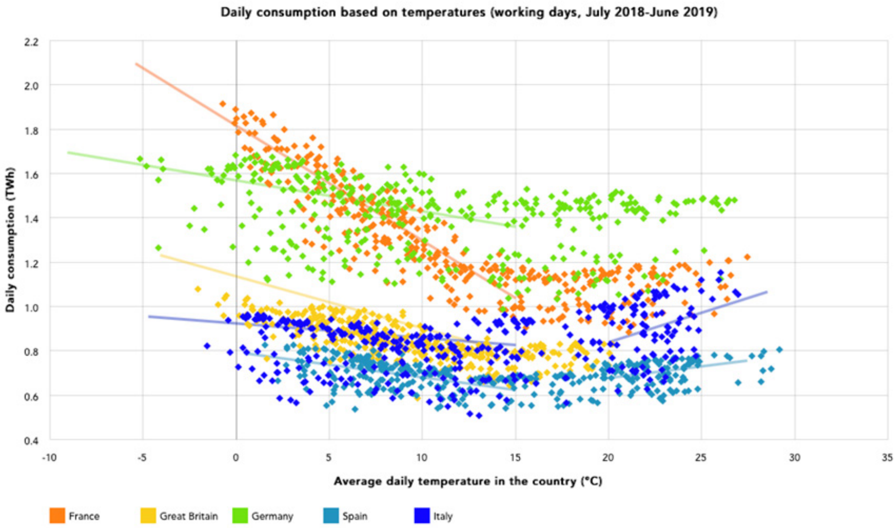

Figure 3.2. Thermosensitivity of electricity consumption in various countries in Europe, in 2019

Source: RTE (2019)

the most substantial sensitivity (about 2 400 MW °C^{-1} at peak time in winter). In contrast, Spain had a much flatter sensitivity curve (RTE, 2019[63]).

In addition, some countries are more sensitive to winter temperatures, like France, where electric heating is well developed. In contrast, countries around the Mediterranean Sea (Greece, Italy and Spain, for instance) have gas-based heating. They are then more sensitive to summer temperatures due to the broader reliance on cooling appliances. In subtropical and tropical regions, the additional meteorological factors, including humidity, solar radiation, near-surface wind and surface pressure (for example, stuffiness of weather under subsidence due to the approach of tropical cyclones) could contribute to the surge of electricity demand during various periods of the day.

No satisfactory physical model exists for demand; therefore, statistical models are generally preferred. Among the most advanced, generalized additive models are widely used. They are easy to implement, do not require substantial computational power, and can be updated and retrained to account for changes in demand patterns or weather model upgrades.

Other models can also be used, such as (multi) linear regression models, autoregressive integrated moving average models or neural networks, depending on the level of accuracy deemed necessary for a particular application and for a specific time range (Suganthi and Samuel, 2012). However, generalized additive models have been widely used in the last few years due to their excellent performance and ease of implementation.

Statistical models require a minimum length of observational demand data for training and validation. As a general rule, it is considered that 5–10 years of hourly data is a sufficient sample. The quality of the training data is critical for the accuracy of the demand model. While some national and regional organizations provide such quality data, they are significantly harder to obtain for developing countries where the data may be available only as pdf files that need stripping.

In addition to the need for long records (minimum 5 years) and high-frequency (minimum hourly) demand data, a recommendation would be to provide a relevant historical period to train demand models when NWP models are upgraded or updated.

Such models are used operationally in many energy utilities for short-term forecasting (Fan and Hyndman, 2012; Goude et al., 2014; Nedellec et al., 2014), but they are also relevant to simulating long time series of

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[63] https://assets.rte-france.com/prod/public/2020-06/bilan-electrique-2019_1_0.pdf.

electricity demand for prospective and climate variability impacts studies (Goodess et al., 2019; Gonzalez et al., 2020; Bloomfield and Brayshaw, 2021a, 2021b; Dubus et al., 2021).

Daily, weekly and seasonal cycles strongly influence demand cycles. Hence, demand forecast models need to consider calendar data such as the hour of the day, the day of the week (weekday or weekend), the position of the day in the year (as an indicator of the season) and holidays (bank holidays and seasonal holidays, when demand is significantly smaller due to lower economic activity). In most countries, the demand dependence on calendar data is the main driver of the demand pattern.

The second key aspect in countries with marked climate variations is air temperature, due to electric heating and cooling in the residential and commercial sectors. In addition to the instantaneous temperature, a running average over a few days allows the inertia of buildings to be accounted for.

Cloud cover or solar radiation is also necessary, as sky brightness controls illumination inside buildings and the need to switch on/off the lights. Cloudiness has a secondary effect. Clear-sky days in winter will allow solar radiation to heat the inside of buildings through windows (a kind of greenhouse effect), whereas this effect will not happen on cloudy days (Apadula et al., 2012). Solar radiation may also play an important role in modelling the impact of embedded/behind-the-meter solar generation on the observed electricity demand.

More marginally, other variables can be considered to refine demand models, such as wind speed (through its cooling effect on buildings) and relative humidity.

The complexity and number of input variables of demand models depend on the lead time of the forecasts or long-term projections. For the latter, some variables are well represented or even unavailable in climate projections, for example, relative humidity (this variable could be derived if dewpoint temperature, alongside the standard temperature, were available). In those cases, the demand model needs to be simpler and should include fewer explaining variables than short-term forecasting models.

3.2.2 Power generation modelling

3.2.2.1 Hydropower

Hydropower generation represents a significant share of the global electricity generating capacity. In principle, it is enough to know the plant's characteristics and the water inflow at its location to calculate the power output at the local scale.

However, plant characteristics (location, installed capacity, head height and turbine characteristics) are not always publicly available or might be challenging to collect, notably because some countries have hundreds, if not thousands of plants. Moreover, actual power generation data and inflows are not systematically available for each plant, often due to competition reasons among plant operators; this poses issues for the validation of models and their calibration in the case of statistical models. The same problem also arises for more aggregated models that calculate the hydropower generation at the watershed, regional or national levels.

In addition, while river flow observations refer to actual data, the same quantity from hydrological models generally corresponds to natural inflows, also called unregulated inflows. These are the inflows that would be observed in the absence of artificial reservoirs or any human activities along the river (for energy generation, but also, for example, in water use for agriculture).

When accurate modelling of the hydropower generation is not available, or when the information is necessary only at a regional/national aggregation level, common practice is to use statistical models that establish a relationship between relevant climatic and hydrological variables with the power generation. In most cases, energy users are more interested in inflows expressed in energy units (for example, megawatt-hours), namely the equivalent energy that could be produced from the available water.

Some statistical models use air temperature and rainfall as the primary predictors. In mountainous regions, the addition of snow-related variables (for example, snow depth or snow water equivalent) is particularly interesting. It provides a proxy for the amount of water (stock) that will melt in spring when the temperature rises (Zampieri et al., 2015). But some climate models do not provide this variable or have significant biases (for example, climate projections). They can likely have non-systematic errors due to the limited predictability of climate models with a lack of sufficient resolution and model physical processes.

Alternative methods can represent the snow stock effect on the annual inflows. This can be done, for instance, by using lagged temperature and rainfall over a few weeks/months (Ho et al., 2020). In principle, the run-off or the river discharge variables from a hydrological model could be used as an additional predictor(s) to these statistical models.

Whenever available, unregulated river flow has an attractive added value as it is more directly related to energy inflows than the air temperature and rainfall alone. For instance, the JRC-EFAS-Hydropower model and dataset (De Felice, 2021) contains the weekly hydropower inflow of pure storage plants and the daily run-of-river generation for 27 European countries. The dataset is based on the river discharge provided by the C3S European Flood Awareness System (EFAS[64]) and on the JRC Hydropower Database (European Commission JRC, 2019[65]). The latter contains the coordinates and some technical information of a large sample of hydropower plants in Europe. Even if it is not exhaustive, the selection covers many plants that allow the country's hydropower generation to be represented reasonably well. C3S EFAS has been used to simulate what hydropower would have been in European Union countries from 1991 to 2019. Future updates might include projections for the future based on climate projections.

3.2.2.2 Wind power

Wind power generation from wind turbines is a highly non-linear conversion process. It varies as the cube of wind speed; therefore, power output estimation is sensitive to wind speed measurements and forecasts errors. In addition, many other parameters are also important, from the atmospheric variables to wind turbine characteristics. On the meteorological side, and depending on the level of accuracy required, atmospheric stability, level of turbulence, air density and the like can also be important. On the technical side, the way the turbine shuts down when the wind speed reaches the cut-off speed (the speed at which the turbine generator is disconnected to avoid failures) is important, as well as the losses due to the vicinity of other turbines.

Depending on the time and geographical scales of interest, wind power conversion models can go from simple approaches considering, for instance, a simple cubic relationship (Tobin et al., 2014) to intermediate complexity models (Saint-Drenan et al., 2020) that consider a limited number of parameters in addition to wind speed, to complex systems mixing NWP, real-time data (weather and power) and artificial intelligence/machine learning techniques. While a linear regression between country average wind speed and wind power production might be sufficient to represent seasonal variations, short-term forecast generation requires much more accurate modelling, including a proper representation of orographic effects.

The accuracy of wind power models has been the subject of abundant literature and is not within the scope of this chapter. However, forecast accuracy is highly dependent on the details and complexity of the wind power conversion model used to calculate the generation and on the wind speed data it considers.

State-of-the-art short-range wind power forecasting systems blend physical and artificial intelligence models to produce the best forecasts for each time frame (Bessa et al., 2017; Haupt et al., 2020; Kosovic et al., 2020; Bastani, 2021). These systems require observational data (in real time and historical) to build and validate the approaches. Such observations can be from surface observations, such as from meteorological towers at the site or nearby, or anemometers on top of the wind turbine's nacelle.

However, when available, hub height wind measurements are generally not easily accessible, mainly due to competition issues among wind farm operators. Therefore, approximations have to be made, for instance, by applying a power or logarithmic law to extrapolate wind speed from standard meteorological measurements (at 10 m) to the necessary height. This introduces uncertainties in estimating the wind power output, which could be reduced by making available more data at the relevant heights.

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[64] https://www.efas.eu/en.

[65] http://data.europa.eu/89h/52b00441-d3e0-44e0-8281-fda86a63546d.

The physics-based models leverage the results from the NWP models described in Chapter 2. Models run by national centres for the region of interest and specially configured models for the vicinity of the wind plants are helpful and recommended, depending on the scope and scale of the prediction effort. Even in this type of application, artificial intelligence is emerging as an innovative addition to more traditional wind power forecasting. Uncertainty forecasting with probabilistic methods is also emerging for high-wind penetration areas, especially for high-speed shut-down predictions, ramping reserves and unit commitment applications.

Recommended practices for the implementation of renewable energy forecasting solutions have recently been published (Möhrlen, 2022[66]). These address the issue that many current operational forecast solutions are not properly optimized for their intended applications. Hence, the IEA documentation recommends: (i) maximizing the value of renewable energy forecast information in operational decision-making applications and (ii) reducing the cost of integrating large amounts of wind and solar generation assets into grid systems through more efficient management of the renewable generation variability.

Longer timescale studies aimed at assessing multiannual to multidecadal climate variability effects on wind power generation generally consider simple to intermediate complexity conversion models (Stafell and Pfenninger, 2016; Gonzalez et al., 2020; Bloomfield and Brayshaw, 2021a). Reanalysis datasets and climate projections have significant biases in surface wind speeds. These biases can seriously affect the power output estimation due to the non-linear relationship between wind speed and power. Progress on this aspect will again come from developing wind measurements at turbine hub height and the direct provision of wind speed at the corresponding levels from standard model outputs.

3.2.2.3 Solar power

Solar power generation is now dominated by PV technologies worldwide (REN21, 2021), mainly driven by strongly decreasing costs over the last decade. PV energy is produced either from plants of significant size or by smaller installations on rooftops, car parks, and industrial and commercial buildings. Like for wind power, various conversion models exist, depending on the time and space scales under consideration. While simple models like linear regression can be sufficient to model PV power at a country level on monthly timescales, more accurate and detailed models are necessary for localized areas and/or shorter timescales.

Prediction of solar radiation and PV power from small installations presents a specific challenge, as it is key to allowing a smoother integration of renewable energy into electricity grids. Ideally, all relevant variables would be collected from each installation to accurately describe the specific system parameters and attempt a detailed solar power prediction for each system.

However, this would be a costly, time-consuming and essentially impractical approach since a variety of features characterize PV installations: (i) PV technology, (ii) inverter type and technology, (iii) panel orientation (including accounting for tracking devices), (iv) shading (which can depend on variables such as solar zenith angle, but also the changing nature of obstructions) and (v) efficiency of the PV panels (dependent on the type of installations, whether free-standing or roof integrated systems, as well as on weather conditions, such as air temperature and wind speed).

Therefore, it is apparent that a deterministic approach to urban or regional PV power forecasting is impractical. Practical strategies for predicting solar power at an increasing level of approximation are thus sought. Such approaches will have to consider PV system aggregation to differing degrees (Pierro et al., 2016, 2017). Sometimes, these approaches are called upscaling. Prediction is derived for a small sample of PV systems, which is then used to infer the behaviour of analogous PV systems over a broader area.

Many attempts at predicting solar power at urban and/or regional levels have been made. Among these, the pioneering work done by Lorenz et al. (2008, 2011) modelled PV installations from a small region in Germany to derive solar power predictions over most of Germany, using solar irradiance forecasts from an NWP model and PV installation information available through power authorities and/or power companies (Lorenz et al., 2014; Chen and Troccoli, 2016).

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[66] https://www.sciencedirect.com/book/9780443186813/iea-wind-recommended-practice-for-the-implementation-of-renewable-energy-forecasting-solutions.

Although specific details of each system are not required, this method attempts detailed descriptions of PV system characteristics, such as the efficiency of PV generators or the module temperature, which are derived using parametrized models. The temporal horizon of their prediction, essentially determined by the irradiance forecast, is from 1 hour to 3 days ahead.

More recently, IEA Task 16 on solar resources for high penetration and large-scale applications launched activity 3.2, dedicated to this aspect (Pierro et al., 2022). It aims to represent better the PV power generated at a local scale and its variability. This will be necessary to better integrate PV energy into the distribution and transport grids.

Box 3.2 provides a good example of power generation and demand modelling under heatwaves in southern Europe.

3.2.2.4 Thermal power

Existing and future thermal power plants, including nuclear, also depend on climatic factors. Their cooling systems rely on water (from the sea, rivers or lakes) or the atmosphere (for those plants equipped with air cooling systems). The former cooling systems require information on coastal SST or river flow and temperature. Air cooling systems require information such as air temperature and relative humidity, turbulence intensity or atmospheric stability.

Each plant may have a specific design that makes it challenging to have a generic model for thermal power plant cooling. Moreover, there are rules – defined to protect local ecosystems – restricting the maximum temperature of the water that a cooling system can discharge into a river (Magagna et al., 2019). There are some models available in the literature, for example, that of van Vliet et al. (2012).

3.2.2.5 Small-scale transmission operations

The power transit capacity of a power line depends on air temperature, wind speed (direction and intensity), solar radiation and intensity of the power that transits into the cables. The higher the intensity, the more important the Joule effect, which increases the losses by heat dissipation and expands the lines, which lengthen and move closer to the ground. This can cause electric arcs and therefore risks to the environment and population. Thus, regulatory criteria set the maximum power intensity in the cables, considering the ambient air temperature. The standard approach is to use seasonal values of the maximum temperature. However, a more dynamic approach that would allow variations in the current intensity depending on the air temperature would optimize the line transit capacity. This is known as DLR.

DLR is a promising way to optimize the use of power networks. However, it requires high-resolution and localized temperature, solar radiation and wind speed and direction data to estimate the power capacity from real time to a few hours ahead. Typically, targeted modelling needs to be performed using mesoscale models (resolution of a few kilometres) or even large-eddy simulation models (hundreds of metres).

Similarly, the dimensioning of new infrastructure and adaptation of existing infrastructure requires tailored and complex modelling to provide information on the time evolution of climate-related risks (window of emergence of the risk considering different thresholds, hierarchization of risks and so forth). This is important to the dimension of the new infrastructure so it can operate under future climate conditions. An underestimation of climate change effects may put the system under pressure or even cause damage. But, an overestimation of climate change effects will necessitate unnecessary investments and higher costs to society.

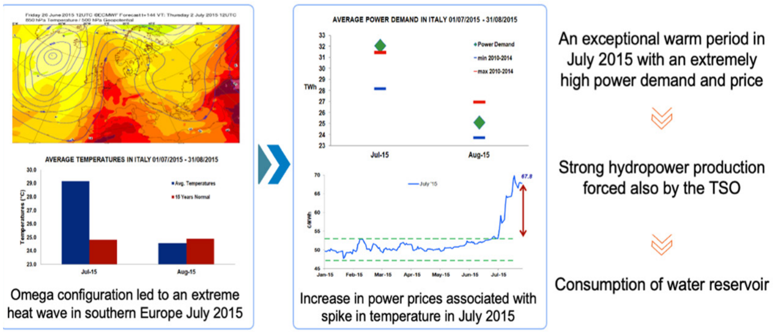
Box 3.3 provides another example of an advanced product based on an energy conversion model that links meteorological data to electricity consumption together with other sources of data.

Box 3.2. Heatwaves in southern Europe and implications for energy generation and demand (case study of the SECLI-FIRM project)

The European Union H2020 SECLI-FIRM project (http://www.secli-firm.eu) aimed to demonstrate how improving and using long-term seasonal climate forecasts can add practical and economic value to decision-making processes and outcomes, in the energy and water sectors. This was achieved though case studies co-designed by industrial and research partners.

The main objective of this case study was to illustrate the benefits of designing adequate decision-support products for the identification of extreme summer heatwaves, which have a major impact on the power system. More specifically, the focus was on how a major energy player like Enel can effectively manage the risks associated with extreme climatic events.

This case study focuses on seasonal forecasts of surface temperature. It explores the skill in predicting extreme summer weather such as that which occurred in Italy in July 2015. Temperatures in Italy in that month were about 5 °C above the previous 15 year average. Figure 3.3 shows the effects of the weather extreme on power demand. In July, power demand reached a value of ~32 TWh, which was above the maximum over the last 5 years. This can be compared to the much lower August power demand when the temperature was close to its climatological value. Electricity price dynamics are associated with air-conditioning demand spikes (net of total renewable production). This is considered in the power price management and hedging of generation portfolio.



Omega configuration led to an extreme heat wave in southern Europe July 2015

Increase in power prices associated with spike in temperature in July 2015

An exceptional warm period in July 2015 with an extremely high power demand and price

Strong hydropower production forced also by the TSO

Consumption of water reservoir

Figure 3.3. (Left) meteorological conditions, (right) power demand and prices and (right) consequences of the July 2015 Southern European heatwave

Source: SECLI-FIRM (2021b)

The ECMWF single model seasonal forecasts and a multimodel combination of four different models (from ECMWF, Météo France, DWD and the Met Office) were assessed for 1, 3 and 5 months before July 2015. The seasonal forecasts of 2 m temperature, total precipitation and 10 m wind speed were spatially aggregated on Enel geographical domains of interest and used as input for Enel internal econometric models. In addition, econometric simulations using multi-year monthly climatologies (1993–2014) and actual values – spatially aggregated over the same areas – were computed to obtain a base case scenario and a "perfect forecast" scenario. The former represents Enel's current use of the seasonal forecast. The latter is used as a benchmark for testing the performance of the seasonal forecast.

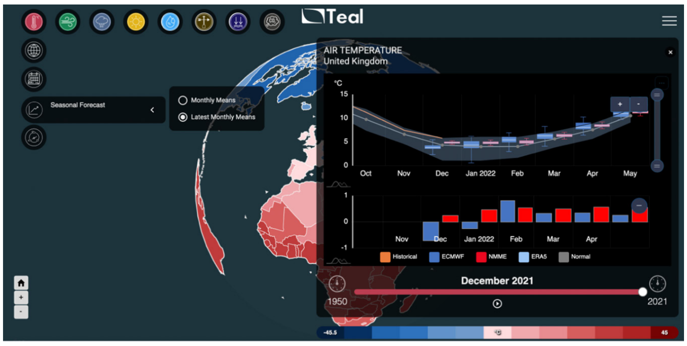


Figure 3.4. Teal's representation of seasonal forecasts for temperature, displaying two forecast systems, ECMWF and NMME, together with the historical (ERA5) data and range

Note: In the lower part of the graph, anomalies of the two seasonal forecast systems are also displayed.
Source: WEMC (n.d.)*

A performance indicator allows measurement and evaluation of the added value of the seasonal forecast, tailored to Enel's decision-making process. This indicator was computed for the economic output of seasonal forecasts (climatology and actual). The indicator performance reflects the behaviour of weather variables and their sensitivity to the high temperature of July 2015. The results show that when seasonal forecasts indicate the temperature is significantly higher than the climatology, as in the case of this specific event, the performance indicator approaches the "perfect" forecast value.

A simple graphical representation was co-designed to assist with assessment of the seasonal forecasts and aid management decisions. It was based on Teal, an online visualization tool that enables users to explore climate variables for the past 70+ years, for the future (to 2100), and for seasonal climate forecasts on a horizon of 6 months ahead (see Figure 3.4).

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* The public version is available at: https://tealtool.earth.

Box 3.3. Innovative predictive control system for air conditioning at Hong Kong International Airport

Using big data analysis of meteorological data, flight schedules and electricity consumption data, CLP Power Ltd, Airport Authority Hong Kong and HKO co-developed a predictive control system (Figure 3.5) for air conditioning at Hong Kong International Airport to predict cooling demand for the passenger terminal building (CLP, 2022*).

This cooperation made Hong Kong International Airport the first airport in the world to adopt a predictive control system for its air conditioning. With the upgraded chiller system, it can save an estimated 5.1 GWh of electricity a year, equivalent to a reduction of about 1 900 t of CO_2 emissions. The system saves energy, provides a comfortable environment and enhances passenger airport experience.

The project has demonstrated collaboration between the private and public sector in applying energy, operation and meteorological data to achieve carbon neutrality by 2050.

Figure 3.5. Predictive control system for air conditioning at Hong Kong International Airport

Source: HKO

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* https://www.clp.com.hk/content/dam/clp-group/channels/media/document/2022/20220114_en.pdf.

3.3 Identifying gaps and issues

3.3.1 Data gaps

Modelling the relationship between meteorological and energy (output) variables requires high-quality observed data to calibrate and validate the models. The lack of high-quality and gap-free high spatial and temporal resolution energy data is a critical problem for the development of energy models. In particular, high-quality data from renewable energy sources, especially wind and solar, could enable a quality shift for the data assimilation in the state estimations, especially in areas with otherwise rare observations, such s developing countries and offshore regions, as was demonstrated in the EWeLiNE project and the Wind Forecast Improvement Project (WFIP)[67] that fed the IEA recommended practices for the implementation of renewable energy forecasting solutions (Möhrlen, 2022[68]).

The following issues are the most frequent and problematic (cf. section 2.5):

- **Data availability:** Energy data are not always available at the relevant spatial and temporal resolution or may not be available at all. This could be due to the lack of obligation to meter and report the data. The data often exist but are considered strategic to the owning company due to competition issues.

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[67] https://esrl.noaa.gov/gsd/renewable/wfip.html.

[68] https://www.sciencedirect.com/book/9780443186813/iea-wind-recommended-practice-for-the-implementation-of-renewable-energy-forecasting-solutions.

- **Metadata availability:** The accurate description of datasets and their characteristics is essential to identify possible changes in how the data are collected, curated and validated. Metadata are critical to identify and document possible inhomogeneity in the data.

- **Data formats and standards:** Weather and climate data have international standards and common formats defined by WMO and a long history of data sharing among countries. The energy sector is less advanced on this topic, and much needs to be done to achieve commonly agreed conventions. However, good progress is being made with activities under the C3S energy operational service (C3S, n.d.a[69]) or openmod (openmod, n.d.[70]).

Weather and climate data also pose some issues. In particular, the renewables industry is evolving fast, and new data are required regularly. These data are not permanently stored by weather and climate producing centres; changing their practices can take a long time, even if consistent requests by the industry are made. For instance, in the early 2010s, the wind energy industry requested that 100 m height wind speed (and at other heights) were made available in weather forecasts. Still, it took several years before they were eventually routinely delivered. Considering the rising number of wind farms with different hub heights, it would be more than relevant to have wind speed (and wind direction) provided at multiple levels from near ground to elevations of 250 m.

A trade-off between data storage requirements and usability for the energy industry must be found. Routinely computing and storing more levels of wind speed data come with a cost, but so does the need to postprocess limited (10 m) data, including the uncertainties and errors that arise from approximate vertical interpolation laws. From the observational point of view, the WFIP and EWeLiNE projects tested the use of meteorological data from wind farms in NWP model assimilation without success due to a lack of quality, and recommended improving that quality.

Climate projection datasets (for example, PRIMAVERA) generally do not provide hourly data for impact modelling, except for a few model runs. Energy modellers raised the need for hourly data to run their impact models. But changes are slow given that the climate community does not respond to the need. In addition, climate modellers must choose between user requests and storage capacity.

Regarding solar radiation, new panel technology can take advantage of global irradiation, direct irradiation (mainly concentrating solar plants and PV panels with sun-tracking systems) and diffuse radiation (bifacial PV panels). However, the different components of solar radiation reaching the ground are not always available from NWPs and even more so from climate models. Global solar radiation is provided only at daily resolution for forecasts at a lead time longer than the medium range, making it nearly impossible to resolve the diurnal cycle. Although the information content of individual forecasts in terms of solar radiation may be limited, higher temporal resolution data would allow improved statistical analysis such as risk assessments.

3.3.2 Uncertainty about the future

Future management of net zero power systems, including higher flexibility in supply and demand and extensive penetration of renewables, will be different from that of the systems in place today. There are knowledge gaps in modelling the new components that are currently non-existent (for example, bidirectional electric vehicles), and significant uncertainties about the future technologies. What will the efficiency of solar panels be, and what impact will storage solutions have on households and production units? Will new wind turbines behave differently at low and high wind speeds? How will heat pumps evolve, and how will heat decarbonization affect system adequacy (Deakin et al., 2021)? Will thermal power plant cooling systems become more resilient to changes in meteorological parameters and in response to upgraded regulatory obligations?

Uncertainties about the impact of climate change are critical too. These include defining which climate emissions scenarios (RCPs and SSPs) to use with different energy mix scenarios to ensure the assumption of GHG emissions is consistent with the energy mix scenario. For instance, RCP8.5 with a 100% renewables

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[69] https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-energy-derived-reanalysis?tab=overview.

[70] https://openmod-initiative.org.

scenario is irrelevant. This issue is even more accentuated when comparing global emissions scenarios (as used by projection models) with regional policies (for example, the European Union Green Deal). Climate change may also alter wind and solar resources. However, climate scenarios differ significantly only after 2040–2050; in the near future, they are almost indistinguishable from each other (Bloomfield et al., 2021).

Uncertainty also comes from the scalability of renewable energy sources. For example, the offshore wind capacity factor may decrease due to short distances between wind farms and wake effects in strong offshore wind energy development scenarios.

Climate models have made significant progress in quality and in their ability to represent recent past climate. Model evaluation has also improved. However, research is still needed to help users select relevant sub-ensembles among the vast amount of data available. Impact models generally cannot use all the ensembles (for example, CMIP6).

3.4 Bridging the gaps between weather and climate models and energy industry needs

Energy system models run at specific timescales. In most cases, short-term forecasting is done at a 1 hourly time step, but finer time steps are now common in many energy markets. In Europe, the standard reference time step is 1 hour, but several countries have already shifted to 15 minutes and 5 minutes (as in Australia), which is likely to become the norm within the next few years. As more variable generating capacity is integrated into the grid, electricity prices will probably become more volatile (Green and Vasilakos, 2010).

For adequacy studies (supply/demand balance), the appropriate time step is that of energy markets, currently 1 hour, but most likely less in coming years. These studies aim at assessing the operating conditions of power systems 10–30 years in advance. Therefore, there is a large gap between the needs and the available climate data from climate projections, which currently are 3 hourly at best, with a few exceptions. Until 1 hourly data become routinely available, temporal interpolation methodologies need to be developed, keeping in mind that a relevant representation of the high-frequency variability from a statistical point of view is required.

The study of future energy systems will require new data that are often not or only partially available from climate projections, like, for example, direct solar irradiation, relative humidity and river temperature. There is growing recognition of the need for time-synchronized wind, solar and demand data for future adequacy studies. The impacts of climate change need to be factored into the analysis, as do the magnitude and frequency of weather events. There should be close collaboration among the energy industry, climate scientists and service providers, to identify the gaps, define priorities and propose pathways to reach the necessary targets.

An essential application of weather data in the energy sector is for capacity expansion models (CEMs) (Pierro et al., 2021; Prina et al., 2021). CEMs are used for long-term energy system planning (10–30 years ahead), calculating the optimal combination of electricity generation/storage technologies and transmission assets needed to meet future energy demands under various input variables and system constraint scenarios. These will include future projections of energy generation capital/operational and levelized costs for energy technologies and policy constraints (for example, 50% renewable target or 80% carbon emissions abatement target). CEMs are used, for instance, in the IEA Energy Technology Perspectives series (for example, IEA, 2020a[71]), National Renewable Energy Laboratory work for developing countries (Blair et al., 2015[72]), modelling for the Government of the United Kingdom of Great Britain and Northern Ireland (Department for Business, Energy & Industrial Strategy, 2020[73]) and the Australian Energy Market Operator's Integrated System Plan (AEMO, 2020[74]).

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[71] https://www.iea.org/reports/energy-technology-perspectives-2020.

[72] https://www.nrel.gov/docs/fy16osti/64831.pdf.

[73] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/943714/Modelling-2050-Electricity-System-Analysis.pdf.

[74] https://aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en.

CEMs require input regarding the potential output of renewable energy generation technologies (wind power, solar power and hydropower) in the form of time series of short-term (for example, hourly) variability at a range of locations within the energy system domain. CEMs generally use typical meteorological years based on data from the past. In addition to not being a good choice to consider interannual variability, typical meteorological years cannot, by definition, consider the effects of future climate change.

Owing to computational constraints, CEMs often even use a subsample of a full calendar year of weather data as inputs (for example, a week from each season), to expose the optimization to different combinations of wind and solar resources and demand profiles. The models will then determine, often using linear programming techniques, the minimum requirements of the capacity of wind turbines, solar PVs and other generation technologies, and transmission upgrades and augmentations so that the future demand projection can be securely met.

Using the optimization technique, a CEM searches the solution space for combinations of multiple technologies distributed over the domain to maximize the benefits of spreading out variables of large geographic regions while simultaneously trying to minimize transmission costs. A third dimension also calculated is the appropriate amount and location of storage technologies (for example, lithium-ion batteries and pumped hydro energy storage).[75]

Weather data for CEMs is often derived from climate model reanalyses at an appropriate spatial resolution such that the temporal and spatial variability in the time series of wind and solar resources is closely representative of that in the real world. With climate change, it becomes increasingly important to develop similar datasets based on climate projections rather than historical climate information.

4. DELIVERING WEATHER AND CLIMATE SERVICES THROUGH CO-PRODUCTION APPROACHES

Interactions and engagement among all relevant actors are crucial in all stages of the value chain of W&CSs for the energy sector (cf. Chapter 1, particularly Figure 1.9). They are critical to understanding context, building partnerships, co-exploring needs, co-designing and co-developing products and/or solutions in a W&CS, as well as co-evaluating it. They are also crucial for effective implementation of weather and climate solutions in support of the net zero emissions target, in terms of adaptation and mitigation.

This chapter describes some approaches, methodologies and concepts in delivering W&CSs through co-production approaches that emphasize user engagement and close cooperation. These approaches need to be adapted to context, geography and specific user needs, and may vary depending on the climate and/or weather service at hand, its maturity and its audience (for example, based on the sector or experience).

This chapter starts by providing an understanding of what it is meant by co-production. It then looks at relevant actors and their engagement, before describing in more detail the co-production process and principles. It concludes with suggestions for assessing the co-production process and its outcomes.

4.1 Co-production

The notion of co-production is underpinned by a shift from top-down creation and transfer of knowledge from producer to user to knowledge creation that is “socially robust and thereby more readily applicable for addressing real-world problems in a given context” (Taylor et al., 2017). Co-production thinking argues that to meet these scientific and social robustness requirements, the boundaries between science, policy and practice need to be better understood and then, if needed, be crossed or transgressed based on deep

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[75] See initial studies about co-optimizations of generation, storage and transmission (Huva et al., 2012, 2016).

engagement and collaboration between all relevant actors, that is, those traditionally operating inside, outside and between science, policy and practice (Taylor et al., 2017).

Thus, co-production can be understood as the process of producing usable, actionable knowledge through collaboration among knowledge producers, intermediaries and those who use knowledge to make decisions. These decisions may span personal choices, and organizational, management and policy decisions.[76] Co-production processes are based on sustained collaboration among these actors to produce useful, actionable and socially robust knowledge (Goodess et al. (2019), based on Meadow et al. (2015) and Beier et al. (2016)).

The concept of co-production first arose in public service administration in the 1970s, and has become prevalent in the field of sustainability since the early 2000s. Co-production aims to ensure a user-driven approach rather than a more traditional data-driven one. This can be achieved by overcoming barriers presented by top-down decision-making processes, increasing efficiency and effectiveness, and improving legitimacy by establishing a sustained dialogue among stakeholders.

Co-production approaches are designed to help overcome impediments to the uptake of W&CSs, including the following (Briley et al., 2015; Rubio-Martin et al., 2021):

- Lack of awareness of stakeholders to their vulnerability to climate change and related changes in meteorological conditions
- Perceived low priority of weather and climate change impacts in activities compared to other issues
- Lack of user trust towards either the weather and climate information or the producer of the service
- Differences in language and terminology between producers of weather and climate information and stakeholders, resulting in lack of understanding
- Lack of clarity in problem identification in possible W&CS solutions
- Heightened user expectations about the service, not in line with provider capabilities
- Inappropriate delivery (in content, format and/or approach) of the W&CS
- Adoption of an inadequate business model by the service provider (see Chapter 5)

To better understand the processes underlying the co-production of climate services, Bremer et al. (2019) identified different perspectives from which they conceptualized a model of co-production. This model comprises eight complementary lenses through which the co-production of climate services and climate science can be viewed, as summarized in Table 4.1. Co-production may not neatly fit into one of these lenses, but may encompass several complementary perspectives.

The different perspectives described by the co-production lenses in Table 4.1 also indicate that co-production varies in accordance with context, people involved, purpose of the co-production process, funding, time and resources available (Carter et al., 2019). Carter et al. (2019) suggest looking at co-production approaches along a co-production spectrum, which ranges from consultative to immersive. At one end of the spectrum, the consultative process is predefined, based largely on consultation and static. The immersive end of the spectrum provides flexible and iterative approaches that are open to input from all engaged actors. Levels of engagement among relevant factors are discussed in more detail below.

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[76] This is a wider definition than that of Meadow et al. (2015), to include knowledge producers outside of science and decisions outside policy and management. See also Weichselgartner and Arheimer (2019).

Table 4.1. Perspectives on co-production processes in climate services (analogous considerations apply for weather services too)

Perspective	*Description*
Constitutive lens	Exploring the relationship between climate services and long-held ideas about weather and seasons and how these affect user acceptability of the solution(s), as well as the impact that climate services have on redefining local understanding of the climate and climate action.
Institutional lens	Understanding and mobilizing the institutional and governance capacities, experience, expertise and resources needed as inputs required to co-produce climate services as well as any impacts on these.
Interactional lens	Understanding how the context in which climate services are produced and used is shaped by institutional structures, processes, interactions, cultures, sociopolitical processes and legal frameworks; and how institutions are affected by climate services as well as the co-evolution of markets for climate services with the political, legal and socioeconomic systems.
Joint services lens	Understanding the context for developing new climate solutions by, and any linkages among, public and private markets in the co-evolution and provision of climate services, as well as any issues related to trust including use of public data for profit and impact of climate services on traditional public services such as weather forecasts.
Empowerment lens	Exploring how to engage stakeholders meaningfully throughout the product life cycle (joint design, production, evaluation and use of climate services), how to integrate non-scientific knowledge with scientific knowledge and how to assess the impact of climate services on other knowledge systems such as traditional or local knowledge.
Pedagogical lens	Identifying any hindrance to understanding and use of climate services among user groups, perceived knowledge gaps, and opportunities for learning and capacity-building.
Interactive research lens	Fostering collaboration and dialogue among various actors to ensure successful co-production of high-value, high-quality solutions.
Extended science lens	Exploring scientific processes that involve diverse criteria of knowledge quality and value such as citizen science and taking into account ethical issues related to climate services.

Source: Adapted from Bremer et al. (2019)

4.2 Actor interactions and engagement

While it is possible to develop W&CSs without involving all relevant actors, co-production is recognized as a key element in the development of useful, usable and used climate services (Vaughan et al., 2018). Broadly, co-production relies on three groups of actors (Carter et al., 2019[77]):

- **Knowledge producers** create weather and climate data and information (see Chapter 2). Through active engagement with users and intermediaries, knowledge producers can ensure they are providing the most usable, useful and used knowledge, thus enabling successful uptake of W&CSs. Knowledge producers may include: NMHSs; researchers; private sector knowledge producers; and national, regional and global climate and atmospheric research centres.

- **Intermediaries** support interaction and engagement between producers and users. They act as connectors, or knowledge brokers, in co-production. These actors may have a good overview of the stakeholders,

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[77] https://futureclimateafrica.org/coproduction-manual.

processes and institutional settings in which the W&CSs are to be co-produced. The role of these actors is to create linkages and ensure meaningful interactions among actors, enable a common language and understanding, facilitate knowledge exchange and support the co-production process (see section 4.3) (Carter et al., 2019). Intermediaries may include sectoral experts, NGOs and advocacy groups, international cooperation programmes, extension services, social scientists, and public engagement and communication experts.

- **Users** at local, national and international scales, defined as individuals or organizations that benefit from access and use of weather and climate information (Carter et al., 2019). This is a diverse group who will act based on the information provided by the knowledge producers. Users may also be intermediaries of producers of knowledge. Engaging with users of W&CSs and understanding their needs is paramount to fruitful co-production. It is essential, together with users, to identify and understand the decisions the service can address.

Table 4.2 describes some of the key actors engaged in W&CSs for the energy transition in support of the net zero emissions target and their focus areas, according to the broad categories presented above. While each actor in the table is placed under one of these groups, there is some fluidity and overlap among them. For example, research institutions can act as knowledge producers and intermediaries, and government ministries can be either intermediaries or users. This will depend on the context of co-production, and the needs and abilities of the actors involved, as discussed in more detail in section 4.3. While the creation of useful, usable and used W&CSs, in principle, necessitates the interaction of all three categories, this is not a strict requirement. In particular, a W&CS could simply be created by either a producer or an intermediary and presented to the user as a “finished” product. However, it is likely that lack of consultation with users, the ultimate beneficiaries of W&CSs, will lead to useless, unusable or unused W&CSs.

Table 4.2. Main actors and their roles in uptake of W&CSs for energy transition

Actor	*Key roles/functions*
Knowledge producers	
Meteorological services	Producers of some or all among the following information that may be used for W&CSs: (i) quality historical and real-time meteorological data (including collection and archiving) and (ii) short-term to medium-range weather forecasts (sub-seasonal, seasonal and decadal), climate forecasts and climate projections (including issuance and verification). May also develop new science.
GPCs and RCCs	Support collection of data and development of new science, models and products. Issue and verify climate forecasts and/or climate projections.
Private sector providers	Collecting data (for example, ground station observations) and/or create relevant knowledge, tools and products to help their energy sector users manage operations and risks. May include private companies specializing in meteorology and internal groups within large energy or insurance companies.
Research institutions	Science agencies within government, research institutes or universities that produce new data, models, portals, impact analyses or other research outputs. Can enable development, refinement and documentation of energy or climate-related data, and can also act as an intermediary.
Intermediaries	
Government ministries	Advise on barriers and opportunities for the uptake of W&CSs in support of the energy transition, and can provide sector-specific knowledge of stakeholders, policy and legislative requirements and needs. Include environment, energy and business/trade ministries. May also be users of W&CSs, if tailored to their needs, for instance to inform policymaking.

Actor	*Key roles/functions*
Local authorities	Can facilitate access to other key actors, remove barriers to the uptake of W&CSs and net zero projects, and utilize W&CSs for their own operations, planning and engagement activities. Can act as intermediaries or users of W&CSs. Instrumental in planning processes, for example, for renewable energy projects.
NGOs	Not-for-profit organizations that conduct work in the climate change, climate services and/or energy spaces. Can provide advocacy, communication, outreach, education or other areas related to climate services and/or energy transition.
International cooperation activities	Provide practical guidance to users, often through close interaction with them, on the best use of weather and climate data, and compile user manuals. They also propose industry standards.
Energy/climate consultancies	Provide expertise in W&CSs, energy transition and/or co-production processes. Can act as either intermediaries, knowledge producers or both.
Local forecasters	Are familiar with local weather and climate conditions and can provide context-specific insights with regards, for example, to best placement for new renewable energy facilities.
Communicators and media organizations	Important for communicating weather and climate information to users. Can help raise awareness to the needs for and uses of W&CSs, highlighting their benefits and practical applications, as well as co-production processes.
Users	
Energy companies	Support decision-making in the production, provision and/or distribution of energy by using W&CSs. Their needs are diverse and range from operational decisions to strategic planning to trading.
(Re-)Insurance companies	Use W&CSs to support hedging and risk transfer decisions, by reducing volatility, to help increase energy systems resilience and prepare towards climate change impacts.
Project developers	Responsible for full range of low-carbon energy project development and are engaged in securing land rights, interconnection rights, permits, tax agreements, or other agreements and contracts for building energy projects and so forth. May use W&CSs for evaluating a range of projects (for example, wind, solar and wave projects at various sizes), using data about energy resources, climatological and meteorological conditions to assess feasibility, economic viability and climate resilience.
Investors	May include those with business backgrounds who invest in energy projects. Evaluate the return on investment of energy projects and invest in new energy projects. Will likely be mostly interested in risk exposure and climate resilience of proposed low-carbon energy projects.
General public	Consumers of science information, weather and climate forecasts and impacts on public health, daily life, cost savings and energy security. May benefit from W&CSs to monitor and/or manage their energy production (typically rooftop PV panels), demand and climate risk exposure.

Frameworks for user engagement

There are various theoretical frameworks that inform the types, extent, frequency and motivation of user engagement strategies (also known as participatory processes).

User- or human-centred design is a process often used in commercial product development to incorporate users and their needs in the design of a product, service or offering. Various investigative and generative methodologies are utilized to understand user needs, including surveys, interviews and brainstorming, so that solutions are purpose built to suit specific needs.

Design thinking similarly focuses on the user during design so that feasibility, visibility and desirability are equally considered when creating solutions. IDEO, a global design company, is often credited with inventing this term though similar processes have been utilized since the early 1900s to improve engineering practices (IDEO, n.d.[78]).

Both approaches emphasize that with closer user involvement, a service or solution is more likely to meet user expectations and needs. Within these frameworks, there is a general process, refined for research purposes, that begins with understanding the problem, empathizing with users, defining needs, conceptualizing solutions, developing prototypes and testing results (Pontis, 2015[79]).

Various levels of engagement may be applied to enable successful co-production. The specific approach depends on the most appropriate level of engagement and also on what is achievable and attainable. As illustrated in Figure 4.1, these levels of engagement range from passive, through interactive, to active engagement through focused relationships (Hewitt et al., 2017[80]):

- **Information provision** aims to provide potential users with relevant information through passive engagement (mostly one sided). This may include websites and web-based tools, as well as other information dissemination materials, such as leaflets, posters and noticeboards, particularly in places with limited Internet access. This level of engagement may be most suitable when users need to be informed of W&CSs, but not actively engaged in co-production.

- **Interactive dialogues** rely on multiway communications and include building trust, co-learning and co-producing. This level of engagement is more interactive and is based on continued dialogue among intermediaries, users and producers of W&CSs. It may be most suitable when the service to be co-produced includes numerous actors and aims to build a public/generic service (for example, co-production of the C3S European Climatic Energy Mixes (ECEM) Demonstrator[81] and documented by Goodess et al. (2019)).

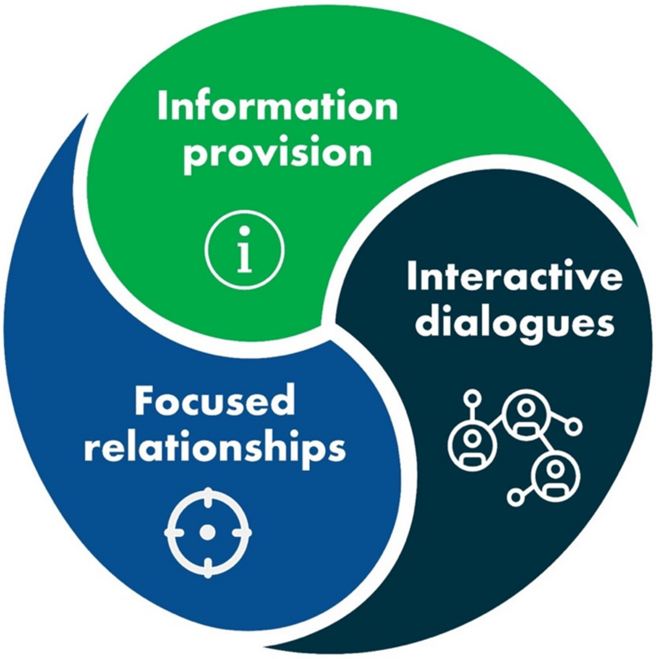

Figure 4.1. Levels of actor engagement

Source: Adapted from Hewitt et al. (2017)

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[78] https://designthinking.ideo.com/history.

[79] https://sheilapontis.com/2015/06/04/design-thinking-revised.

[80] https://doi.org/10.1038/nclimate3378.

[81] http://ecem.wemcouncil.org.

- **Focused relationships** include either one-to-one or small group contact. They enable highly active, iterative engagement to provide an in-depth understanding and tailoring of bespoke services, as well as building lasting trust and client relations. These may be more appropriate when tailoring W&CSs to commercial and/or confidential user needs (for example, case study developments under the European Union SECLI-FIRM project[82]).

Table 4.3 presents some of the participatory tools typically used to achieve effective user engagement.

Beyond the example activities listed in Table 4.3, there are additional considerations to include when engaging stakeholders. First, it is important to ensure the appropriate stakeholders within the three categories (producers, intermediaries and users) are identified, invited and included in the conversations. Stakeholder mapping and analysis can be used for this purpose. Second, within targeted stakeholder groups and/or organizations, the importance of engaging champions, or early adopters, is key to enabling successful co-production. These individuals need to be committed and have time to drive engagement and co-production forward to allow the network to evolve and expand over time. Third, the commitment of time and resources to these efforts should not be underestimated, and adequate resources should be allocated in advance. Fourth, including partnership and stakeholder engagement experts from the outset may help remove many obstacles and barriers along the way. Moreover, thinking about system integration and seamless approaches to co-production of W&CSs may support improved user acceptance and uptake.

Table 4.3. Examples of participatory tools in support of user engagement strategies

Participatory tool	*Description*
Participatory workshops and roundtables	Activities during which stakeholders of varying backgrounds or sectors may be brought together to an in-person or virtual space to co-develop a W&CS. Can be enhanced using expert facilitators, including cartoonists for scribing (for example, the European Union EUPORIAS project climate service principles (Buontempo et al., 2018) and the C3S ECEM project (Goodess et al., 2019)).
Consensus-building activities	Activities that allow stakeholders to assess an issue or proposal and work together to find a common ground, identify possible solutions and deliver a consensus-based plan. Can take place during stakeholder workshops.
Charrettes	Activities that help develop new climate solutions and any linkages between public and private markets in the co-evolution and provision of climate services, In addition, activities related to trust, including use of public data for profit and impact of climate services on traditional public services such as weather forecasts.
World cafés	Activities that allow stakeholders to better understand how the context in which climate services are produced and used is shaped by institutional structures, processes, interactions, cultures, sociopolitical processes and legal frameworks. In addition, activities that look at how institutions are affected by climate services as well as the co-evolution of markets for climate services with the political, legal and socioeconomic systems.

Table 4.4 presents the matrix underpinning the ECEM stakeholder engagement. The target audience for the purposes of the stakeholder engagement plan can be divided into four main groups with differing objectives and engagement methods. These groups, subdivided in terms of their differing technical and policy expertise, and the related likely specific interests in the ECEM Demonstrator, are: (i) energy companies, TSOs and distribution system operators (DSOs) (strategic level); (ii) energy producers, TSOs and DSOs (technical level); (iii) national and international organizations (strategic level); and (iv) climate and energy service providers. The main message at the strategic level is to raise the project profile and ensure involvement and at the technical level to incorporate user requirements into the design of the demonstrator.

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[82] http://www.secli-firm.eu/case-studies.

Table 4.4. Stakeholder engagement matrix

Category	*User (who?)*	*Engagement objective (why?)*	*Message (what?)*	*Method of communication (how/ when?)*	*Communi-cation tools*	*Evaluation method*
Energy producing companies, TSOs, DSOs	Technical experts	To ensure the demonstrator is directly relevant to the energy sector	Awareness of project Need to identify detailed parameters for the demonstrator Input into the development of climate variables, energy indicators and the demonstrator	Direct contact and 1:1 meetings Specifically, SH WSs eliciting priorities and requirements and energy mix scenarios during breakout groups	SH WSs, PowerPoint presentations, webinars/ tutorials, flyers, web content, emails, social media	Feedback from SH WSs, online feedback forms, direct queries and surveys
Energy producing companies, TSOs and DSOs	Strategic experts	To raise the project profile to achieve strategic level engagement in the project	The demonstrator will facilitate better infrastructure operations and planning and ultimately improve energy adequacy	1:1 meetings and tailored presentations by project team	PowerPoint presenta-tions, flyers, web content, emails, social media and SH WSs (particularly second half of project) Presentations at conferences and WSs Specifically, SH WS3, WS4 and WS5 reinforcing key features and benefits	Feedback from 1:1 meetings, SH WSs in second half of project and surveys
National, regional and international organizations	Policy experts	To ensure the demonstrator provides useful guidance to policymaking	The demonstrator will facilitate better policy formulation for infrastructure planning and ultimately advance energy security	1:1 meetings and tailored presentations by project team Presentations at conferences and WSs Specifically, SH WSs to reinforce key features and benefits	PowerPoint presentations, flyers, web content, emails, social media and SH WSs	Feedback from 1:1 meetings, SH WSs and surveys
Climate and energy service providers	Private sector service developers	To utilize climate and energy expertise/ knowledge in development of the demonstrator To promote use of the demonstrator	Awareness of project Need to canvas expert views on development of the climate variables, energy indicators and the demonstrator The demonstrator will make the job easier	Existing networks, conferences, abstracts, journals and press releases (for example, from the Press Office)	Press release, scientific posters, abstracts, webinars/ tutorials, web content and social media	Feedback at conferences, networking, direct queries and surveys

Category	*User (who?)*	*Engagement objective (why?)*	*Message (what?)*	*Method of communication (how/ when?)*	*Communi-cation tools*	*Evaluation method*
ECEM Advisory Committee	Sector experts	To provide a sounding board for strategic decisions	Awareness of project Canvas feedback on project strategic decisions	Advisory Committee teleconference meetings (quarterly)	SH WSs, PowerPoint presentations, webinars/ tutorials, flyers, web content, emails and social media	Feedback from quarterly tele-conference meetings

Note: The focus in this table is mainly on the specific expert – the user (second column) – who is key to a successful engagement, more than the industry category (first column). SH = stakeholder; WS = workshop.

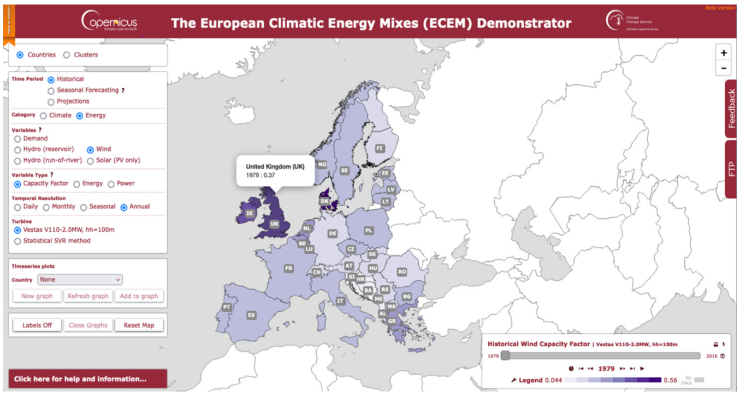
An important consideration when engaging stakeholders is clarity and transparency in the communication. The activities described in this chapter, namely around co-production, are perhaps more relevant for climate services rather than weather services, as the latter are in a more mature development (including commercial) phase for which design and development is typically performed on a one-to-one basis with specific users. Weather services are more established, with several products, datasets, tools and other resources available and known to the field. Still, there is room for engagement and co-production, for example in how to present probabilistic forecasts. This is for instance the case of weather services for public good, as with early warning systems to alert populations of predicted impactful events such as floods or heatwaves.

Given the burgeoning field of climate services, there may be greater opportunities to incorporate user feedback via engagement mechanisms to define challenges and possible solutions. Nevertheless, user engagement can and should occur at any level of maturity of the service, even if periodically, to ensure evolving challenges and user needs continue to be addressed appropriately. Additionally, as available meteorological data, technologies, models or tools change, solutions can also evolve to incorporate data with greater resolution and robustness and better representation of uncertainty. This is important, as new datasets, models and tools are continually developed and frequently shared by knowledge providers (see Box 4.1 for an example of stakeholder engagement performed for the energy sector).

Box 4.1. Stakeholder engagement and gap analysis performed by the C3S ECEM project

The overall objective of the ECEM[*] stakeholder engagement plan is to raise the profile of the project among prospective users of the ECEM Demonstrator[**] (Figure 4.2) and to ensure the technical requirements of the demonstrator are considered in its design.

To produce a relevant and useful user-driven and scientifically robust end-to-end proof-of-concept demonstrator for the energy sector, close engagement with stakeholders to assess their priorities and requirements in the formulation of energy mix scenarios is critical.



● Countries ○ Clusters

Time Period ● Historical ○ Seasonal Forecasting ? ○ Projections

Category ○ Climate ● Energy

Variables ?
○ Demand
○ Hydro (reservoir) ● Wind
○ Hydro (run-of-river) ○ Solar (PV only)

Variable Type ? ● Capacity Factor ○ Energy ○ Power

Temporal Resolution ○ Daily ○ Monthly ○ Seasonal ● Annual

Turbine
● Vestas V110-2.0MW, hh=100m
○ Statistical SVR method

Timeseries plots

Country None

Figure 4.2. ECEM Demonstrator (displaying the wind power capacity factor)

Source: C3S, ECMWF

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[*] https://www.wemcouncil.org/wp/european-climatic-energy-mixes.

[**] http://ecem.wemcouncil.org.

The main technical/policy stakeholder categories identified with the stakeholder engagement matrix can be further subdivided into a more granular structure to help identify gaps in outreaching to prospective users of the ECEM Demonstrator. Table 4.5 presents a gap analysis, with the aim of ensuring ECEM reaches out to as many prospective users of the ECEM Demonstrator as possible. This analysis focuses on the generic products and service to be provided by ECEM as detailed in the note under Table 4.5.

Table 4.5. Stakeholder gap mapping

Category of organization	*Typical capacity (no. of staff)*	*Type of information*	*Geographical coverage*	*Example of stakeholder*
Smaller energy generator companies	<100	Energy data and time series	Cluster	Infinis
Large energy generator companies	>100	Climate data and time series	Cluster, national and international	Enel
DSOs	Varies	Energy data and time series	Cluster	Électricité Réseau Distribution France
TSOs	>100	Climate data and time series	Cluster and national	Red de Transporte de Electricidad
Energy market operators	>100	Climate data, energy data and time series	Cluster and national	National Grid
Energy traders	Varies	Climate data and time series	National and international	RWE AG
Oil and gas exploration and extraction companies	>100	Climate data	Cluster	Shell
Power plant developers	<100	Climate data	Cluster	Energias de Portugal Renewables
Energy infrastructure providers	Varies	Climate data	Cluster	Amokabel
Biofuel producers		Climate data	Cluster and national	Archer Daniels Midland
Power plant operators	Varies	Climate data and time series	Cluster	Siemens
Big energy users	>100	Energy data and time series	National and international	Google
(Re-)Insurance companies	>100	Climate data, energy data and time series	Cluster, national and international	Swiss Re
National policymakers	>100	Time series	National	French Environment and Energy Management Agency
International policymakers	>100	Time series	International	European Environment Agency
NGOs	Varies	Time series	National and international	PlanBleu
Climate and energy service provider	<100	Climate data and energy data	Cluster, national and international	Inside Climate Service

Category of organization	*Typical capacity (no. of staff)*	*Type of information*	*Geographical coverage*	*Example of stakeholder*
NMHSs	>100	Energy data and time series	Cluster, national and international	Met Office
Research institutions	>100	Climate data, energy data and time series	Cluster, national and international	Fraunhofer Institute
Energy communicators	<100	Time series	National and international	Cornwall Energy
Science communicators	<100	Time series	National and international	European Science Communication Institute

Note: Category of organization (first column) is a subclassification of the categories in Table 4.4. Capacity (second column) is the typical size of the organization in terms of number of staff (larger or smaller than 100 people; this is not a critical definer, but it provides a rough guide about process and flexibility to adopt new products/services, particularly with regard to insourcing versus outsourcing. Type of information (third column) refers to the level of technical detail (climate data, energy data or area averaged time series of energy supply and demand). Geographical coverage (fourth column) refers to the size of areas of interest (for example, subnational clusters). Example of stakeholder (fifth column) provides an example of an organization in the given category, mainly for illustrative purposes.

4.3 Co-production processes and principles

Theoretical and practical approaches to co-production vary. However, there seems to be broad agreement among researchers and practitioners regarding the key elements of co-production, which are illustrated in Figure 4.3 (cf. also Figure 1.9). The building blocks of this process can be adapted for use in various contexts and scenarios. In many cases, co-production is not implemented in practice – for instance, in cases when consultations with users do not go into sufficient detail or when user requirements are only partially followed – and it can therefore fall short of meeting user expectations. It is also hard to demonstrate that co-production

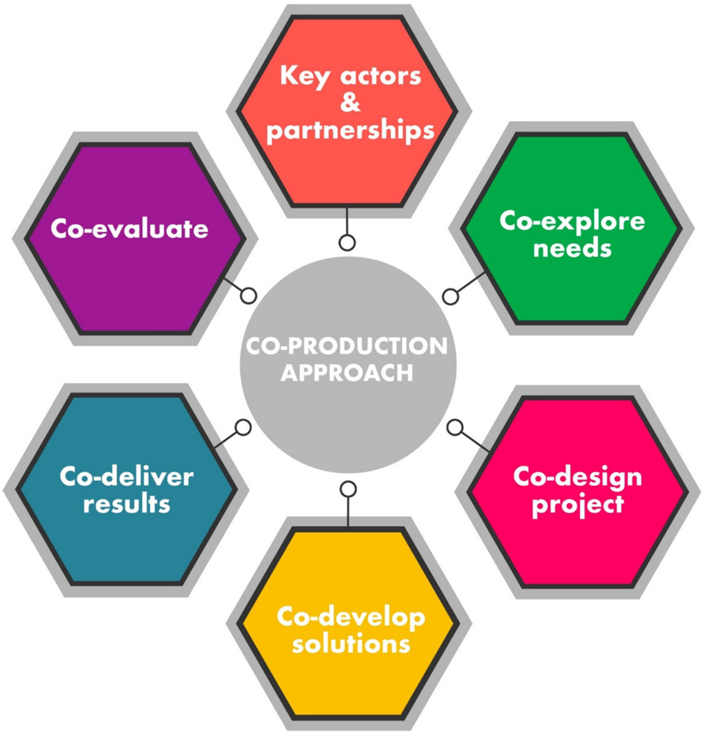


Figure 4.3. Core elements of co-production

Source: Adapted from Carter et al. (2019)

has really been achieved, as discussed in more detail in section 4.4. Thus, the process outlined below can be used to guide co-production and co-evaluation.

Identify key actors, and build partnerships and common ground: Ideally, all relevant stakeholders and potential partners should be included from the onset of the co-production process to ensure its success, inclusiveness and validity. These may include producers, users and intermediaries of W&CSs (as discussed in section 4.2). The selection of actors is dependent on the areas of weather, or climate-related concern, sector and geographical coverage (Carter et al., 2019). Stakeholder mapping can be useful in provisional identification of partners.

Following initial identification and consultation with these stakeholders, other relevant partners may be identified and approached, so they can be included in the process. It is important to understand the relationships among all stakeholders, and their different responsibilities, capabilities, and legal roles and mandates. Additionally, the roles and responsibilities that each partner will play within the team need to be established. It is imperative to ensure a shared understanding of the intention, priorities, process and desired outcomes is developed among all involved stakeholders from the outset. Equally, it is important to enable use of the same language. This includes language barriers, where partners may speak different languages, and also ensuring all partners share the same interpretation of key words and jargon, as some words may mean different things to different people.

Co-explore abilities and needs: Collaboration is key in identifying and understanding the needs of users, abilities of producers and capacity of intermediaries to co-produce W&CSs (Cash et al., 2003). It is important to understand the decisions that need to be made and their overall context (Beier et al., 2016). Actor needs may vary and can be differentiated according to: common needs across sectors and/or locations; differentiated needs by sector and/or location; multiple entry points and types of decisions; and different starting points, capacities and stages of development (Webb et al., 2019; Tart et al., 2020). The top-down approach of simply asking users what information they want does not work. Rather, the process should be iterative. It requires building of understanding and trust through continuous dialogue and negotiations.

To enable successful co-exploration, Beier et al. (2016) recommend users to approach knowledge producers with a need, goal or problem, rather than request a product. Likewise, they suggest knowledge producers should ensure they understand the decision to be made and its context. They also recommend all partners to invest in at least one in-person (or in today’s reality, online) meeting to specify the types of decisions to be made and the information needed to support those decisions. This process enables knowledge producers to better understand the decision context, user needs and risk management approaches. It also allows users to understand what information and knowledge are available, limitations to their use and analysis, and uncertainties. This process will allow for more robust co-designing, as discussed below.

Co-design: This is seen as an essential component of co-production of W&CSs (Mauser et al., 2013; Goodess et al., 2019). Co-design takes place at the project proposal or scoping phase, once the needs and abilities of all partners are understood. It is the first phase of the co-production process, in which partners develop a project and define the issues they would like to address and which meet their collective interests and needs (Watkiss et al., 2018).

Co-develop solutions: This involves building on issues identified, exchange of knowledge and inputs from all actors of varying expertise to improve methodologies, uptake, and use of weather and climate information and solutions. This building block results in agreed-upon outputs that aim to address the needs of users, enabling better utilization of W&CSs. Co-development should enable continuous feedback from users to improve delivery of W&CSs.

Co-deliver solutions: This involves focusing on the proper packaging and communication of the agreed collaborative services or solutions to ensure they are useful, usable, salient and legitimate. It is important in the co-delivery process that all parties involved agree on the communication method(s), are acknowledged for their contribution and can use the solution or service. Actors who will be using the solution need to understand and be confident enough to use it. Intermediaries who will disseminate the solution (for example, media outlets, NGOs and training bodies) must understand the solution and be able to communicate and build the capacities of users to maximize utility of the solution (see, for example, the Finnish climate and energy plan – a solution that was co-developed through various research programmes (IEA, 2022b)). The actual co-delivery of a W&CS is not always practical, as it critically depends on the complexity of the solution. In such cases, it is more appropriate to simply talk about delivery.

Co-evaluate: This refers to the evaluation of the process rather than the (technical) content of the service itself. In this sense, it touches on all other elements in the co-production cycle to allow for continuous feedback and adjustments. It is also an important step at the end of the entire co-production process for the identification of successes, failures and lessons learned that can inform future activities, and also to establish the overall level of success of the service creation.

Overall, co-production approaches require sustained, reciprocal dialogue based on mutual respect; integrating different types and scales of knowledge and values; dealing with multiple world views; and negotiating the outcome of the co-production process (see Box 4.2 for an example of a co-production process).

Box 4.2. Pursuing data product co-production and co-development through the NASA Applications Programs in the United States

In the NASA Earth Sciences Division, one way that the Applied Sciences programme enables co-production and capacity development is through Applications Programs. These programmes are associated with various individual satellite missions and seek to ensure the sustained use of satellite data for societal benefit. Applications Programs link science with society, starting with identifying potential data end users, supporting partnership development and fostering the development of case studies or decision-support activities.

To ensure the accessibility, usability and actionability of the data that each mission will collect, Applications Programs seek to ensure their data will reach a diverse set of end users and benefit society. The Applications Programs engage with individuals and groups, including scientists, policymakers, practitioners and other professionals to use their data for practical societal needs. One of the goals of the Applications team is also to share feedback with the mission science team to ensure user perspectives result in improved data products (for example, engage in co-production).

One specific activity that Applications Programs facilitate to meet these goals is the Early Adopter Program. This program promotes applied science and applications research; it provides potential users with proxy data products before a launch, trains them to use these products, and fosters interactions between Early Adopters and NASA Science Team members to enhance algorithms and data products for wider utility. Early Adopters are those with practical applications of NASA remote-sensing data who can incorporate data into their decision-support tools, models, systems or applications. Early Adopters are provided with access to datasets and resources from NASA, and give feedback to NASA on data accessibility and usability, as well as demonstrate the value and impact of remote-sensing data from specific missions for specific applications.

One of the benefits of the programme is that Early Adopters can participate in activities to help them use these simulated or proxy data products so they are better prepared to ingest the “real” data products when the respective mission is on-orbit. Such programmes have included a diverse range of activities to develop capacity and build partnerships, including sponsoring hackathons, offering training or tutorials with NASA science teams, hosting informal social media channels, publishing papers in scientific journals, publicizing the mission at traditional scientific conference venues (such as the American or European Geophysical Union or others) and non-traditional, practitioner-focused conference venues (such as the American Water Resources Association or Air and Waste Management Association), conducting site visits and holding monthly or quarterly teleconferences.

There are various examples of NASA Early Adopter programmes, including:

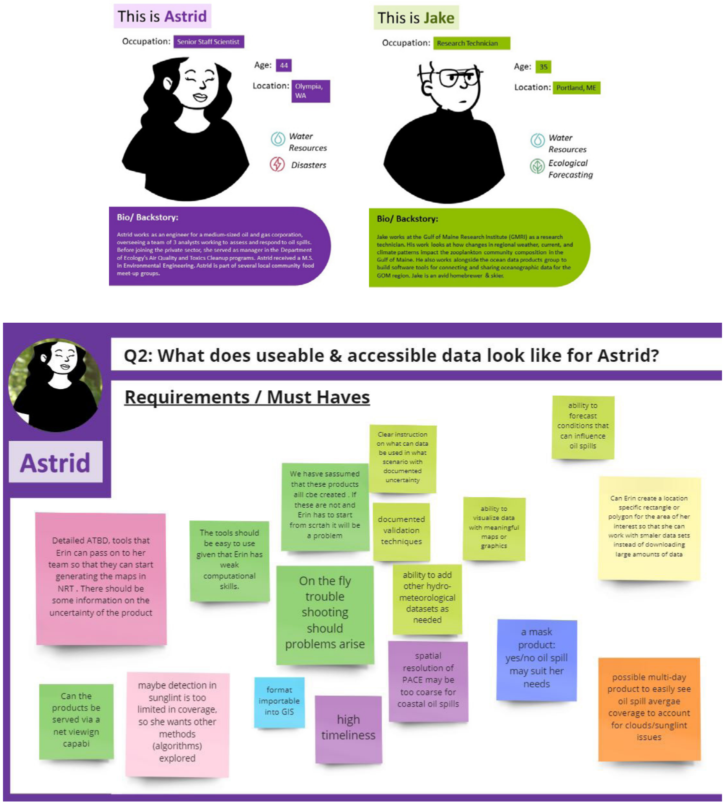
- NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) programme: https://pace.oceansciences.org/app_adopters.htm
- NASA Tropospheric Emissions: Monitoring of Pollution mission: https://weather.msfc.nasa.gov/tempo/
- NASA–Indian Space Research Organization Synthetic Aperture Radar mission: https://nisar.jpl.nasa.gov/engagement/early-adopters/
- NASA Surface Water and Ocean Topography mission: https://swot.jpl.nasa.gov/applications/overview/

Applications Programs offer additional activities in pursuit of co-production and co-development. For example, the NASA PACE (https://pace.gsfc.nasa.gov) Applications Program facilitates focus sessions and workshops to foster co-production and co-development activities collaboratively with data end users, partners and other stakeholders. The PACE mission is the next great investment of NASA in hyperspectral and polarimetric data for various ocean, atmospheric and climate-related applications. Scheduled to launch in early 2024, the PACE observatory will extend and improve the NASA 20 year record of satellite observations in these important applications.

To engage more effectively in the co-production of PACE data products and related activities, the PACE Applications team utilizes a design thinking approach. Design thinking allows the team to understand user needs through various phases, including understanding user needs, defining solutions, ideating, prototyping and testing, and evaluating progress and accomplishments. To put this process into practice, the team utilizes the concept of user personas, involving archetypical users whose goals/needs represent the PACE user community. Personas help the PACE Applications team better understand the goals, concerns and needs of the diverse user community, including non-traditional data users, as shown in Figure 4.4.

In turn, the PACE team can better design products, training, communications and other mission resources to satisfy user needs and goals and therefore be successful. For various community events, the PACE Applications team develops personas to represent a range of industry users from research to government to the private sector. During co-production breakout sessions, participants jointly identified different challenges and pain points, as well as realistic, tailored Earth observation and PACE-specific solutions and opportunities.

Some of the feedback received relates to topics such as data discovery (for example, interoperability, accessibility, data quality, metadata and documentation availability, and file formats) and training (for example, availability of training, tutorials and case studies). The PACE Applications team has incorporated this community feedback into its programming to ensure PACE data are usable and accessible for a variety of possible users, thereby expanding the eventual reach and societal benefit of PACE data and products.



Astrid works as an engineer for a medium-sized oil and gas corporation, overseeing a team of 3 analysts working to assess and respond to oil spills. Before joining the private sector, she served as manager in the Department of Ecology's Air Quality and Toxics Cleanup programs. Astrid received a M.S. in Environmental Engineering. Astrid is part of several local community food meet-up groups.

Jake works at the Gulf of Maine Research Institute (GMRI) as a research technician. His work looks at how changes in regional weather, current, and climate patterns impact the zooplankton community composition in the Gulf of Maine. He also works alongside the ocean data products group to build software tools for connecting and sharing oceanographic data for the GOM region. Jake is an avid homebrewer & skier.

Detailed ATBD, tools that Erin can pass on to her team so that they can start generating the maps in NRT . There should be some information on the uncertainty of the product

The tools should be easy to use given that Erin has weak computational skills.

We hasve sassumed that these products aill cbe created . If these are not and Erin has to start from scrtah it will be a problem

Clear instruction on what can data be used in what scenario with documented uncertainty

documented validation techniques

On the fly trouble shooting should problems arise

ability to add other hydro-meteorological datasets as needed

ability to visualize data with meaningful maps or graphics

ability to forecast conditions that can influence oil spills

Can Erin create a location specific rectangle or polygon for the area of her interest so that she can work with smaler data sets instead of downloading large amounts of data

a mask product: yes/no oil spill may suit her needs

spatial resolution of PACE may be too coarse for coastal oil spills

Can the products be served via a net viewign capabi

maybe detection in sunglint is too limited in coverage, so she wants other methods (algorithms) explored

format importable into GIS

high timeliness

possible multi-day product to easily see oil spill avergae coverage to account for clouds/sunglint issues

Figure 4.4. (Top) Use of personas to better understand goals, concerns and needs of the diverse user community, including non-traditional data users and (bottom) a user elicitation activity

Source: NASA PACE Applications Program, https://pace.oceansciences.org/

To improve the process and outcomes of the co-production of W&CSs, Carter et al. (2019) identified 10 principles for good co-production, as shown in Figure 4.5.

To summarize, the various principles and theoretical perspectives on co-production outlined in this section provide the motivation and context for implementation of the co-production process as described in the next section. True co-production is very different to the traditional top-down approach. The time and effort required from the outset to really deliver co-production should not be underestimated.

4.4 Co-production evaluation of weather and climate services

When evaluating benefits and relative successes of co-production of W&CSs, various factors play important roles. These may include (Vaughan and Dessai, 2014; Goodess et al., 2019):

- Processes of co-production discussed above, including problem identification, understanding user needs, capacities and context
- Supportive partnerships, stakeholder engagement and information provision through continuous communication
- Socioeconomic value of W&CSs (see Chapter 5)

Addressing these aspects may improve the credibility, legitimacy, usability, saliency and uptake of W&CSs. As discussed above, the co-production of W&CSs is an iterative process. Thus, evaluation plays a key role in supporting the uptake of these services. Evaluation of W&CSs can take place either before their roll-out (ex ante evaluation), after their completion (ex post evaluation) or during implementation (intermediate evaluation), which may help "course correct" the process (Bruno Soares et al., 2018; Perrels, 2020).

The literature on the evaluation of co-production of W&CSs offers various frameworks through which to evaluate these (Vaughan and Dessai, 2014; Meadow et al., 2015; Goodess et al., 2019). Here, and closely following Schuck-Zöller et al. (2017), it is suggested to focus on two core dimensions for evaluation.

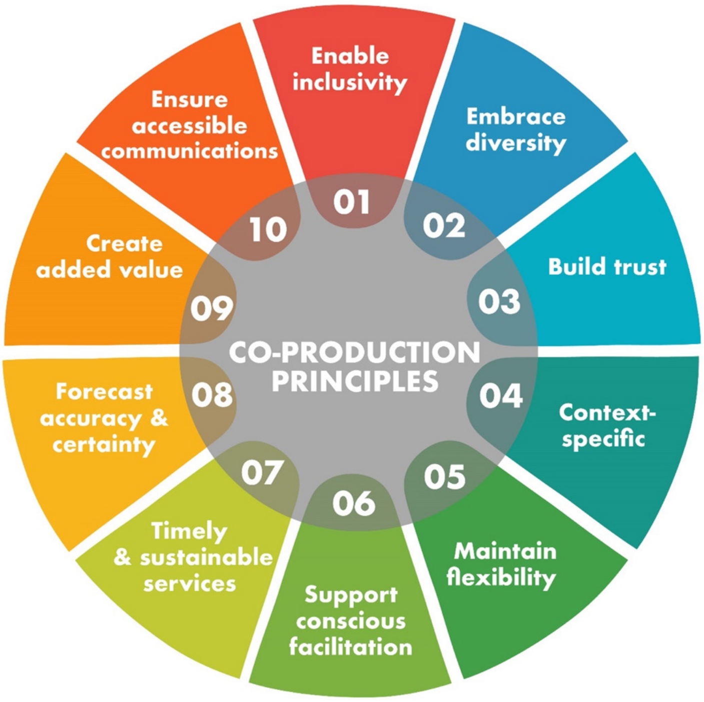


Figure 4.5. Principles for good co-production

Source: Adapted from Carter et al. (2019)

Process evaluation to evaluate co-production (or other processes) of W&CSs can take place along three main lines of evaluation:

- Problem identification, scoping and structuring include identifying and framing the problem to be addressed, understanding user needs, scoping the scale at which to take action and framing the challenge to be solved by the W&CS.

- Process implementation can assess to what degree the building blocks of the co-production process summarized in Figure 4.3 (and Figure 1.9) are followed, barriers to uptake and possible course correction.

- Stakeholder engagement, relationships and communication are key to ensuring successful co-production, as discussed in section 4.2 and agreed upon by scholars (Vaughan and Dessai, 2014; Meadow et al., 2015; Goodess et al., 2019).

Results evaluation along the work of the Organisation for Economic Co-operation and Development (OECD, n.d.[83]; Schuck-Zöller et al., 2017). Results evaluation needs to be distinguished among output, outcome and impact:

- Quality of outputs, where outputs are the products, capital goods and services resulting from an intervention, as defined by OECD. In W&CSs, quality of outputs encompasses quality, robustness, reliability, formats, and methods of delivery of forecasts and projections data, and more generally of services.

- Quality of outcomes, where outcomes are short- and medium-term effects of the outputs. These may include usability of new products and services (Schuck-Zöller et al., 2017), knowledge produced, capacity built (see Chapter 6), communities of knowledge created (Gardiner et al., 2018) and socioeconomic value realized (as discussed in more detail in Chapter 5).

- Impacts are long-term effects generated by the evaluated intervention. These are difficult to evaluate, and may include sustainability and replicability of intervention over time, along other context-specific criteria.

Table 4.6 summarizes some guiding questions for evaluating the criteria presented above. These can be adopted according to context, process and resources of each W&CS to be evaluated. Data-collection methods will also need to be adopted to local context and available resources. While this is a preliminary list, it provides a useful start for creating future monitoring and evaluation schedules.

This chapter has examined the principles and processes for, and evaluation of, co-production of W&CSs. The next chapter looks at ways of implementing these through realizing SEBs, harnessing business models, identifying suitable policy interventions and creating partnerships and collaborations.

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[83] https://www.oecd.org/dac/results-development/what-are-results.htm.

Table 4.6. Evaluation guidelines for W&CSs

Co-production evaluation of W&CSs	*Criteria*	*Guiding questions*
Process evaluation	Process identification/ scoping	Is the problem adequately identified and framed? Are stakeholder needs and abilities understood? Are the spatial and temporal scales in which the problem is targeted well defined? Are the context and boundaries for the problem clearly defined?
	Process implementation	Are the co-production building blocks followed? Are there barriers to uptake? Does the process need adjusting?
	Stakeholder engagement	Have all relevant actors been included? Is the level of stakeholder engagement adequate? Are communications targeting all stakeholders? Have new networks and relationships been forged?
Results evaluation	Outputs	What are the products, goods or services? Are these outputs of good quality? Are they reliable, robust and validated?
	Outcomes	Has new knowledge been produced? Have new communities of practice been formed? Has stakeholder capacity been built? Have SEBs been realized?
	Impacts	Are outcomes sustainable, scalable and replicable over time? Are co-benefits realized over time?

5. SUPPORTING UPTAKE OF WEATHER AND CLIMATE SERVICES FOR THE ENERGY SECTOR

The energy sector has long recognized the need to introduce W&CSs into the decision-making processes of the energy sector's key values to society. These include aspects such as energy security, provision of reliable and clean energy sources, and, in particular, contributing positively to the transition to net zero emissions pathways. The uptake of W&CSs in general, and for the energy transition in particular, is under development, but it can be enhanced by sustaining and purposely strengthening the following core elements (see also Figure 5.1):

- Realizing SEBs
- Harnessing business models
- Identifying key policies
- Creating partnerships and collaborations

Each of these elements is discussed in some detail below, and insights based on experiences from existing services are also provided.

Figure 5.1. Core elements to support the uptake of W&CSs for the energy transition

5.1 Socioeconomic benefits of weather and climate services in support of energy transition

5.1.1 Assessing socioeconomic benefits

The use of meteorological, hydrological, oceanographic and related information can deliver great benefits, to the energy sector, and also to society more broadly. This information can enable individuals, households, organizations, businesses and governments to make informed decisions that mitigate the impacts of weather and climate variability, climate change (WMO, 2017) and climate-related disasters (WMO, 2015a). This will ultimately support the net zero emissions transition, as discussed throughout this publication.

While it is not always possible to attribute how climate events can affect energy systems and therefore their operations, management and planning, they can be categorized in terms of:

(i) Slow-onset events, which are related to long-term changes, for example, global temperature increase over the past 100+ years.

(ii) Natural variability events, which are related to natural fluctuations such as (tropical) storms or the large-scale ENSO phenomenon.

(iii) Extreme (or rapid change) events, which are also related to natural phenomena, but in this case, changes occur more rapidly (on the scale of a few days) and might be induced by a combination of natural variability and long-term changes, possibly exacerbated by the latter.

A distinctive feature that emerges from these descriptions is that the severity and the impact of events generally increase from category (i) to (iii), while at the same time, their predictability decreases from (i) to (iii). Although category (iii) events might have a lower occurrence, or probability, their impact or damage can be substantial over short time frames (for example, a severe heatwave can bring hours or days of electricity supply disruptions due to the soaring electricity demand for air conditioning). However, impact or damage for categories (i) and (ii) can also creep up over time (for example, increased summer temperatures may pose a significant threat for thermal power plants that are using rivers/lakes for cooling).

Therefore, it is difficult to say whether slow-onset events have more or fewer impacts than rapid change events in the long run. Critically, all three categories need to be accounted for to support the energy transition properly and effectively towards net zero. For simplicity, these are presented sequentially in the following, noting that in practice they are not independent of each other.[84]

5.1.1.1 Slow-onset events

Slow-onset events refer to the risks and impacts associated with events that gradually change over long periods of time (decades). These include increasing temperatures, desertification, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea-level rise and salinization.[85]

Such slow changes can affect energy production and consumption in many ways. For example, a rise in the global temperature could affect hydropower generation by accelerating snow and glacial melt and increasing evaporation loss from reservoirs. It could also decrease electricity generation from thermal power plants and solar PVs by derating capacity and causing difficulties in cooling (van Vliet et al., 2016; IEA, n.d.).

5.1.1.2 Natural variability events

In addition to the observed slow changes, there are many natural variations or oscillations of the climate system that can affect specific regions or even most of the world, such as ENSO, NAO, the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation (Norel et al., 2021). While these oscillations are largely independent of slow changes, their strength and manifestation can alter due to climate change. For instance, this will affect ENSO, the largest global oscillation (after the seasonal variations), via increased SST variability in the Pacific Ocean. SST then drives much of the variability in other climate variables such as precipitation, which affects large areas in low and mid latitudes, and is projected to intensify and shift eastward.

Variations related to the oscillations of the climate system affect energy systems in many important ways, in terms of production and demand. ENSO provides the most prominent impacts (for example, it is often considered as one of the main causes of marked inconsistency in precipitation projections in South America affecting streamflow and hydropower generation (IEA, 2021d[86]). However, even the more regional and less strong NAO, between its positive and negative phases, may yield a difference in the mean wind power output of up to 10% (Brayshaw et al., 2011).

5.1.1.3 Extreme (or rapid change) events

With the steady rise in global temperatures, extreme weather events across the world have significantly increased in terms of intensity, coverage and duration. The number of natural disasters across the world, which are mainly meteorological, climatological and hydrological events, has shown a steady upward trend from 1980 to 2018, as illustrated in Figure 5.2.

In 2018, the world experienced more than 800 major natural disasters, four times more than in 1980. Between 2000 and 2019, the number of climate-related disasters, including extreme weather events, doubled. The number of major floods more than doubled, while storm incidences also increased, over the same period. Floods and storms were the most prevalent extreme weather events (UNDRR, 2020[87]).

From 1970 to 2019, disasters attributed to weather, climate and water hazards overall resulted in the loss of 2.06 million lives, with 82% of deaths occurring in low- and lower-middle-income countries (according to the World Bank country classification). These disasters also resulted in US$ 3.64 trillion in economic losses between 1970 and 2019 (see Figure 5.3), with 88% of losses occurring in upper-middle- and high-income countries (WMO, 2021b[88]). Considering decadal variations in the period 1970–2019, damage related to natural disasters increased significantly over time (Figure 5.3).

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[84] A fourth category is that of "catastrophic events". These are low-probability events and highly uncertain (such as the shutdown of global oceanic thermohaline circulation), yet their impacts could be substantial.

[85] https://unfccc.int/wim-excom/areas-of-work/slow-onset-events.

[86] https://www.iea.org/reports/climate-impacts-on-latin-american-hydropower/climate-risks-to-latin-american-hydropower.

[87] https://www.undrr.org/publication/undrr-annual-report-2020.

[88] https://library.wmo.int/doc_num.php?explnum_id=10989.

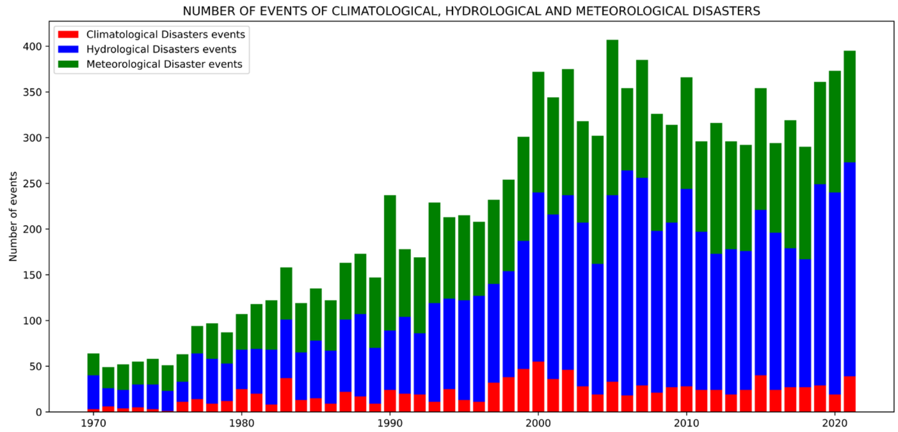

Figure 5.2. Number of natural disasters on a global scale (1970–2020)

Source: Produced based on data from EM-DAT[89]

In light of these different types of events, the evaluation of SEBs of W&CSs is a critical step in demonstrating their support to the energy transition under a changing climate. By measuring and evaluating socioeconomic impacts of the services, it is possible to identify successes and failures in delivering value. Barriers and gaps may exist in the service delivery that prevent the climate information from unleashing its potential value. These analyses can aid understanding where the services fail to deliver value (for example, design stage, service delivery and non-optimal use) and can inform possible improvements (S2S4E Climate Services for Clean Energy, 2020[90]; Dkhissi et al., 2021[91]).

Valuing SEBs that result from W&CSs is also an important part of justifying investment in the provision and delivery of climate and weather information (Suckall and Bruno Soares, 2020[92]). For example, it has been

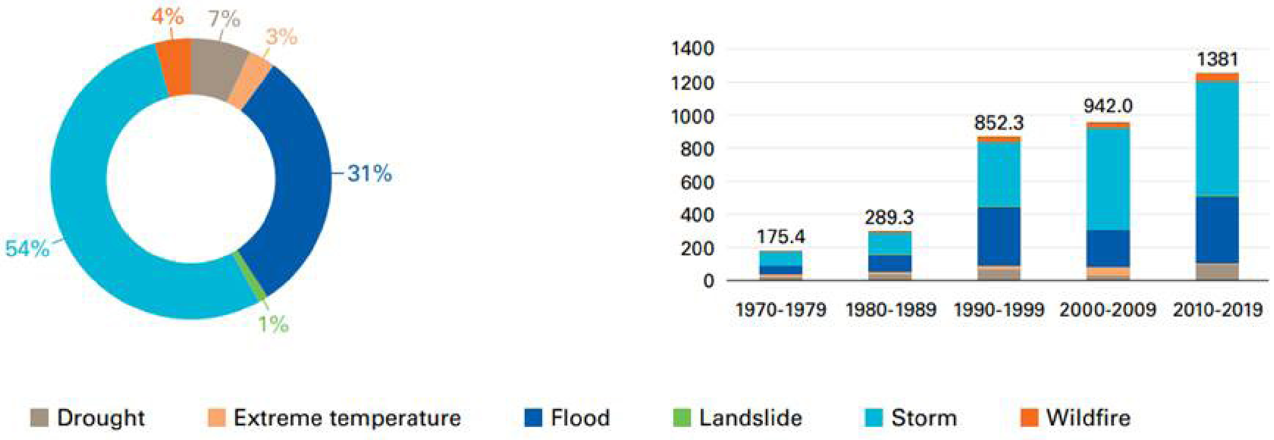

Figure 5.3. Percentage and amount (US$ billion) of economic losses from natural disasters, 1970–2019

Source: WMO (2021b)

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[89] https://www.emdat.be/.

[90] https://s2s4e.eu/sites/default/files/2020-11/S2S4E_White_Report_final.pdf.

[91] https://focus-africaproject.eu/wp-content/uploads/2021/09/FOCUS_Africa_D6_1_Methodology_to_asses_ssocio_economic_impacts_of_climate_services.pdf.

[92] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/business/international/arrcc_mop_wp4_seb_evaluation_guidance-final.pdf.

estimated that with a relatively modest spend of about US$ 1 billion per year, upgrading early warning systems across all developing countries in the world would potentially result in between US$ 300 million and US$ 2 billion per year of avoided asset losses, saving 23 000 lives per year and generating additional benefits of up to US$ 30 billion per year (Hallegatte, 2012).

Demonstrating the socioeconomic value of W&CSs is particularly important for public and private stakeholders providing the merit goods of W&CSs. These are goods that "engender more societal and private benefits than (initially) recognised by its potential consumers" (Musgrave, 2008). Due to lack of information and transparency, potential users may find it hard to understand the benefits of using these services. If the provision of merit goods is left entirely to the private sector, they may be potentially undersupplied and underconsumed. This certainly applies to the energy sector. According to a study by the World Bank, a project to build a resilient infrastructure without appropriate climate risk data can cost 10 times one that has sufficient climate information (Hallegatte et al., 2019[93]).

5.1.2 Determining what needs to be assessed

The energy transition towards net zero emissions enhances multiple synergistic benefits for the economy, society and environment, and supports the goal of sustainable development. W&CSs can facilitate the uptake of net zero emissions solutions and pathways.

The evaluation of W&CS SEBs for net zero W&CS transition includes several impact categories, as illustrated in Figure 5.4 and discussed below. This framework captures benefits in an illustrative manner, with the potential for additional indicators to be included contextually. Moreover, some of the impact categories can be attributed to more than one benefit category. For example, in addition to being a social benefit, access to energy and electricity can also be viewed as an economic benefit, as it can stimulate different sectors of the economy. This framework can help in assessing benefits of W&CSs for energy transition.

Economic benefits: W&CSs for the energy transition can improve the quality of economic development. Their use can stimulate investment in the construction of relevant infrastructure and contribute directly to economic growth. This can occur for instance through the provision of highly accurate and spatially resolved reconstructions of the past climate over several decades, together with calibrated and quality controlled climate projections. These services allow for a better estimation of the uncertainty in the expected resources (wind power, solar power, hydropower and so forth), with consequent lower costs of borrowing and less volatile returns.

Similarly, the availability of high-quality forecasts for renewable energy generation, particularly for the more variable ones (such as wind and solar power), allows for improved electricity grid balancing, and therefore a reduction in electrical and economic losses. Such availability also allows for more reliable planning of

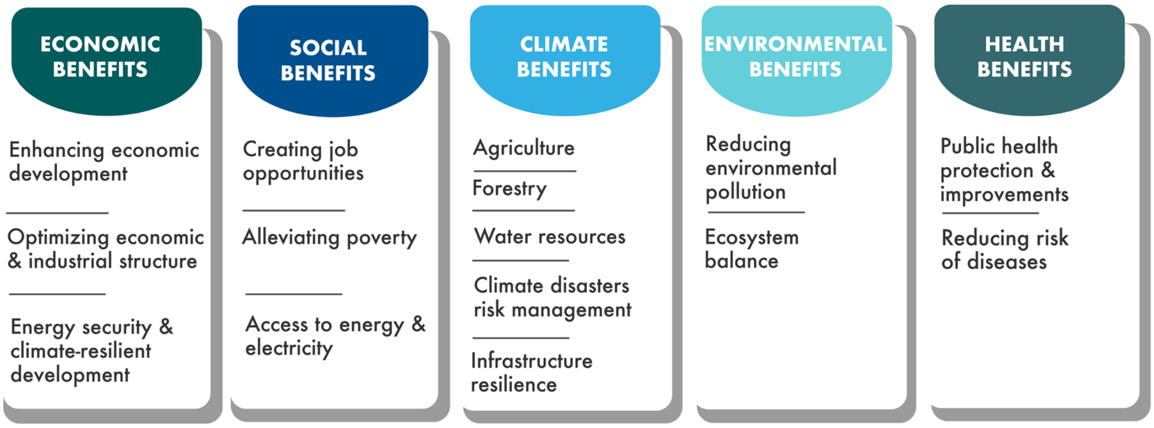

Figure 5.4. SEBs of the W&CS framework

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[93] https://openknowledge.worldbank.org/handle/10986/31805.

new renewable energy power plants, again with consequent reductions in the costs of capital investment. Indeed, the transition to a green, zero-carbon industry and energy production drives economic growth in underdeveloped regions and promotes the coordinated and win–win development of regions.

There are also indirect economic benefits. W&CSs can support the clean energy transition by addressing the adverse impacts of climate change on renewable energy (which tends to be sensitive to weather events), promoting sustainable development by ensuring reliable energy services, boosting energy security through coping with climate-driven disruptions and reducing risks from climate disasters (IEA, 2022c[94]). They can also help promote grid interconnection among countries, to maximize the use of abundant clean energy resources, and promote clean energy technology investment.

Social benefits: The burgeoning W&CS enterprise in support of the energy transition can create numerous new job opportunities. In so doing, it can alleviate poverty and improve health and well-being. Clean energy infrastructure investments are already creating many direct and indirect jobs (IRENA and ILO, 2021). In addition, by also securing electricity access in regions with concentrated poverty-stricken populations such as Africa and Asia, social equality and justice can be enhanced, in line with the poverty reduction and poverty alleviation Sustainable Development Goal (SDG 1).[95]

While infrastructure investment is an indirect benefit to W&CSs, these services are, or will be if not already present, an integral part of the functioning of energy systems, with consequent job expansion and creation in W&CSs too. Moreover, climate services can help to anticipate and better manage the mid- and long-term impacts of climate change on climate immigration, with consequent benefits in terms of poverty alleviation and well-being. Furthermore, as experienced with COVID-19, climate-resilient energy systems can support recovery from a pandemic (IEA, 2020b[96]).

Climate benefits: The immediate aim of W&CSs is to offer accurate information to energy users (for example, calibrated seasonal climate forecasts) to help reduce risk and operational and management costs. This is done by assessing the impact of climate information on operational planning and portfolio management and by quantifying the added value provided by calibrated and tailored information for each specific application.

The optimal use of these W&CSs will lead to a better supply–demand balance in the energy and water sectors, therefore positively contributing to climate change adaptation (forecasts represent soft adaptation measures) and mitigation.[97] Implementation of the concept of green and low-carbon development can control the cumulative emissions of the global energy system within this century to less than 500 Gt of CO_2, to achieve the global temperature increase control goal specified in the Paris Agreement.

Environmental benefits: The ongoing expansion of clean power generation and the promotion of solutions for water provision and pollution control can improve environmental conditions such as emissions reductions of air pollutants such as of sulfur dioxide, nitrogen oxides and fine particles, improvement in water quality and reduction of water scarcity (Gleick, 2022[98]).

Through the monitoring of the vast number of environmental factors related to energy exploration, extraction, production and consumption (for example, concentrations of pollutant gases from gas extraction), W&CSs can play a key role in supporting implementation of relevant environmental policies, by ensuring their targets are met, or indeed in revising them based on scientific evidence.

Health benefits: Similarly to environmental benefits, investment in W&CSs for energy systems is critical for establishing monitoring systems to track pollutants (especially air and water) to help control and reduce

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[94] https://www.iea.org/reports/climate-resilience-policy-indicator/policy-preparedness-for-climate-resilience.

[95] For an in-depth discussion on the impact of climate indicators on SDGs, see WMO (2021c).

[96] https://www.iea.org/commentaries/clash-of-crises-how-a-climate-resilient-electricity-system-can-help-us-tackle-climate-change-and-covid-19.

[97] http://www.secli-firm.eu.

[98] https://www.iberdrola.com/shapes-en/peter-gleick-how-water-systems-affect-greenhouse-gas-emissions.

pollution-induced health problems (Lancet Countdown, 2019; WHO, 2021[99]) including the reduction of deadly disease risk, therefore helping to prolong the life expectancy per capita. As in the case of China, for which investment in electricity generation based on renewables and non-fossil fuels is now key to tackling the chronic issue of severe air pollution in many cities (48 Chinese cities are among the top 100 most-polluted cities in the world) (O'Meara, 2020[100]), W&CSs can be crucial in assessing the effectiveness of such investments and their related policies.

5.1.3 Evaluating socioeconomic benefits

W&CSs can offer a wide range of benefits to society, including in the market and non-market sectors. For market damage losses (such as the direct economic damage caused by weather and climate disasters, agriculture damage, energy bills for rising prices or increasing heating/cooling needs), it is relatively easy to quantify market value based on the changes of activities and prices.

However, some of the key outcomes of W&CSs are referred to as non-market activities. These may include a reduction in the number of hurricane deaths following an early warning, or an increase in food security following delayed planting in response to a seasonal forecast. These impacts cannot be observed immediately in the marketplace.

Thus, many of the non-market impacts are intangible and hard to quantify, such as lives saved, improvement of health conditions, environmental benefits and ecosystem service value (Lazo et al., 2011). Moreover, it is important to acknowledge that W&CSs are one of the many variables that affect the market and non-market sectors. For example, a peak in energy prices may be driven by climate variability, but it can also depend on the oil and gas markets and geopolitical factors. The challenge is to detect and isolate the non-climate elements, to assess the real impacts of W&CSs.

The main methods used to evaluate the value of W&CSs are: (i) contingent valuation, (ii) revealed preferences, (iii) economic modelling, (iv) avoided costs, (v) benefit transfer and (vi) participatory methods (see Table 5.1). The selection of methods is driven by many factors, including research question specification and data availability. Some methods are better suited to answer a particular question than others.

Table 5.1. Methods used in SEB evaluation of W&CSs

Method	*Description*
Contingent valuation	Uses elicitation approaches such as interviews and surveys to determine how much respondents would be willing to pay for a specific weather or climate service
Revealed preferences	Measures consumer preferences for a weather or climate service by observing their purchase behaviour
Economic modelling	Common modelling techniques are: • Decision analysis: Uses models to examine the decisions taken when people have access to W&CSs and when they do not • Equilibrium modelling: Examines changes in supply and demand, and price effects of using W&CSs, measuring overall gains and losses • Econometric modelling: Examines statistical relationships to determine specific outcomes associated with the use of W&CSs
Avoided costs	Determines the economic costs that are avoided due to using W&CSs
Benefit transfer	Takes the findings of an original evaluation of a W&CS and applies them to a new geographic or policy context
Participatory methods	Employs a range of participatory methods to produce a deep qualitative understanding of the benefits of W&CSs for end users

Sources: WMO (2015a); SECLI-FIRM (2019); Suckall and Bruno Soares (2020)

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[99] https://www.lancetcountdown.org/; https://www.who.int/en/news-room/fact-sheets/detail/climate-change-and-health.

[100] https://media.nature.com/original/magazine-assets/d41586-020-02464-5/d41586-020-02464-5.pdf.

If the impact must be assessed at the microeconomic level, for example for a renewable energy producer using the service, decision modelling, avoided costs and participatory methods can be effective approaches. At the macroeconomic level, equilibrium modelling can be selected, for instance to estimate the contribution to an increase of renewable energy supply in the energy mix. However, also in the case of W&CSs for the energy transition, the best methodology to apply should be selected on a case-by-case basis (for a more detailed description of the applicability of the various methodologies, see WMO (2015a), SECLI-FIRM (2019) and Suckall and Bruno Soares (2020)).

W&CSs for the energy sector can also benefit other sectors of the society (for example, air quality, disaster management, agriculture, water management, infrastructure and forestry). Therefore, when evaluating W&CS benefits, it is important to clearly define the scope of the analysis and to pay attention to likely over- or underestimations deriving from non-climate variables. Sensitivity analyses help to assess the level of confidence associated with the results.

The timing of the evaluation also matters. Normally, evaluation studies can be differentiated between ex ante and ex post analyses. In the ex ante studies, the objective is to predict the value of W&CSs before their provision, whereas the ex post studies assess an existing service based on historical or current use. Ex ante studies typically identify a baseline (how decisions are currently taken) and try to compare it with the decision simulated using W&CSs to understand the potential value. Assumptions are needed with respect to the uncertainty associated with the analysis. The ex ante analyses are important as they provide insights before implementation of the services and can support investment decisions.

In the ex post studies, assumptions may be made about what would happen if the service did not exist. If the service has been operational for a sufficient time, it is possible to collect data to measure the performance. Qualitative social science methods can help understand the value of the forecasts. The ex post studies are useful for learning, to improve future performance and widespread adoption (WMO, 2015a).

The evaluation may demonstrate that the service does not bring the expected SEBs, or could even suggest a negative impact. Once the assumptions in the selected SEB assessment methodology are stated, it is more straightforward to investigate the cause of the failure in value delivery. At any point of the service value chain, there may be a gap that prevents the service from unleashing its full potential. The cause(s) may be entailed in the service or can derive from external factors preventing optimal application. Identifying the source of value loss is important to inform the co-production, delivery and/or use of the service. A couple of simple clarifying examples follow.

The user may not benefit from the application of an energy demand forecast indicator because, for instance, the range of uncertainly is too wide. In this case, the provider should revise the indicator. The same indicator may fail to deliver value because it is delivered when key operational decisions have already been taken. In this case, while the indicator may contain useful information, it is important to identify which processes can be speeded up to make the information available in time to be considered by the user. Finally, even if a peak in demand is correctly predicted with sufficient notice, if the user faces technical or organizational problems preventing the change of action accordingly, no benefits will be generated. Understanding user barriers is therefore also critical. Intermediaries with strategic expertise beyond climate can facilitate this process. Acknowledging the problem is the first step towards its resolution. Here again it is apparent that engagement with users is key.

Box 5.1 provides an example of economic assessment for upgrading energy infrastructure against extreme weather events in the Russian Federation.

5.2 Business models for sustainable weather and climate services for the energy sector

5.2.1 The weather and climate services market

While innovation is happening in W&CSs, their uptake in the energy sector is not increasing at the same pace for climate services as it is for weather services, with the former lagging behind the latter by about 10 years. Aside from the traditional valley of death and “twilight zone between technical invention and (commercially)

Box 5.1. Economic assessment of power transmission line modernization, accounting for the risk of extreme weather events in the Russian Federation

Voeikov Main Geophysical Observatory in the Russian Federation has carried out justification of measures to adapt power transmission facilities to heatwaves, strong winds, squalls and ice-rime deposits based on the technical modernization of power transmission lines, using economic assessment of investment project effectiveness. A phased modernization strategy is being adopted: replacing worn-out and outdated infrastructure, and particularly overhead power transmission lines, with alternatives that are more resistant to negative weather impacts and less costly.

The economic risk associated with the impact of a certain hazardous phenomenon characterizes the potential damage caused by this phenomenon and is adequate for valuing the costs of eliminating the consequences (responsive adaptation). Consequently, in a territory with known characteristics of hazardous phenomena (recurrence, intensity and significance of trends) and the level of industrial development, capital investments in preventive adaptation measures will gradually lead to a decrease in economic risk and will correspond to the profit stream from the project.

A study was carried out on the example of the Northwestern Federal District of the Russian Federation, which includes 10 regions. The regional departments of the Russian Federal Service for Hydrometeorology and Environmental Monitoring provided data on the frequency of hazardous weather events, their intensity, coverage area, exposure time, magnitude and significance of trends in each of the regions under consideration. Energy companies and the district's Ministry of Energy provided information on the power grid facilities.

The results of the study showed that the values of specialized indicators of wind loads on the power grid remained nearly unchanged over the period 1961–2011. However, in the north of this territory (especially on the Arctic Ocean coast), atmospheric loads associated with wet snow deposits increased significantly. It was also found that the impact of heatwaves on the power grid in this region was insignificant, but the risks of power supply disruption due to high air temperatures in more southern regions increased significantly at the beginning of the twenty-first century.

Assessment of the adverse consequences of a hazardous phenomenon and economic risks (damages) showed that most of the study area lies in the zone of unacceptable (excessive) risks ($>10^{-2}$), which are mainly due to the increasing likelihood of severe weather activity.

Assessment of investment projects showed that for different areas of the Northwestern Federal District, the power line adaptation projects have different levels of effectiveness. For example, the most effective adaptation strategy was for the Murmansk and Kaliningrad regions. For the Arkhangelsk and Leningrad regions, the values of the internal rate of return were close to the discount rate, which makes adaptation projects marginal in terms of efficiency, and an increase in the discount rate may make them prematurely unprofitable. For the territories of Novgorod, Pskov and Vologda regions and the Komi Republic, the proposed measure as an adaptation of power transmission lines was unprofitable. Here, it was more profitable to accept the option of reciprocal adaptation by elimination of the consequences of severe weather effects to the power lines.

successful innovation" (Hermansen et al., 2021), which may affect any enterprise, climate services uptake requires a considerable amount of additional engagement with users for consequent development of new products (as discussed in Chapter 4). The reason for this additional work lies in the complexity and inherent uncertainty of the climate information (for example, seasonal forecasts; for a more detailed overview, see Chapter 2).

To better understand the differentiation between weather services and climate services, it is useful to take a step back. A weather or climate service is not unique among other possible services, including public or commercial (for example, financial services). While these services naturally differ from each other in terms of their specific purpose, some common features can be identified (Troccoli, 2018[101]):

- **Maturity**: How long have they been around?
- **Tangibility**: Is it something that can easily be related to?
- **Level of risk**: How reliable and/or accurate is the output/product?
- **Trustworthiness (or credibility)**: How much can the service provider be trusted?

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[101] https://link.springer.com/chapter/10.1007/978-3-319-68418-5_2.

Table 5.2 compares these features for weather services and climate services, complemented by the level of "caution" of the specific service. Specifically, the comparison in Table 5.2 emphasizes that climate services carry a higher level of risk or caution (for example, of the likelihood or certainty of climate forecast) than weather services. To attempt to reduce these levels of cautioning as much as possible should be a focus of the experts involved in the development of climate services, but also weather services to a certain extent. In general terms, this reduction can be achieved through co-production (therefore involving co-design, co-development and co-evaluation), as discussed in Chapter 4. This chapter focuses on improving the uptake of these services through appropriate mechanisms. Box 5.2. provides an example of a developed business weather service for an early warning system.

The global market for W&CSs was measured for the first time in 2010/2011, and was estimated to amount to € 36.6 billion. Following a steady annual growth rate of about 7.5%, similar for the traditional weather and the emerging climate services markets, the sector reached € 52.2 billion globally in 2015/2016 (Poessinouw, 2016). In these years, weather services represented about 53% of the combined W&CSs provided. However, there is huge variability depending on the end-user sector.

Table 5.2. Qualitative comparison between weather services and climate services based on four representative features

	Maturity	*Tangibility*	*Level of risk*	*Trustworthiness*
Weather service	H	M	M	M
Climate service	L	L	H	M

Note: The three qualitative levels H, M and L stand for high, medium and low, respectively. The levels have been established in comparison with other types of services (for example, financial and medical). These are associated with colours to indicate the level of caution. So for instance, a high maturity (for example > 30 years) carries a low level of cautioning (green) whereas a high risk carries a high level of cautioning (red).

Source: Troccoli (2018)[102]

Another large source of uncertainty in the partitioning between weather services and climate services is the provision of historical data such as reanalyses. Given their wide applicability, these are hugely popular datasets, and, depending on their specific use, these data could be considered either in the weather or climate (or even both) service domain. The largest share of purchased climate services (almost 24%) in 2015/2016 was advisory services, risk assessments and decision-support tools.

In relation to W&CSs, Lazo et al. (2011) estimated that economic activity in the United States attributable to weather variability could be 3.4%, or US$ 485 billion, of the 2008 gross domestic product. Perhaps even more telling is the private capital being invested in the W&CS enterprise, albeit predominantly in the weather service component. According to figures, in the first quarter of 2021, more than US$ 350 million of venture capital was invested in W&CSs (with one single investment equal to nearly US$ 250 million, to be spent on satellite monitoring infrastructure). A study by Cortekar et al. (2020) found that in the European market, after the water sector, the energy sector is the target of the highest number of climate services. It is also estimated that despite public providers still being dominant, the number of private sector providers is growing.

As stated by a European Commission road map (European Commission, 2015):

> An aspect of the climate services market that requires better understanding is the implication of the coexistence of both private and public domains within that market, also considering that also the private sector may be the owner of data and data products. This includes the implication for demand and supply, and the nature of relationships between services operating within these two domains that can support the strengthening of the overall market.

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[102] https://link.springer.com/chapter/10.1007/978-3-319-68418-5_2.

Box 5.2. Early weather warnings to safeguard electricity supply in Beijingcation-specific weather forecast information in China

To better safeguard Beijing's electricity supply security, the Energy Service Team under the China Meteorological Administration has cooperated with the Beijing branch of the State Grid (http://www.sgcc.com.cn/ywlm/index.shtml) since 2017. As a mega city, Beijing has high requirements for a continuous and safe power supply. Extreme weather events such as rainstorms, floods, gales, hail and cold waves have caused great threats to the operation of Beijing's power grid. In recent years, failures of the main distribution network caused by various meteorological disasters and their derivative factors accounted for more than 50% of all failures.

Using advanced information technologies, such as multisource data analysis and power grid lean geographic models, the China Meteorological Administration established a precise early warning system for meteorological disasters (Figure 5.5). Through in-depth integration of meteorological and power grid considerations at the data, system, business and organization levels, the system has realized accurate disaster warning for more than 10 types of disasters, such as wire icing, conductor galloping and water flooding of transformer substations. The project team established a series of differentiated early warning models or algorithms for each substation and each base tower.

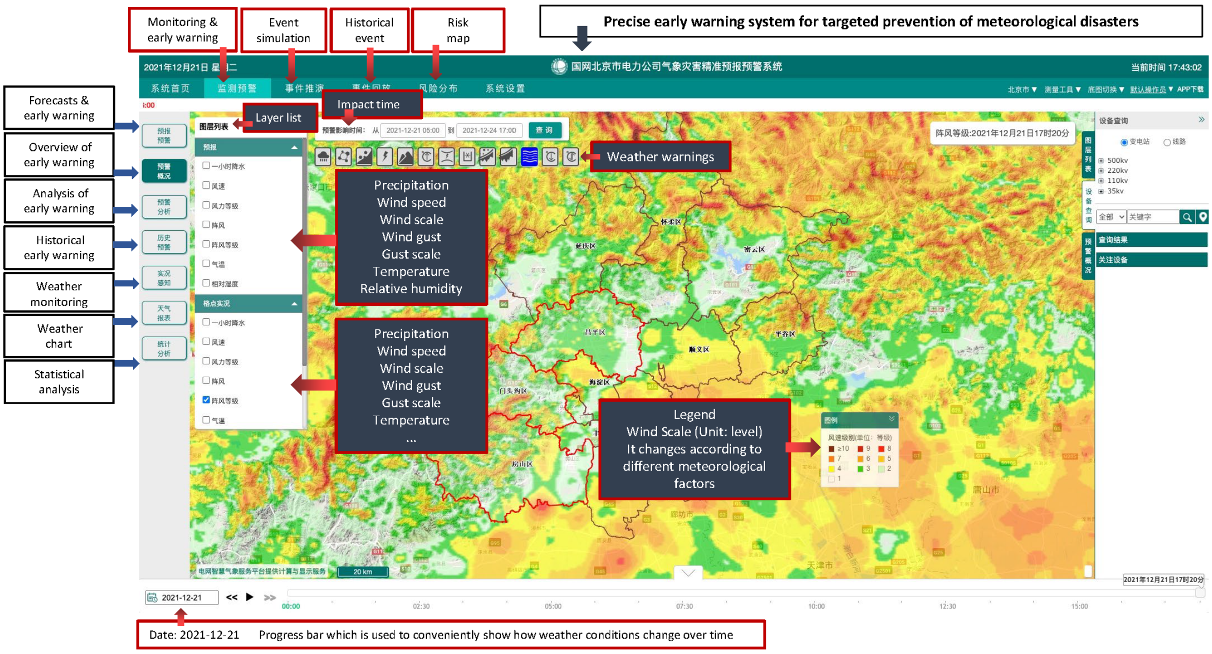

Figure 5.5. Early warning system for the Beijing branch of the State Grid

Source: China Meteorological Administration

To achieve accurate monitoring and forecasting, weather information needs to be updated every 10 minutes. A mobile operation application was also developed to achieve the rapid transmission of monitoring, forecasting and early warning information. Forecasts of disaster events and the deduced conclusion of their impact on the power grid are crucial.

Project team members must comprehensively consider meteorological conditions, historical disasters, topography and landform, and historical extreme weather conditions, to determine whether the power grid equipment will be affected by mountain torrents, mudslides and urban water logging. The system has detailed analysis reports for the historical climate conditions of equipment based on the climatological data. However, the system also needs to consider impacts under different future climate change scenarios. These are all great challenges.

Using this system, the power grid has experienced significant economic benefits, residents have enjoyed stable power transmission and power grid operators have better safety protection. The system helps the grid to achieve flexible dispatch during disasters, thereby helping the grid avoid or reduce serious disaster losses (for example, equipment losses, power outage losses and casualties). It also reduces the cost of emergency management and disaster prevention.

In addition, pressure on power grid employees has been reduced. While difficult to quantify, the economic benefits the system creates are still increasing. Social benefits are also significant. The system helps to improve efficiency and reduce the costs of disaster prevention. It effectively solves the coexistence of excessive disaster prevention costs and insufficient prevention of power cuts. It helps to effectively improve the level of regional safe power supply, which greatly reduces possible social and economic impacts of power outages.

The system has been fully applied in the Beijing branch of the State Grid, and has become essential for emergency management, disaster prevention deployment, operation and maintenance of the capital's power grid. The system plays an important role in ensuring the safety of power supply, facilities and personnel, especially during the flood season and extreme weather events. This project has also been praised by railways, petrochemicals and new energy industries, and has broad application prospects in the future.

Suitable business models are needed to enable W&CS sustainable market growth and value creation. W&CSs are knowledge-intensive business services, relying on high human capital capacities (Brenner et al., 2018). The common characteristics of these services, as summarized by Larosa and Mysiak (2020), are as follows:

- Knowledge is input and output, enabling context-specific decision-making. For this reason, it is difficult to standardize these services.
- Services provided are based on close interactions between providers and clients, based on processes of co-production (see Chapter 4). Often, the final products are highly tailored to specific customer demands and needs.
- The development of these business services supports co-production of innovation, through product and service development, work practices and valorization.

However, weather services and climate services in particular, are plagued by business models that are not well adapted to a private sector profitability culture (Brasseur and Gallardo, 2016). Thus, the uptake and implementation of W&CSs requires reliance on innovative business models and often multi-stakeholder partnerships.

5.2.2 Business models

Broadly, business models can be understood as "the logic of the firm, the way it operates and how it creates value for its stakeholders" (Casadesus-Masanell and Ricart, 2009).[103] The Business Model Canvas, presented in Figure 5.6, is often used as an analytic framework to understand business models and to assist with the planning of a new business (Osterwalder and Pigneur, 2010). This is an extended version of the Business Model Canvas presented by Larosa and Mysiak (2020).

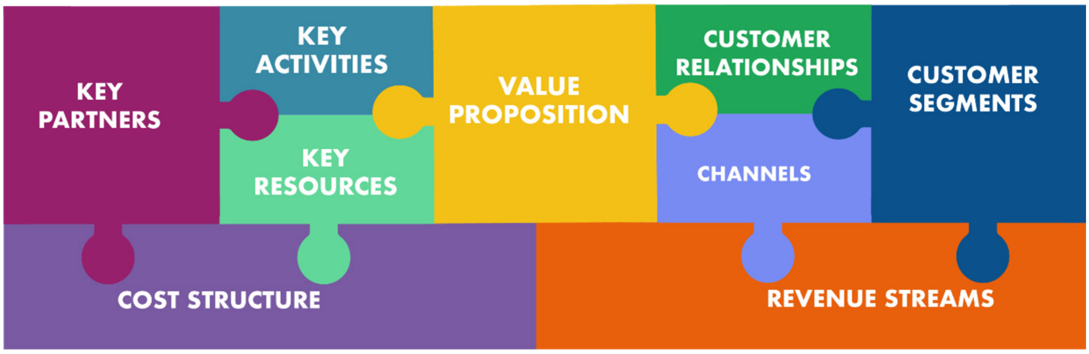

Figure 5.6. The Business Model Canvas

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[103] For an in-depth discussion on business models, see for example Fielt (2013).

The left-hand side of the canvas relates to product or service development, while the right-hand side focuses on the relationship of the business with its customers. The **value proposition** combines these two aspects, aiming to satisfy user needs and creating value (Larosa and Mysiak, 2020). **Key partners** include all stakeholders involved in establishing a successful business model (as discussed in more detail in Chapter 4 and later in section 5.3). **Key activities** encompass all stages of service and/or product development, aiming to reach target users in the most cost-effective way. For this publication, these activities relate to the W&CS value chain framework presented in Figure 1.9.

Key resources are the "physical, intellectual, financial and human inputs required to trigger activities and ultimately deliver the value proposition" (Larosa and Mysiak, 2020). **Customer segments** include different actors who may be interested in the proposed product or service. Each of these may have their specific needs (as discussed in Chapter 4). Thus, segmentation enables specific needs to be understood and business priorities defined, for example, through mass and niche markets. **Customer relationships** are equally adapted to the needs of customers and business priorities. These relationships are maintained through various **communication and dissemination channels**.

The range of available climate services have been categorized as four ideal types. This categorization is based on two dimensions of how services are offered to the market, as illustrated in Table 5.3, and elaborated below. While the discussion focuses on climate services, as per Visscher et al. (2020), analogous considerations apply for weather services.

Table 5.3. Typology of (weather and) climate services

	Generic	*Customized*
Focused	Maps and apps • General climate services • For all users • Made freely or cheaply available	Expert analysis • Mono- or multidisciplinary climate services • Tailored to specific decision-making situations • Offered commercially
Integrated	Sharing practices • Mutual climate and climate policy services • Made freely or cheaply available • Tailored to specific decision-making situations	Climate-inclusive consulting • Interdisciplinary management, engineering or policy services including climate data • Among knowledgeable peers • Offered commercially

Source: Visscher et al. (2020)

Maps and apps: Using these, users have quick and inexpensive access to climate data, enabling more robust and objective decision-making. Meteorological and research institutes are central to the provision of information, as well as intermediary bodies that bring users and data together. Services are often free or inexpensive, and the institutions involved in data provision often have restrictions on commercial operations. Therefore, these services frequently rely on public funding from national and international bodies. For commercial entities, revenue streams can also be derived from advertising and sponsorship deals.

Expert analysis: This provides focused climate data, tailored to specific user needs, most commonly on a commercial basis. Climate experts take a pivotal role, providing tailored expert advice to inform user decisions. These services are often provided by commercial consultancy firms and market-oriented branches of meteorological and research institutes. Governments play a role as clients of these services, and also in supporting and legitimizing the use of these professional services.

Climate-inclusive consulting: Like expert analysis, this type provides tailored advice. Here, commercial, interdisciplinary consultancies (for example, planning, finance services, engineering and policy) "create and deliver climate services by integrally taking climate data and projections into account when advising decision makers on a broad range of subjects, such as infrastructure, investment or corporate strategy" (Visscher et al., 2020). The advice is tailored by the consultant to enhance customer decision-making and value added. For these types of services, an integrated data infrastructure may be required to allow scalability and also ensure robust replicability.

Sharing practices: Users are sometimes also producers of climate data. Identification, benchmarking and sharing best practice among knowledgeable peers, spanning the public, private and third sectors, is central to the provision of these services. Exchange is facilitated by databases, platforms and events. These are usually sponsored by either public bodies or commercial platform providers.

As illustrated above and throughout this publication, the revenue streams for W&CSs rely on a range of public, private and third sector actors. An example of private sector initiatives is that of AXA Climate, which offers risk management advisory activities using insurance data and climate modelling to support the sectoral activities of clients, including industry, investors and the public sector. The service is directed towards integrating climate risks into investments, operation, insurance decisions and climate disclosure objectives. Of particular relevance here are climate risks such as coastal floods, storm surges, tsunamis and sea-level rise.

5.2.3 The case of weather and climate services for energy transition

For W&CSs to be adopted operationally, the energy sector usually demands highly tailored services. While energy sector users also welcome information from generic services (for example, when assessing the general features of a forecast), customization adds value to the user. This is in line with the price difference at which these services are normally offered, starting from free or low prices for the generic products (see Table 5.3).

However, there are some non-negligible costs associated with the production of W&CSs that are independent of the level of tailoring. Weather and climate models are data intensive, and data acquisition has high costs. There are also costs associated with operating and maintaining the services on a regular basis, such as data processing, and storage.

The revenue that can be obtained from generic services is often insufficient to offset the elevated fixed costs to run a profitable business. Public body intervention is justified in the presence of positive externalities deriving from the service's usage (for example, when the consumption of the weather and climate information has positive effects on third parties) (Perrels et al., 2020).

Tailoring requires additional costs associated with product development and delivery. In fact, a customized climate service may offer, for example, user-specific indicators, higher resolution and sometimes integration with non-climate data (for example, population data). Service-level agreements for customized services usually entail close relationships with clients and expert support. Different pricing structures can be selected by the provider. In general, these services are commercially viable.

One barrier is the time it takes to acquire user trust. The complexity – and novelty for climate services – of the integration of W&CS information into decision-making processes often requires careful testing before trust can be gained. In the case of climate services, the impacts of their application in an operational environment are hard assess due to the time it takes for the actual event to happen, and, related to this, also due to the small data samples. For instance, in the case of seasonal forecasts, there are typically about 40 years of retrospective forecasts available, hence 40 individual months (40 Januarys and so forth), so only 40 data points that can be used to assess the forecast system.

Nonetheless back-testing can be used to simulate the benefits that the user would have gained in the past with the service (see, for example, the SECLI-FIRM case studies[104]). This can help reduce the trial period and shift the focus of the testing onto the usability of the service. The "trust barrier" is especially relevant for those companies entering the market that need to sustain an important upfront investment before being able to acquire clients.

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[104] http://www.secli-firm.eu/case-studies.

Intermediaries can alleviate the trust issue while facilitating the tailoring process. The intermediary can be a third-party business that enters the value chain between the provider and the end user. Intermediaries can address different areas of the relationship with the client (business development, innovation management, marketing, legal issues and so forth). The intermediary can also entirely uptake the service and deliver it as part of another integrated service. The intermediary in these cases is likely to already have a deep knowledge of the end-user needs and an established relationship.

These types of intermediaries are likely to contribute to the entire co-development cycle of the services (Hermansen et al., 2021; see also Figure 1.9 on the framework for co-production). However, while intermediaries can be effective at strengthening the link between provider and user, they also add to the cost and complexity of the engagement, and hence increase the barrier to entry of start-ups.

Finally, standards can raise trust and reduce transaction costs (costs associated with the search, selection and acquisition of the climate service). Standards can be applied to quality control and assurance, as well as to the way information is presented (Larosa and Perrels, 2017).

5.2.4 Examples of best practices

One of the purposes of collaborative projects such as those funded by the European Commission is to exploit[105] the results produced by the projects. This can involve creating road maps, prototypes, software and so forth. Among the goals of exploitation, a key one is fuelling innovation, including via the commercialization and development of products.

In the case of W&CSs, exploitation has been challenging. This is partly because these projects have a large component of research, even if they are classed under the research and innovation category. This makes the final output unproven for exploitation, particularly when it comes to commercial exploitation. Therefore, few good practice stories exist in this sector. One such example could be represented, at least partially, by the work done by two successive European Union projects ANEMOS[106] and SAFEWIND.[107]

The aim of the ANEMOS project was to develop advanced forecasting models to predict wind power with emphasis on situations like complex terrain, extreme weather conditions and offshore prediction, to assist with the integration of large amounts of wind power into the grid. The prediction models were implemented in a software platform and installed for online operation at onshore and offshore wind farms by the end users participating in the project.

With SAFEWIND, these models were extended to include uncertainties in the forecasts, for instance, by means of ensemble forecasting. This is important because misestimating meteorological conditions or large forecasting errors (phase errors, near cut-off speeds and so forth) are costly for infrastructure (for example, unexpected loads on turbines) and reduce the value of wind energy for end users.

One of the main achievements of these two projects, but particularly the first one, was to form an enterprise that allowed commercialization of the output: a wind forecasting system called ANEMOS. This enterprise had, as one of its customers the Australian Energy Market Operator,[108] which commissioned ANEMOS as its first operational Australian Wind Energy Forecasting System in 2008. This system, which was updated over the following several years, was then followed by its analogous Australian Solar Energy Forecasting System, the implementation of which started in 2012 and was built using the Australian Wind Energy Forecasting System infrastructure. Having implemented an operational system based on a research project, and for a market and conditions external to those originally developed for, the European one, this can be considered a success story in terms of exploitation of results in a commercial environment.

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[105] In this context, "exploit" is taken to mean making use of results in a commercial, societal or political purpose.

[106] https://cordis.europa.eu/project/id/ENK5-CT-2002-00665.

[107] https://cordis.europa.eu/project/id/213740.

[108] https://aemo.com.au.

Box 5.3 provides an example of W&CSs for energy trading in Croatia that contributes to reducing operational costs and multi-risk exposure, and increasing efficiency.

Box 5.3. W&CSs for energy trading in Croatia

W&CSs can support cost-effective power system operations, energy portfolio management and trading optimization. Better prediction of weather-sensitive energy demand, inflow, prices, adequacy and market behaviour improve optimization of energy trading, energy generation, water management and maintenance. This contributes to reducing operating costs and multirisk exposure, and increasing overall efficiency.

In general, smart grid stakeholders, such as TSOs and DSOs, balance group leaders, suppliers and aggregators, have a challenging role in coping with a gap between securing electricity supply and mitigating the many risks they face in daily operative processes. Those risks include meteorological and hydrological events, IT issues, power system failures, power market price volatility and corresponding illiquidity in critical moments.

To assist in operative activities, every balance group leader must deliver their schedule of forecasted behaviour of their individual portfolio for the day ahead and the next day, in an hourly resolution. Accuracy of such forecasts and corresponding schedules depend on the forecast quality of input factors such as weather forecast, inflow forecast, load forecast, wind and solar forecast, price forecast, adequacy forecast in the individual portfolio, the network and the whole market (liquidity) and the power system. The main goal in the optimization process is to minimize costs to customers while maximizing profits.

In the Hrvatska Elektroprivreda's (HEP Group, the national energy company of Croatia) portfolio, the situation is even more complex. More than 60% of total electricity generation capacity comes from hydropower plants, where most energy storage is too small for seasonal optimization. Profit maximization goals are therefore often constrained by inflow unpredictability and water value in corresponding storage.

Some 40% of other renewable energy sources, and particularly wind power, needs to be incorporated into the portfolio through existing regulations. Reliance on conventional, usually uncompetitive, thermal power plants with volatile prices of natural gas, coal and CO_2 emissions units, poses additional challenges, while scarcity of reserves and supply routes additionally emphasizes the topic of risk preparedness.

Unexpected cross-border bottlenecks and power system stability issues highlight the core mission of power systems: providing security of supply to every customer in every moment of their need. Climate change brings more extreme weather and hydrological events (such as heatwaves, droughts and floods) and does not leave enough necessary redundancy for volatilities in the power system and on the market.

Weather impacts on the power system may affect electricity demand, electricity generation and network operation simultaneously. HEP uses knowledge from past and current weather conditions, and also from weather forecasts too. This knowledge is used for different purposes: past data for verification and analysis; current data for activation of ancillary services and remedial actions, rescheduling, intraday trades, schedule re-plans and short- to long-term forecasts for day-ahead up to year-ahead portfolio management and trading; renewable energy generation forecasting; filling/discharging of reservoirs; maintenance; and long-term investment conditions.

To deal with net effects of weather on the energy system and support regular operation of the power system, HEP Trade Ltd, on behalf of HEP, performs the purchase and sale of electricity, gas, emission units and green certificates.

To support portfolio optimization and trading, HEP and DHMZ conduct operational collaboration using a range of W&CSs. These include the DHMZ real-time data exchange, national short-range weather forecasting system ALADIN-HR, extended to medium range with ECMWF forecasts adapted to energy sector needs, forecast verification and warnings from the DHMZ/Meteoalarm warning system. Additionally, DHMZ performs climatological analysis of heating and cooling degree days and analysis of past weather conditions over selected river basins. It also maintains a set of energy-relevant meteorological stations.

HEP uses different methods (such as neural networks, heuristics, and statistical and risk analyses), adequate tools and empirical solutions in such portfolio optimization that incorporate load, inflow, price and adequacy forecasting. All of these processes are continuous, with different time decompositions and revised every day, in hourly and 15 minute resolutions for these periods obeying strict KPIs. The accuracy of these KPIs is important for:

- Intraday re-planning and trading for all balance group leaders in Croatia that have load customers in their portfolio and system operation processes
- Accurate and efficient day-ahead portfolio optimization, trading and scheduling of every used asset
- Portfolio optimization and starting a trading process early enough according to accurate load and other forecasts

In general, energy trading activities bring economic benefits through optimization of costs and support externality mitigation through greater usage of renewables. They also bring SEBs through increasing energy security and enhancing resilience through reduced vulnerability to extreme weather.

With regard to economic benefits, the effects of extreme weather (such as floods, freezing rain, droughts, storms and extreme winds) on the energy sector in Croatia have large economic costs that may be mitigated by efficient use of W&CSs. For example, a single freezing rain event in 2014 is estimated to have left some 14 000 households (80% of the population in the region) without electricity and caused € 15 million in damage to the energy infrastructure in Croatia.

Generally, the net economic benefits of weather services in energy operations are much harder to assess. As HEP has roughly 90% of all load customers in its balancing group, there is no doubt that use of accurate weather forecasts and energy interpretation are a major help in achieving both the following optimization goals in daily operation processes:

- Price minimization – saving resources for "peak hours", especially in circumstances of huge load, weather and price volatility
- Profit maximization – trading and risk hedging at different time-horizons to maximize the power of the asset in an arbitrage

5.2.5 Sustainable business models

Businesses (as well as any other activities, commercial or not) do not operate in isolation, but exist within an ecosystem. The same applies to W&CSs. They can generate positive impacts beyond the customer value (such as SEBs associated with the services for the energy transition previously analysed in section 5.1), yet they can negatively affect the ecosystem at the same time. Classical business models focus solely on creating and delivering value to the costumers while generating value for the business owner and shareholders. Whereas, sustainable business models take a holistic approach, therefore considering also how value is generated for the ecosystem (Figure 5.7).

Life-cycle analysis is considered an essential concept for developing sustainable business models (Evans et al., 2017). It consists of measuring the environmental impact of a product or service throughout its life cycle, from the resources used to create the product or service to its end-of-life destination. It includes assessment

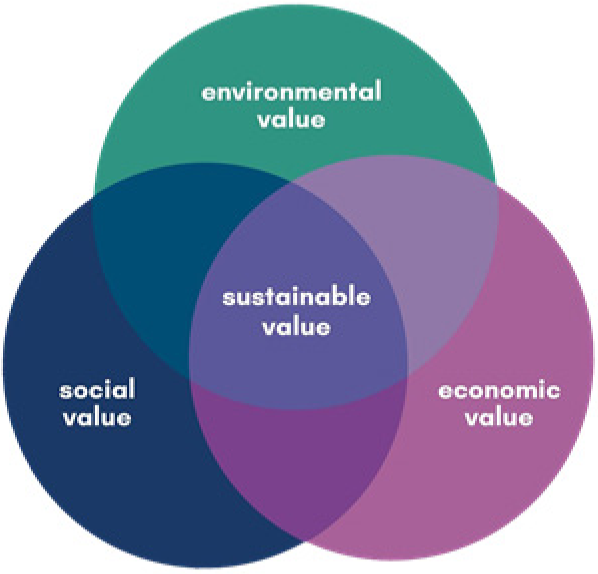

Figure 5.7. Value definition in sustainable business models

Source: Evans et al. (2017)

of all the processes undertaken by the business, as well as by each third party involved in creating and using the product or service (ISO, 2006[109]).

Given one of the core values of W&CSs should be sustainability, it is a shortcoming that the negative impacts generated in their life cycle are not sufficiently discussed. That the mitigation and adaptation benefits outweigh the environmental costs does not mean there is no margin for improvement.

For example, W&CSs are based on models that require supercomputers to run, although to different extents depending on the type of model, the amount of data and the type of service being produced. Supercomputers are highly energy intensive; therefore, choosing computational services powered by renewables would be the obvious choice to limit carbon emissions generated at this stage of the service's value chain.

More generally, it would be important for private and public sector W&CS providers to analyse their entire value chain (including supply and delivery), calculating the impacts of damaging elements and investigating possible solutions. W&CS providers could become role models for sustainable business innovation, minimizing the environmental costs while maximizing their uptake, and ultimately the overall benefits generated.

5.3 Role of public policies

5.3.1 Barriers and policy instruments

The capacity of W&CSs to generate benefits beyond those recognized by end users, creating positive externalities, classifies them as a merit good. W&CSs for energy are often not solely beneficial for their users, but have broader impacts on energy transition as well as on society and the ecosystem (see Figure 5.7). It has also been mentioned that if the provision of such services is left entirely to the private sector, they are likely to be undersupplied and underconsumed. Thus, appropriate policy interventions can correct this potential market failure.

The quality and availability of W&CSs have increased at great speeds in recent years, thanks to institutional support and advances in technology. However, these services remain underutilized. The scholarly community identifies this as the "usability gap" (Findlater et al., 2021). The reasons behind this gap have been thoroughly discussed in two European Union projects: European Market for Climate Services (EU-MACS)[110] and MArket Research for a Climate Services Observatory (MARCO).[111]

Both projects analysed the market for W&CSs and mentioned several obstacles to their uptake that appropriate policies could help address. The obstacles mentioned include: the lack of incentives for incorporation of these services into organizational practices; that sectors tend to have a short-term decision-making orientation; information asymmetries, meaning that potential users may have difficulties in evaluating the quality of the services offered; and lack of awareness of the existence of these services, or of their usefulness from the end user's point of view.

Additionally, user needs are sometimes not well understood by the services development community, and providers face lack of resourcing for the delivery phase. However, EU-MACS and MARCO reported the situation up to the end of 2018, when these projects ended. Given ensuing investments, such as the continuous support by the European Union to especially climate services development, exploitation of W&CSs is slowly improving.

There are different types of policies that could address these barriers. For simplicity, policies can be categorized into seven broad categories: regulation, legislation, guidelines, service provision, fiscal measures, environmental/social planning, and communication and marketing (Michie et al., 2011), as illustrated in Figure 5.8. Each of these policy categories can be implemented within a spectrum of compliance from voluntary to mandatory (Howlett, 2019).

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[109] https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.

[110] https://cordis.europa.eu/project/id/730500.

[111] https://cordis.europa.eu/project/id/730272.

Figure 5.8. Policy instrument categories in support of W&CS uptake

Table 5.4 summarizes the policy categories, providing definitions and examples of each category, with reference to W&CSs in support of the energy sector.

Table 5.4. Summary of policy categories

Policy category	*Definition*	*Example*
Legislation	Making or changing laws	Requirements for large power plants to provide W&CSs
Regulation	Establishing rules or principles of behaviour or practice Enforcing the legislation	Establishing rules on data transparency, quality assuranc e and accessibility (see section 5.3.2)
Guidelines	Creating publications that recommend or mandate practices, including changes in service provision	Producing and disseminating protocols
Environmental/ social planning	Designing and/or controlling the physical or social environment	Using town planning and other planning tools in support of energy transition
Fiscal measures	Using subsidies/taxes to reduce/ increase the financial costs	Reducing taxes for companies providing W&CSs or for renewable energy companies
Service provision	Delivering a service	Delivery through platforms such as C3S CDS
Communication and marketing	Using print, electronic, telephonic or broadcast media	Training and communication campaigns to raise awareness about W&CSs

Policies can incentivize the uptake of climate services directly or indirectly. Direct policy measures are those that specifically address W&CSs. Indirect policies are linked to W&CSs, but not necessarily in an explicit way. For instance, measures that, even if broader in scope, support one or more stages of W&CS co-production and delivery can be considered closely linked (for example, open data policies). Similarly, measures that enable the resilience and reliability of renewables (for example, storage, demand management systems and measures to increase the flexibility of the grid) can be considered as indirectly linked, since W&CSs are tools that can support implementation of those measures. Other measures, such as the adoption of renewables, can ultimately increase the need for W&CSs in the sector, since the effectiveness and efficiency of renewables are dependent on climate variability and climate change.

Indirect policies are more frequent than direct ones (Kielmanowicz and Salel, 2017[112]). An example at European Union level is the European Union Risk Preparedness Regulation 2019/941 (European Union, 2019) included in the Clean Energy for all Europeans package. The regulation explicitly requires the European Network of Transmission System Operators for Electricity to use weather information for adequacy assessments. Seasonal assessments are also required, but without direct requirements for seasonal forecasts applications.

As concluded by the EU-MACS project, there is no optimal policy mix for promoting services uptake; therefore, a strategy needs to be composed by sectors, States and regions built on their abilities and market conditions to address their needs. Some widely discussed policy measures in the W&CS fields are next reported.

5.3.2 Policy intervention areas

A comprehensive policy analysis is out of the scope of this publication. However, this section briefly presents some policy recommendations relevant for W&CS uptake.

5.3.2.1 Demand-driven funding

Research policies should invest adequate funding on the demand side of climate services. Special attention should be paid to the critical phase after research and innovation projects have ended. At this stage, there are needs for maintenance, development and tailoring according to user needs. The co-design of W&CSs should take these aspects into account from the beginning. Moreover, Hermansen et al. (2021) suggest offering complementary exploitation grants and seed funds to those research and innovation projects with exploitation potential. End users should be involved in these funding decisions (Hermansen et al., 2021). In the case of Europe, such (competitive) grants are available through for instance the European Union, the European Space Agency (ESA) and the European Institute of Innovation & Technology. Moreover, to assist with the lowering of barriers to entry for W&CSs, the European Union has introduced a support mechanism, which applies to European Union funded projects, in an effort to fully exploit their results: the Horizon Results Booster.[113]

5.3.2.2 Supporting seamless systems

Decision-making in the energy sector deals with actions at different timescales according to climate modelling. Yet these are often perceived as a continuum by users. Seamless systems should facilitate usage of the services across decision-making areas. Future research and innovation actions should support the technical development of methods and services that bring together all relevant temporal scales, from weather forecasts up to projections, with a focus on the provision of indices and tailored products consistent across temporal and spatial scales.

5.3.2.3 Climate risk reporting, transparency and accountability

The lack of incentives in the usage of W&CSs for some private sector actors and the short-term business orientation for other businesses can be tackled by legislation on accountability and reporting transparency regarding exposure to climate change risks. Specifically, with regard to company reporting, TCFD[114] was launched in 2017. TCFD started from the recognition that climate change presents financial risk to the global economy and therefore that financial markets need clear, comprehensive, high-quality information on the impacts of climate change. This includes the risks and opportunities presented by rising temperatures, climate-related policy and emerging technologies in the changing world. If widely adopted, TCFD could provide a powerful boost to the development and exploitation of W&CSs.

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[112] https://s2s4e.eu/sites/default/files/2020-06/s2s4e_d62.pdf.

[113] https://www.horizonresultsbooster.eu.

[114] https://www.fsb-tcfd.org.

5.3.2.4 Standards

As mentioned in section 5.2, potential W&CS users face significant transaction costs (those costs associated with the search, selection and acquisition of services). Definition of standards can alleviate transaction costs and ease uptake. Standards on quality control, assurance and the way the information is presented would reduce the information asymmetry. Such standards could be championed by organizations such as WMO following, for example, International Organization for Standardization standards adopted by analogous services.

5.3.2.5 Open and affordable data policies

Open data policies can support the creation of new W&CSs, increase user awareness on their availability and usability, and accelerate uptake of existing ones. For NMHSs in developing countries, open data policies can imply access to global ensemble systems, as mentioned in a WMO White Paper (WMO, 2021a) (see section 5.4.1 below). In Europe, member States differ greatly on their open data policies and public data reuse practices (Cantone et al., 2020[115]). "Open data" does not necessarily imply free of charge, as some services can be maintained only with exchange of a fee that helps cover part of the production and/or delivery costs. However, policies should aim at making data as affordable as possible.

An example of a service that promotes an open data policy is C3S, coordinated by the European Commission and implemented by ECMWF. C3S provides climate data across a wide range of user-centred sectoral applications, illustrated across worldwide case studies. Buontempo et al. (2020) highlight the reasons behind the commitment to open data by C3S, as well illustrated in its three main pillars:

- A climate-resilient society can be built only if enough professionals are involved in the development, distribution and use of climate-informed services.

- For this to happen, it is necessary to eliminate the barriers that prevent access and easy manipulation of high-quality climate data.

- For the quality of the service to be sufficiently high, it is necessary to have an operational set-up that could curate the data and provide the necessary user support, examples of good practice and training.

However, it should be noted that while the Copernicus data policy, and hence C3S, is an enormous step forwards for Europe, there are still limitations in data availability. For instance, seasonal climate forecasts are available only at a reduced geographical resolution (a standard 1° × 1°), and, more critically for business, with a delayed delivery time (forecasts are made available about a week later than when they are produced and available to paying users).

With data being a core element of W&CSs, and given WMO is the organization in charge of the international coordination of weather and climate data, the following section 5.3.3 focuses on data with particular attention to WMO policies.

5.3.3 Data for weather and climate services and WMO policies

Meteorological data are essential to WMO and its Members – from recording and transmitting measurements, to inputs and outputs of state-of-the-art models, to channels used to deliver information and services to users, to analytics that describe how, when, where and why they use data. However, how effectively data are used in different sectors to meet sectoral and societal needs is of great importance. For example, in the energy sector, weather, water and climate data are needed over the short term to support responses to severe weather events and market, over the medium term to facilitate operations and planning maintenance, and over the longer term for historical climate insight and assessment of future impacts for building climate-resilient energy systems.

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[115] https://drive.google.com/file/d/1GyKjA_RhW6z9er1WJIb1zEy3Vjr-XT70/view.

It is recognized that developing countries face the biggest challenges in many aspects related to developing W&CSs for the energy sector, with data being one. One of the aims of WMO and its community is thus to ensure global connectedness. WMO has published a series of data policies containing these principles and to which its Members commit (see Table 5.5; WMO, 1995, 1999, 2015b).

Table 5.5. Resolutions and relevant data-related WMO publications

WMO resolutions and publications related to data policy	*Description*
Resolution 40 of the Twelfth World Meteorological Congress (WMO, 1995) Resolution 25 of the Thirteenth World Meteorological Congress (WMO, 1999) Resolution 60 of the Seventeenth World Meteorological Congress (WMO, 2015b)	Historically, Members committed to WMO data policies as prescribed in these resolutions
WMO Unified Data Policy (WMO, 2022a)	The latest approved update on WMO data policy provides a unified approach for the international exchange of Earth system data for all WMO domains and disciplines. It reinstates the policy of free and unrestricted international exchange of core data. Members should ensure that users from all sectors – public, private and academic – are granted free and unrestricted access to the declared Earth system data, without charge and with no conditions on use.
Geneva Declaration of 2019 (WMO, 2019c, Resolution 80) *Guidelines for Public-Private Engagement* (WMO, 2021h) *WMO Strategic Plan 2020–2023* (WMO, 2019d)	These recognize and provide guidance on the rapid growth of data produced by the private sector. The Geneva Declaration represents WMO high-level policy on public–private engagement (PPE) and reflects the new paradigm of cooperation and partnership among stakeholders from all sectors of the weather, climate and water enterprise needed for a concerted response to global societal risks related to extreme weather, climate change, water scarcity and other environmental hazards.
Manual on the WMO Information System (WMO, 2021g)	The main access to core data provided by countries is through this manual. Members are asked to make available a catalogue of recommended data to facilitate their use under the established conditions.

The latest WMO data policy[116] is on Earth system data policy, for which WMO has pledged to broaden and enhance free and unrestricted international exchange (WMO, 2022a). Earth system data is a rapidly expanding and evolving area of innovation in terms of sources, distribution, variables covered and technology. Successful implementation of meteorological data application in any sector, energy included, will depend on the use of all these data streams as they are highly interconnected. The observational and other core data necessary to perform weather, climate and hydrology monitoring and prediction efforts by WMO Members according to the WMO unified data policy (WMO, 2022a) are:

- *Manual on the WMO Integrated Global Observing System* (WMO, 2021d)[117]
- *Manual on the High-quality Global Data Management Framework for Climate* (WMO, 2019a)[118]

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[116] https://library.wmo.int/doc_num.php?explnum_id=11256.

[117] https://library.wmo.int/index.php?lvl=notice_display&id=19223.

[118] https://library.wmo.int/index.php?lvl=notice_display&id=21686.

- *Manual on the Global Data-processing and Forecasting System* (WMO, 2021e)[119]
- *Technical Regulations, Volume III: Hydrology* (WMO, 2021f)[120]

Meteorological and hydrological data are already among the most complex types of data to manage. They are big in quantity, and are heterogeneous, dynamic, multidimensional, inherently geospatial and multitemporal. These data are used for critical safety purposes and are essential to major socioeconomic activities. They are required to always be operationally accessible, in real time, through a diversity of formats, protocols and standards. They also form the basis of a reliable, long-term climate record, on which key economic and policy action plans depend.

All these considerations, from the complexity and availability of data to the demand placed upon them, will further increase in coming years. Data volumes, diverse sources of data, big data analytics, growing demand for open data, and commercial data and services are among the emerging data issues following the production chain from measurements to service delivery. WMO has also provided a general view on these emerging data issues (WMO, 2019b[121]).

These issues are partially behind the need for increased national and international collaboration on Earth system data. The rationale is similar in nature to the driver for international data exchange, and it concedes that: “Data sharing creates mutual benefits for all stakeholders” (WMO, 2022a). Regional or national open data policies for access to public data require public agencies, including NMHSs, to provide free and open access to all their data. In cases where additional mechanisms for facilitation of free access are needed, the possibility to recover the marginal costs incurred for data reproduction, provision and dissemination could be applied.

Facilitating a dialogue between the public sector and private companies active in a country could result in the use of private sector data to fill the gaps and optimize the national integrated observing networks. Meteorological data collected from renewable energy power plants are a good example of using private energy company data in the public sector. In the latest WMO data policy (WMO, 2022a), Members are obliged to ensure core data, purchased from private sector data providers, are appropriately licensed for free and unrestricted international exchange.

Reciprocally, private sector stakeholders should consider approaches to data sharing in certain situations, such as for data needed in critical situations related to saving lives and protection of property. This comes with the understanding that all sectors commit to their social responsibility and contribute to delivery of the public good. The main difference of these data, from the policy and business model perspective, is that they are produced with private investment and thus have a specific private sector owner. Nevertheless, the general recommendation of the Geneva Declaration (WMO, 2019c, Resolution 80[122]), which has been developed in close consultation with the private sector, encourages data sharing with stakeholders under mutually beneficial, fair and transparent arrangements.

The WMO Information System (WMO, 2021g[123]) and WMO Integrated Global Observing System (WMO, 2021d[124]) concepts acknowledge and enable the uptake of private sector data into WMO systems at national and international levels. This approach is expected to bring efficiency and innovation, as well as support sustainability. The demand for accurate and reliable user-specific services in different sectors (for example, energy) and for a new generation of weather and climate intelligence products (for example, for urban areas and megacities) will inevitably require more integration of private sector data into the data assimilation for high-resolution weather and climate prediction (WMO, 2021g).

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[119] https://library.wmo.int/index.php?lvl=notice_display&id=12793.

[120] https://library.wmo.int/index.php?lvl=notice_display&id=10700.

[121] https://library.wmo.int/doc_num.php?explnum_id=10124.

[122] https://library.wmo.int/doc_num.php?explnum_id=9827#page=254.

[123] https://library.wmo.int/index.php?lvl=notice_display&id=9254.

[124] https://library.wmo.int/doc_num.php?explnum_id=11157.

Finally, given the importance of research as a key enabler of successful weather and climate prediction, and its continued contribution to all WMO application areas, collaboration on data with the research sector is also particularly important for WMO, NMHSs and other related national agencies. Open data policies are well recognized to facilitate science and maximize the value of data in academic settings. Most data providers from the research community are of a non-commercial nature, and they generally do not charge for access to data. However, they may request attribution of the source of the data, when used as a basis for scientific publications and also if they are integrated into operational products and services.

Despite the significant progress in making data more freely available (such as in the case of the WMO resolutions and publications mentioned above), massive barriers still exist. For instance, unlike in the United States where data paid for by the taxpayer are freely available to all, data policy in Europe is such that acquiring data for weather or seasonal climate forecasts is often a huge obstacle, as its price can reach a few hundred thousand euros a year. This is an enormous barrier to entry for most start-ups, unless they have some strong financial backing from wealthy investors (for example, venture capitalists).

However, data policy in Europe is slowly changing, and data from European meteorological services, which constitute a large share of data available globally, should become mostly free by 2025 (ECMWF, n.d.d[125]). Meanwhile, there are also homologous data freely available, but they normally come at a lower temporal or spatial resolution, or more often both, as well as in a less timely manner.

5.4 Partnerships and cross-sectoral collaborations

5.4.1 Understanding public–private engagement

The successful uptake of W&CSs for the energy transition requires close collaboration among a multitude of public, private and third sector partners, as well as with research and academic organizations. These partnerships and other collaborative endeavours are part of a global shift towards increasingly hybrid forms of governance that mix the more traditional command-and-control regulations with market and network approaches (Jordan, 2008; Jordan and Matt, 2014). An illustration of this change was formalized with the 2030 Agenda for Sustainable Development, where SDG 17 stresses the importance of the "Global Partnership for Sustainable Development" and recognizes cross-sectoral and multi-stakeholder processes as key.

WMO has promoted the establishment of this collaboration culture at least since the mid-1990s, especially with regard to W&CSs. The Twelfth World Meteorological Congress consolidated the first guidelines for information exchange with private actors. It refined the guidance and policies aimed at encouraging and enabling Members to pursue mutually beneficial partnerships and engagement among all sectors and stakeholders, to enhance weather, climate and water services for business, individuals and society as a whole.

In 2019, at the eighteenth session of the World Meteorological Congress, WMO released the Geneva Declaration. This Declaration represents the WMO high-level policy on PPE and reflects the new paradigm of collaboration and partnership among stakeholders in the cross-sectoral efforts needed for a concerted response to global societal risks related to extreme weather, climate change, water scarcity and other environmental hazards. WMO defines PPE as "the various forms of interaction and collaboration between entities from the public, private and business sectors, as well as academia and civil society, in the production and delivery of weather, climate, hydrological, marine and related environmental data, information and services to users worldwide" (WMO, 2022c[126]). At the heart of the WMO PPE approach are the core principles outlined in the WMO principles for PPE (WMO, 2021h[127]) as follows:

- People first principle – recognizing the priority of saving life and property and enabling economic productivity through provision of essential meteorological, climatological, hydrological and environmental information.

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[125] https://www.ecmwf.int/sites/default/files/ECMWF_Roadmap_to_2025.pdf.

[126] https://public.wmo.int/en/our-mandate/how-we-do-it/public-private-engagement-ppe.

[127] https://library.wmo.int/doc_num.php?explnum_id=10607.

- Fair and transparent relationships between non-commercial and commercial entities.

- Ensuring mutual benefit – while the public sector is more likely to invest in long-term programmes and underpinning infrastructure, the private sector is more apt at applying innovation and promoting the uptake of emerging technologies. Together, these sectors can cooperate to ensure mutual benefits.

The first WMO Open Consultative Platform White Paper on the future of weather and climate forecasting (WMO, 2021a[128]) lists several reasons why working towards an increase in PPE is crucial to reach the objectives under the net zero transition:

- The private sector dominates many investment sectors that could be linked to climate services and therefore can help mobilize financial resources and technical capabilities, leverage the efforts of governments, engage community efforts and civil society, and develop innovative climate services technologies.[129]

- As section 5.3 discussed, the private sector is increasingly producing its own data. In some regions, data deficits are a real concern due to lack of public investment. Thus, PPE and public–private partnerships could fill in this gap, by adapting the data to the needs of other stakeholders in the net zero transition.

- Academia is called upon to perform an important role in scientific consulting on high-risk research, in the short and long terms. The increasing applied research activity by the private sector can generate cross-fertilization among these stakeholders.

- With the implementation of ethical codes as well as transparency policies, open communication practices, including data sharing among relevant stakeholders in weather and climate information, may unlock the potential of science and technology to speed up and meet the outcomes of this transition.

- Key private sector actors are already investing in artificial intelligence, through high-risk innovation support by public funds. Because of the dissemination capacity of such global players, technologies developed under their efforts in collaboration with academia and the public sector can fill in important gaps in the necessary advancement of technologies.

For academia–industry collaborations in PPE in hydrometeorological services, the article by Frei (2021) lists the benefits for universities and industry of such partnerships, including:

- For universities: Access to additional funding, receiving feedback and guidance from industry partners, access to jobs for students, and greater capacity to innovate for entrepreneurial-minded students with the creation of strong bridges between the industry and the universities due to the student-to-employee pipeline.

- For industry: Talent acquisition and new ideas that can become successful start-ups, including with the commercialization of new technology that contributes to the net zero transition. Additional benefits include access to faculty leaders and thus high-level scientists. Also, these collaborations can bring efficiency through research-cost avoidance.

In this regard, a second Open Consultative Platform White Paper addresses the biggest challenges facing the global W&CSs community by focusing on evolving roles and responsibilities of National Meteorological or Hydrometeorological Services and how they engage with other stakeholders in a multisector enterprise, to better serve society and better use available resources (WMO, 2022d[130]).

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[128] https://library.wmo.int/index.php?lvl=notice_display&id=21856#.Yg9mX-jOFnJ.

[129] See an illustrative example with the platform of weather intelligent start-ups: https://tracxn.com/d/trending-themes/Startups-in-Weather-Intelligence.

[130] https://library.wmo.int/doc_num.php?explnum_id=11246.

5.4.2 Role of partnerships in service value chains and associated barriers

Multi-stakeholder collaboration processes can take different forms. These include "partnerships", defined as a process of "working with international agencies, other organizations, academia, the media and the private sector to improve the range, quality and delivery of critical environmental information and services" (WMO, 2021h). They also include policy dialogues, which according to OECD pursue two main objectives: developing policy agendas at several governance levels that consider the interests of all partners and facilitating behavioural change through the advancement of corporate practices as well as the standards that the industry sets (OECD, 2016[131]). Policy dialogues can be institutionalized dialogues and can be established through mechanisms such as multi-stakeholder networks and platforms, cross-sectoral roundtables and specialized hubs.

In 2017, the EU-MACS project reviewed the market conditions of climate services. One of the studies conducted surveys with weather- and climate-related stakeholders, and yielded an overview of the climate services value chain, showing the presence of the different stakeholders in the various stages of co-development. PPE is expected to enable the sustenance of this value chain as well as helping in its creation, according to a World Bank study on the power of partnership (World Bank, 2019; Frei, 2021).

The World Bank lists several barriers to effective PPE, including underestimation of a well-developed value chain, and considers also the plurality of stakeholders in addition to NMHSs or related public entities. The World Bank report emphasizes that to understand a country's value chain, there are three main elements to identify: "*maturity* of the hydromet value chain (how mature is the hydromet value chain and each element of the value chain in a given country); *sector balance* (to what extent do the public, private, and academic sectors contribute to the hydromet value chain); and *policy framework* which shapes the hydromet value chain" (World Bank, 2019).

In least developed countries (LDCs), public–private partnerships could be slowed down due to:

- Knowledge gaps in climate services, resilience investments, private sector finance and the role of private sector finance in climate services.
- Lack of research and development in the private sector in particular, and its role in climate services.
- Inadequate information and expensive datasets. In many African countries for example, access to datasets is challenging due to public policy.
- Institutional abilities being rigid and inflexible to embracing new ideas, innovation and creativity.
- Technological and financial resources being limited.
- Human capabilities being limited and inaccessible.

5.4.3 From theory to practice: Cross-sectoral partnerships and collaborations

The critical role of cross-sectoral interactions to support the uptake of W&CSs for the net zero transition in the energy sector is undeniable. For instance, the link between the energy and water sectors is evident in the case of hydropower production for energy, and the competing use of water for other purposes (for example, in agriculture, flood control and recreational uses). Another example is the link with urban planning as discussed in Box 5.4.

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[131] https://www.oecd.org/dac/peer-reviews/Inventory-1-Private-Sector-Engagement-Terminology-and-Typology.pdf.

Box 5.4. Examples of cross-sectoral synergies

Urban planning and energy

The urban climate is different to that in rural areas in terms of air temperature, humidity, aerosol, wind and precipitation, due to anthropogenic activities. Typically, changes in surface properties by impervious materials and anthropogenic emissions modify the urban atmosphere (Oke et al., 2017).

One example of a unique urban climate is the urban heat island (UHI), in which the urban area is warmer than its surrounding rural area. With global rapid urbanization, millions of people migrate into cities every week. It is therefore critical to understand city–environment interactions to improve the environment and climate experienced by many people on Earth. Cities are unsustainable because they do not produce the necessities by themselves, and require intensive use of energy, water and food. Accordingly, the highly populated urban areas are vulnerable to climate change and natural hazards with regard to shortage of food, water and electric power in a changing climate.

Sustainable urban planning and management play a key role in climate change adaptation to mitigate societal impacts by heatwaves and UHIs, and is one of the primary target sectors for climate services (Cortekar et al., 2020).

Core technology for urban mitigation strategy is green infrastructure such as urban forests and green roofs. However, it remains difficult to assess the benefits and costs of artificially generated urban vegetation. For example, trees shade and hinder solar access and thus impede PV power generation, and air pollution will change due to urban trees because of organic compound emissions, which will be reinforced under global warming. In general, a UHI produces more precipitation in a downwind suburban area, thus providing ample water and clear air in the suburban area. The urban climate is also influenced by building structure and function and socioeconomic evolution (Hong et al., 2019).

Urban mitigation actions related to energy also cover cooling roofs, shading, generation and use of renewable energy, and the use of electric cars. However, there is a lack of multifarious impacts assessment, considering GHG emissions, UHI and atmospheric environment together. To increase urban climate adaptation and move towards carbon net zero emissions in a changing climate, climate services need to provide high-resolution information on the microclimates in cities. In addition, impacts of policy on various issues such as GHG emissions, heatwaves, water supply and electricity consumption need to be investigated (Hong et al., 2019).

Experience gained in projects like SECLI-FIRM highlights the importance and value of tailoring at all stages of climate service development (identification of needs, tailoring of forecasts, development of visualization tools, evaluation and so forth), where the service is aimed at supporting specific user-defined applications and decisions. This case study approach contrasts with the optimal form of stakeholder engagement, which is favoured in the development of a more generic climate service for a broader sector – such as the ECEM Demonstrator (Goodess et al., 2019). While the former approach likely leads to more expandable W&CSs in the short term, the latter would be more appropriate for a wider exploratory approach within and outside the energy sector, therefore likely leading to enhanced cross-sectoral synergies.

Cross-sectoral collaborative research structures

WMO, with its Research Board, has sponsored several cross-sectoral and collaborative research structures. The Board is a coordination body, with the aim to facilitate interaction of existing research communities – the Global Atmosphere Watch programme, WCRP and WWRP – with new and relevant areas of science. The Board has assigned a focal point for WMO SG-ENE, allowing better connection to the different projects and initiatives of relevance to the energy sector.

There are two collaborative structures that stand out: the S2S project and the Integrated Global Greenhouse Gas Information System (IG^{3}IS).

The S2S project is running a real-time pilot initiative (2019–2023) to identify methods to produce and evaluate useful and usable (and how variations within sectors and organizations) application-oriented forecasts and tools, to derive a broad set of best practice guidance that can support NMHSs to move from S2S research into operational products now and in the future. This initiative targets diverse geographic coverage and a range of sectors including energy, humanitarian, defence, disaster risk reduction, civil protection, health, water and agriculture.

The Energy Compact IG^{3}IS aims to bring IG^{3}IS into the energy sector. The goal of the project is to look at the mitigation potential of the sector rather than on a traditional climate service for energy. The project time frame is 2021–2030. The advantage of the observations-based methodology is to ensure consistency of emissions estimates across sectors and scales. The same observations and modelling tools can be used to assess emissions from oil and gas facilities, forests or agricultural land, providing an opportunity to objectively quantify the fluxes of GHGs.[*]

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[*] http://www.s2sprediction.net/.

6. CAPACITY DEVELOPMENT FOR WEATHER AND CLIMATE SERVICES IN SUPPORT OF THE ENERGY TRANSITION

6.1 Understanding capacity development

Capacity-building (or capacity development) is a process through which people, organizations and societies maintain, strengthen, create and adapt their abilities to manage their affairs successfully over time, realigning with changing conditions (GIZ, 2018[132]). Similarly, WMO defines capacity development as “the process of strengthening the abilities or capacities of individuals, organizations and societies to solve problems and meet their objectives on a sustainable basis” (WMO, 2020b[133]).

The development and implementation of W&CSs require multidisciplinary, multiactor and multi-institutional collaborations and capacities at all stages of value chain creation (WMO, 2020b). The widespread and effective use of W&CSs for energy requires significant interactions among a multitude of actors, including public bodies, international cooperating groups, networks and associations, industry stakeholders, project developers, energy experts, policymakers and decision makers, funders and investors, civil societies, affected communities and individuals at various spatial scales. Each of these stakeholders will have different, context-specific capacity needs.

Capacity-building (or development) enables these stakeholders to take ownership and leadership, and help develop and strengthen the skills, abilities, processes and resources that organizations, individuals and communities need. These activities may focus on systemic processes and programmes, be continuous, and be built on a measurable needs-based process, with a systematic approach across teams or larger groups at institutional and organizational scales (USAID, 2011[134]). Capacity-development activities may also include single events, training or ad hoc activities focused on one or a few individuals, depending on stakeholder needs and available resources.

To ensure successful implementation of W&CSs, WMO has identified four spheres of capacity development (WMO, 2020b). These are institutional, infrastructural, procedural and human resources levels of capacity development, as illustrated in Figure 6.1 and defined below. This publication builds on this framework to ensure relevance to the needs and multitude of stakeholders involved in the co-creation of W&CSs in support of the energy transition.

Institutional capacity development refers to capacity development at an organizational or institutional scale, including across teams or larger groups. Related activities may include defining institutional arrangements, roles, responsibilities and legal mandates for developing and delivering W&CSs. Other activities could address materials, tools, resources, support, time or information needed to engage in certain activities. With reference to climate services, an example of institutional capacity could be the establishment of the National

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[132] https://www.giz.de/en/downloads/giz2018-en-orientierungsrahmen-capacity-development.pdf.

[133] https://library.wmo.int/doc_num.php?explnum_id=10272.

[134] https://pdf.usaid.gov/pdf_docs/PNADW783.pdf.

Figure 6.1. Capacity-development (or building) framework

Source: Adapted from WMO (2020b)

Frameworks for Climate Services.[135] These are institutional mechanisms for the coordination, facilitation and strengthening of collaboration among national institutions to improve the co-production, tailoring, delivery and use of science-based climate predictions and services by focusing on the five pillars of GFCS.

Institutional capacity development also includes the development of cooperation partnerships and networks that enable the uptake of W&CSs for the energy transition. These could include stakeholder interactions, regional and global collaborations, and public–private partnerships across and between institutions or organizations. In this context, the stakeholders are numerous and span international donors, development agencies and organizations, national and subnational policymakers and decision makers, private sector partners, grid operators and their associations, researchers and dedicated NGOs.

Infrastructural capacity development refers to the development or strengthening of infrastructure for providing weather, climate and related services. This may include observation systems, computing power, data access, data management and exchanges, weather and climate forecasting and projection, and communication requirements. At a national level, NMHSs commonly own and operate most of the infrastructure required for W&CS delivery, but this can also include private sector actors and research institutions that provide weather and climate data, as well as companies and individuals that manage energy systems. Infrastructural capacity may also refer to the infrastructure needed for operating and managing energy systems, in accordance with weather and climate data received (for example, see Box 6.1). In demand management, infrastructure capacity

Box 6.1. Supporting uptake of renewables in Costa Rica

In 1949, the Costa Rican government established the Costa Rican Electricity Institute (Instituto Costarricense de Electricidad, ICE), to generate the electricity required for development of the country. The institute's aim was to develop physical energy producing sources, ensuring the rational use of natural resources. To address this mandate, the Department of Hydrology was created in 1951 to produce the information and analysis necessary for feasibility studies of hydroelectric projects, for generation systems, energy allocation and planning.

In the early days, efforts were oriented at providing information and hydrological analyses for the feasibility studies. Later, with the operation of hydropower plants, new requirements were raised by users in terms of the need for information on inflow, reservoir water levels, and run-off modelling and forecast. The opening of power generation to private entities and advances in wind energy have changed the paradigm of power generation in the country. This has required the development of new capacities to measure and model the generation of third parties, taking into account that wind energy that can at times represent 20% of the country's power

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[135] https://gfcs.wmo.int/national-frameworks-for-climate-services.

generation. The institute has developed a hydrometeorological network comprising 130 hydrological stations (85% of the country's network) and 260 meteorological stations, corresponding to 40% of the national network.

There have been important developments in wind and solar energy in Costa Rica. Due to implications on energy supply and demand, these developments require close monitoring and modelling under conditions of excess production in the electric system, as well as when there are no favourable conditions for their generation, which implies needing backup energy to supply demand. This backup generally comes from hydroelectric energy and therefore requires an improvement in the forecast for the availability of the resource and its uncertainty. If there is not sufficient backup, thermal power sources must be used, which have a strong impact on the cost of generation and on the environment due to the consumption of fossil fuels. The environmental impact can be estimated in terms based on an estimated emission rate of 713 t of CO_2 GWh^{-1}. For example, in 2019, the total emissions were 68 186 t of CO_2.

To tackle this situation, an ambitious project has started to improve the capacity of the Hydrometeorological Department by providing a new database, 50 more solar observation sites and installation of cluster computing (to improve the modelling and prediction of hydrological and meteorological conditions in specific basins and places where production based on wind and solar sources is predominant). This US$ 19 million project is financed in part by the Inter-American Development Bank, project CR-X1014 (US$ 10 million), and an estimated counterpart from ICE of US$ 9 million.

The main quantifiable benefit of the project is obtained from the sale of surplus energy, due to improvement in the hourly flow forecast used for the pre-dispatch of national generation, which is performed daily in the morning before the dispatch day and from which the surpluses and energy requirements to offer to the Regional Opportunity Market are identified. The National Centre for Energy Control estimates the amount of generated energy. Another derived benefit is a better estimation of the country's solar potential and generation of real-time information on solar radiation and wind at generation sites, to improve energy dispatch.

Main stakeholders

The Hydrometeorological Department maintains direct communication with ICE plant operators and the Energy Dispatch Center. There is a working group for planning the operation of the electrical system, which meets weekly to present the weather, climate and hydrological outlook. This is an open forum where, based on the conditions indicated, decisions are made regarding energy dispatch, plant maintenance manoeuvres and operations such as sediment management. This working group addresses the needs for changes in forecast frequencies, information flows and evaluation of the hydrometeorological service provided. Figure 6.2 provides a visual explanation of the stakeholder mapping of energy sector users in Costa Rica.

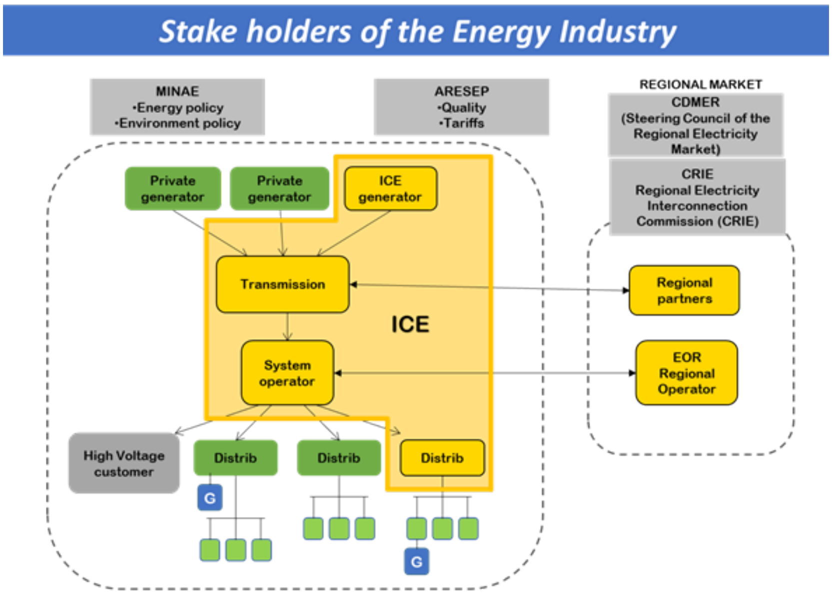

Figure 6.2. Stakeholder mapping of energy sector users in Costa Rica

Note: ARESEP = Autoridad Reguladora de los Servicios Públicos/Regulatory Authority of Public Services; distrib = the process of distribution of energy to clients; G = local and household generation, and distributed power (sun and wind); MINAE = Ministerio de Ambiente y Energía/Ministry for the Environment and Energy; system operator = dispatch and allocation of energy centre; transmission = high-voltage lines; yellow frame encompasses ICE activities.
Source: ICE

may refer to access to data that supports individual demand management (for example, apps on phones, tablets or personal computers, as well as data access).

Procedural capacity development refers to the capacity of stakeholders to undertake all stages of the W&CS value chain process (as described in Chapter 1). It includes understanding user needs and solutions, providing information, co-producing services, operationalizing and co-delivering solutions, informing user decisions and actions, scaling and valorizing, and assessing and evaluating services. Procedural capacity also refers to the availability of regulatory materials, rules and processes to be registered and implemented by all stakeholders. This allows smooth flow of data and information, and a transparent mechanism for charging the costs and all parties' pledges to each other. It also refers to the ability to deliver an efficient and sustained response to disasters, where specific procedures and strategies are needed for a fast response during critical periods.

Different capacities are required for different stakeholders. For example, the development or documentation of processes for operational forecasting (a dedicated 365/24/7 forecasting service) requires capacity for information delivery. Service providers need to communicate clearly with other stakeholders about the accuracy and reliability of the service they are providing, in a way that is clear for non-expert users to understand. These stakeholders often also require development of capacity in implementing co-production and stakeholder engagement processes (as discussed in Chapter 4). Non-expert partners may need to build their capacity with regards to the nature of W&CSs and the benefits of using them. These processes must be documented and accessible, to be effective and sustainable for energy service stakeholders.

Human resources capacity development refers to building and maintaining the capabilities of individuals in a work environment, charged with technical and/or administration responsibilities, to achieve their development objectives over time. The process of building individual capacity for W&CSs related to any sector needs to be adaptive and flexible, and to involve people from the supply (information providers), intermediary (government agencies, NGOs and private sector) and demand (information users) sides. This implies a review of the qualifications, skills and job training required for weather and climate specialists, including those in management positions. It also includes the capacity of end users to make informed decisions based on information relevant to their needs.

Diverse groups of users characterize the energy sector, with tasks ranging from energy use for households to more complex activities like industrial processes, plant operations, power system management and grid coordination. Many of their decisions affect individuals and also the general public. Thus, individual capacity-development activities range from information provision and improved communication, through to targeted training and mentoring for individuals or small groups. For example, learning can take various forms: in-person or online instructor-led courses or workshops, or asynchronous learning (self-paced learning). Courses are offered through international bodies (for example, the WMO Education and Training Programme[136]), universities, research institutes, governmental organizations including NASA (such as the Applied Remote Sensing Training Program[137]), ESA (such as the ESA learning hub[138]) and many more. There are also programmes within developing countries, such as the SWIFT initiative in Africa.[139]

Table 6.1 expands on the levels of capacity development presented above, their scope, key stakeholders, barriers to their uptake and examples of capacity-development activities.

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[136] https://etrp.wmo.int/.

[137] https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset.

[138] https://learninghub.esa.int/.

[139] https://africanswift.org.

Table 6.1. Capacity-development levels in W&CSs for the energy sector

Capacity-development level	*Institutional*	*Infrastructural*	*Procedural*	*Human resources*
Scope	Institutional arrangements, roles and responsibilities, including legal mandates for developing and delivering W&CSs. Arrangements for stakeholder collaboration. Public–private partnerships.	Infrastructure required for providing weather and climate and related services, such as weather stations, data, computing power, bandwidth or Internet access, or other resources.	Definition, development and documentation of adequate processes for operational capacity to co-create, co-produce and co-deliver W&CSs. Also includes communication between W&CS providers and end users.	Building and maintaining capabilities of individuals by means of education and competency-based training. Includes individuals within W&CS providers and all stakeholders within the energy value chain.
Stakeholders	NMHSs, private services, energy commissioners, governmental bodies, or any other relevant institution, organization, agency and other groups such as the National Framework for Climate Services. Also addresses frameworks for fostering collaboration on various spatial scales and among a multitude of stakeholders.	Providers of global, regional subregional, continent-wide weather and climate information and services and energy managers. Also, the ability of end users to access data.	Stakeholders involved in the co-creation of W&CSs for the energy sector across any public and private bodies, research organizations and NGOs.	Individuals from the supply side (information providers, plant operators and so forth), intermediary (government agencies, NGOs and the private sector), transmission and distribution (hybrid grid operators) and demand side (information users).
Barriers*	Mismatches between institutional arrangements and clear legal mandates. Lack of visibility of NMHSs and lack of awareness of weather and climate information generated by NMHSs. Limited technical, financial and human resources. Lack of mechanisms for exchange of information among government agencies. Limited weather and climate knowledge and knowledge about the interdependencies with the energy system. Limited resources or abilities to foster collaborative networks.	Lack of funds to invest in resources, such as computing power, bandwidth improvements and other infrastructure. Providing or receiving energy services may require sufficient computing power and hardware access considering the large file sizes associated with many datasets, tools, models or data products.	Lack of political or managerial will to devote time and resources to the identification, development and documentation of procedures needed for energy service provision. Lack of communication, trust, clear understanding or common grounds for co-creation processes.	Lack of human and economic resources, time, managerial commitment or buy-in to provide capacity development to relevant staff. Training should target multiple individuals to remove potential bottlenecks in the future.

Capacity-development level	*Institutional*	*Infrastructural*	*Procedural*	*Human resources*
Possible capacity-development activities	Visibility of W&CS providers in the national context. Avenues for interaction among W&CS providers and users/clients along the energy value chain. Adequate mandates for W&CS providers to deliver products. Institutional and interinstitutional arrangements.	Provision of surface observations, upper-air observations, weather radar observations, telecommunication and Internet infrastructure and facilities, data management systems, hardware and software, and IT (website, apps and so forth).	Documenting and solidifying procedures for operational forecasting. Training on communication, collaboration and co-production approaches.	Access to technical training. Soft skill training for technical teams. Training on co-production. Support for end users through various levels of user engagement. Access to educational or reference materials. Knowledge-sharing to improve training and other activities.

* Common barriers between all spheres of capacity development (institutional, infrastructural, procedural and human resources): Lack of knowledge of the required quality standards, procedures and good practices for good service delivery.

In all four categories, there is a need for development of quality standards for training. There are already general WMO quality standards; however, guidelines and quality standards for service delivery specific for energy need to be developed, drawing on other publications (IEA, 2021e; Möhrlen, 2022[140]).

Training should aim to fulfil the WMO training standards (WMO, 2015c[141]) and good practices and procedures specified in the Technical Regulations (WMO, 2019e[142]), following the Capacity Development Strategy (WMO, 2015d[143]), to ensure consistency among all recipients of the training programmes.

The levels of capacity-building presented here are useful for better understanding capacity needs (see section 6.2) and proposing suitable capacity-development actions (as discussed in section 6.3). However, there is some overlap among these levels. For example, collaborative networks can be included either under institutional capacity or under procedural capacity. Likewise, some actions to improve individual capacity are also relevant under procedural capacity. Thus, some flexibility is needed when using this framework.

6.2 Capacity needs among stakeholders and across geographies

The status of W&CSs varies significantly across the world. Some countries have well-developed services and capacities. However, others, particularly developing countries and LDCs, require additional capacity to deal with weather- and climate-related risks in general and to apply W&CSs in support of energy transition in particular. In terms of capacity gaps and needs, it is therefore important to distinguish between common requirements that affect a range of W&CS users and the needs of key stakeholders in LDCs. Some of these capacity-development needs are examined below, before looking in more detail at specific challenges for developing countries and LDCs.

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[140] https://iea-pvps.org/key-topics/best-practices-handbook-for-the-collection-and-use-of-solar-resource-data-for-solar-energy-applications-third-edition/; https://www.sciencedirect.com/book/9780443186813/iea-wind-recommended-practice-for-the-implementation-of-renewable-energy-forecasting-solutions.

[141] https://public.wmo.int/en/resources/library/guide-to-the-implementation-of-education-and-training-standards-in-meteorology-and-hydrology.

[142] https://library.wmo.int/?lvl=notice_display&id=14073#.YpSaE1TMK5c.

[143] https://public.wmo.int/en/resources/library/capacity-development-strategy-which-frames-wmo-assistance-national-meteorological.

Box 6.2. Understanding capacity needs in W&CSs for net zero energy transition

In parallel to the preparation of this publication, a short survey was conducted to better understand the perception of capacity needs for the uptake of W&CSs in support of energy transition. People working in this field were approached through social media and professional networks (number of samples = 46). A similar response rate was received from Europe and Africa (35.6% each), followed by Asia (15.6%) and North America and the Caribbean (6.6%), with the remaining 6.6% corresponding to the other two regions (South America and South Pacific). The majority of respondents (43.5%) were closely affiliated with the public and research/academic sectors, 17.4% were affiliated with the private sector, 10.0% with consultancies and 4.4% were from the not-for-profit sector.

When energy stakeholders were asked how important each of the listed factors were in enabling the uptake of W&CSs in support of net zero energy transition, most respondents felt they were either very important or important, as illustrated in Figure 6.3. Supporting policies to uptake W&CSs were considered the most important aspect, closely followed by enabling stakeholder collaboration and ensuring appropriate infrastructure is in place. Note that the targeted audience of this survey (people working in W&CSs for the energy sector) is different from the other survey in Chapter 1 (Figure 1.8), where NMHSs only were asked to participate.

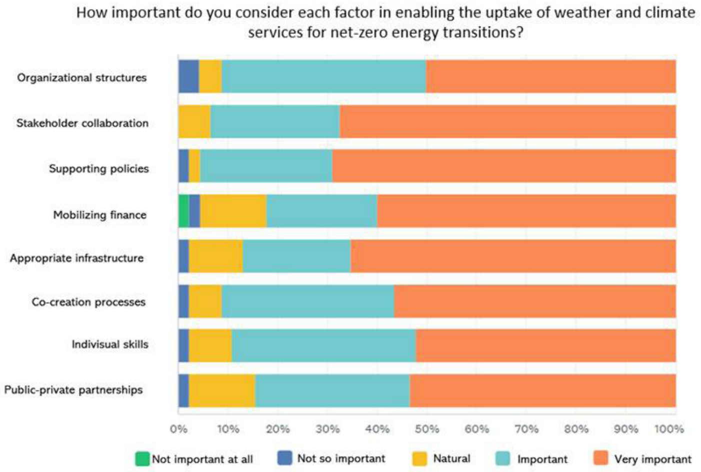

Figure 6.3. Survey results

When asked what solutions were most promising in overcoming obstacles to the uptake of W&CSs for net zero energy transition, most respondents felt that the institutional, infrastructural, procedural and individual capacity-development factors listed in Figure 6.4 were either important or very important. Out of these, enabling cross-sector collaborations through shared activities was considered most important, closely followed by leveraging more funding and promoting a shared understanding of co-creation (or co-production) processes.

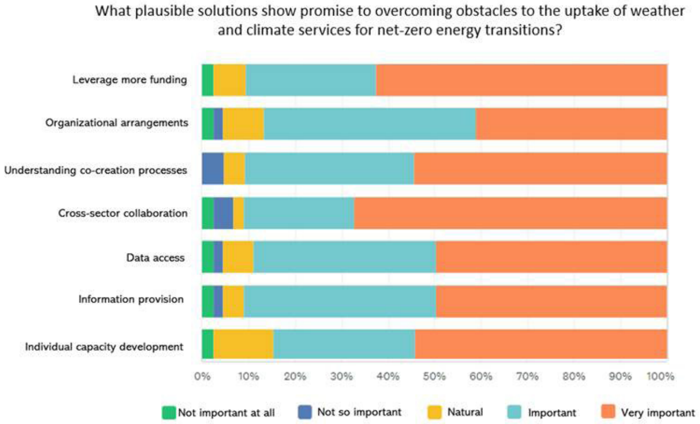

Figure 6.4. Survey results

When asked about capacity gaps for training early career professionals, most respondents felt that providing mentorship and professional development training was the most important capacity-development need, followed by career development and funding opportunities, data access and management, availability of subject matter expertise and adequate training facilities.

When asked how the ability to implement W&CSs could be improved, one respondent noted: "There needs to be more expertise at the intersection of weather/climate and energy. We need people who are trained in: (i) understanding what matters in the energy system (for example, system integration, congestion management, markets and policies) and (ii) evaluating climate information in a way that includes uncertainties (for example, data-type specifics like spurious trends, drifts and the role of internal variability versus forced changes)." Another respondent said: "Enhance computation capacity in data processing, personnel skills development, co-production and co-delivery between institutions, and training and awareness creation for end users for climate services uptake." An additional suggestion was made for "an open, collaborative and sustainable platform with policy support among W&CSs, energy sectors, academics, government departments and intergovernmental agencies on sharing of data and knowledge and to facilitate the exchange of ideas on formulating policies on net zero energy transition."

Additional suggestions included: "A clear link and road map of how weather predictions and supporting services fit into the net zero carbon plan and how the services can assist in planning and execution of projects that aim to reduce carbon emissions" and "W&CSs and research are only useful if done in collaboration with the energy sector and industry. Therefore, cooperation and research between the scientific and energy sectors are imperative."

6.2.1 Overarching stakeholder capacity needs

W&CSs for the energy sector include a wide range of activities such as: the management of meteorological and climatological and linked data (for example, energy systems data); derivation of products relevant for the energy sector from the data; development of techniques and processes to apply the data in the energy sector; and provision of information, analysis and advice to specialist users such as energy experts, energy companies, energy stakeholders and the general public. Box 6.2 provides some results on stakeholder capacity needs in the energy sector.

Capacity needs also vary among stakeholders, such as meteorological organizations, policymakers, energy companies, project developers, investors, researchers, NGOs and the general public. Table 6.2 outlines some common capacity needs and priorities of key energy sector stakeholders involved in W&CSs. However, specific capacity gaps and priorities will vary among stakeholders and also across geographies. For example, while funding may be a concern to meteorological agencies in some countries, it is not a concern in other countries. Table 6.2 builds on the information provided in Table 4.2 regarding stakeholders and their interest in W&CSs.

6.2.2 Capacity-building needs in developing and least developed countries

Capacity-building is an essential component of the effective widespread use, production and design of W&CSs. Moreover, capacity development should align with national and local economic, social and political conditions, to respond to the needs and priorities targeted. However, in many LDCs, several challenges limit the capacity development to improve or retain the needed skills, knowledge, tools and equipment in this field (Rauser et al., 2017; Dike et al., 2018; Langendijk et al., 2019), as discussed below.

To illustrate, in Africa, the following issues have been identified: (i) 25 of the 31 countries were classified as low-income economies, with a gross national income of US$ 1 025 or less per annum, (ii) the 11 countries with the highest proportion of residents living in extreme poverty were in Africa and (iii) despite emitting only an estimated 2%–3% of global CO_2, the continent is predicted to bear the brunt of climate change and related extreme weather events.

Table 6.2. Capacity needs for W&CSs and energy management stakeholders

Stakeholder	*Capacity-development priorities*
Meteorological organizations	Funding, computing power, access to shared data sources. Understanding user needs and building capacity on co-production approaches, communication and cross-sector collaborations.
Policymakers	Training on policy application of W&CSs for energy transition. Understanding interdependencies between the energy sector and weather and climate information, with relevance to policymaking.
Energy companies	Documentation of metadata, validation, accuracy and other metrics. Integration of weather and climate dependency in operational processes. Dealing with uncertainties of forecasts and projections. Methods and tools for making low-carbon energy choices, considering hydrometeorological and climatic conditions. Sharing of data collected by generating facilities (energy demand, energy production and meteorological data) to add value to NWP forecasting models and assimilation for a better co-delivery of the service.
Project developers	Clear and accessible data in an easily understandable format to assess the feasibility of net zero energy project development in light of hydrometeorological and climatic conditions.
Investors	Easy-to-use tools and methods to ensure hydrometeorological and climatic trends are adequately considered in understanding and evaluating the risks associated with uncertainties in the tools and methods to make investment decisions. Benchmarking best practices and knowledge-sharing to support this.
Researchers	Data in formats that can be incorporated into models, tools, algorithm development activities or other research activities. Clear understanding of energy sector user needs. Engagement with transdisciplinary groups such as psychologists or sociologists for addressing user needs and promoting behavioural change and behaviour. Training on stakeholder engagement and effective co-production approaches.
NGOs	Freely available data or services that can be easily digested and shared with a broad audience. Training on the importance of co-production approaches (as defined in Chapter 4) and W&CSs for net zero energy transition.
General public	Tools to make information accessible, relevant and relatable, such as clear labels, units and legends. Providing capacity to understand scientific data through outreach activities and clear communication tools. Development of smart technology for users to closely track energy supply, prices and relation to weather conditions.

These weather extremes, such as extreme rainfall, storms, floods, prolonged dry spells and droughts, and heat and cold waves have severe impacts on communities. Every year, high-intensity weather events result in devastating loss of life and damage to land, property and infrastructure (World Bank, 2010; Shiferawa et al., 2014). Thus, improving the accuracy of weather forecasting and relevant W&CSs is critical for people's safety and for sustainable economic development. Accurate W&CSs will support the energy sector in Africa through predicting and managing variable renewable energy resources, including solar, wind, hydro and biomass, and operation of the associated power plants. They will also support better characterization of the impacts of climate variability and future change on hydro, wind and solar power generation.

In terms of institutional capacity, in developing countries and LDCs, many of the main providers of W&CSs "lack the necessary mandate to interact with users and the capacity to generate and provide the full range of climate services needed by users in an efficient, accurate and timely manner" (WMO, 2014b). This may include legal mandates, interorganizational arrangements to provide W&CSs and institutional arrangements to collaborate with other public institutions, private actors and third sector intermediaries.

Here, there is great scope for **support through international cooperation**. According to the World Bank, large-scale, low-carbon technology transfer is possible only if deployed on a massive scale to developing countries, where technological capacities are still limited (Pigato et al., 2020[144]). Climate and/or low-carbon technologies may include renewable energies, early warning systems or "soft" climate technologies, such as energy efficient practices or training, as well as W&CSs (UNIDO, n.d.[145]). There are numerous international initiatives to support the transfer of climate technologies. For example, capacity-building is a key priority for technology transfer, and there are mechanisms for technology transfer, enabling environments, technology information, technology needs and needs assessments, under the UNFCCC Climate Technology Transfer Framework (UNFCCC, 2016, n.d.[146]). These objectives are implemented by the Climate Technology Centre and Network, which promotes accelerated transfer of environmentally sound technologies for low-carbon and climate-resilient development in developing countries. The Climate Technology Centre and Network provides country-specific capacity-building and advice on policy frameworks,[147] supporting the uptake of climate technologies that reduce GHG emissions (CTCN, 2022). Other international entities that provide capacity-building programmes to support developing countries include: the Global Atmosphere Watch Training & Education Centre, which focuses on capacity-building for Global Atmospheric Watch station personnel,[148] the International Climate Initiative, which assists countries in shifting to a low-carbon economy through capacity-development projects[149] and the Global Environmental Fund, which is the largest public sector funding source supporting transfer of environmentally sound technologies to developing countries (GEF, n.d.[150]).

Infrastructural capacities may include the needs of NMHSs in LDCs for modernization, strengthening and expansion of observational networks and equipment. These include: remote sensing; establishment, or upgrading, of database management systems; strengthening of regional instrumentation and calibration centres; development of telecommunication systems, weather and energy forecasting, postprocessing and service production systems (for example, wind and solar mapping, climate scenarios and finer grid intervals); and storage and archiving of data and analyses (Maletjane, 2012[151]).

Additionally, **limited access to weather and climate data**, due to restrictive data sharing policies and limited collaboration across sectors, is detrimental to the uptake of W&CSs in developing countries and LDCs. Lack of weather and climate data is detrimental for decision-making support and research. LDCs still struggle to secure adequate data access. Africa has one eighth of the minimum recommended weather stations density (WMO, 2019f[152]). This means there is a persistent lack of data in dozens of countries that are among the most vulnerable to climate change. In many of these countries, weather stations are sparsely distributed and government investment in weather monitoring is limited. Even where data do exist, sharing between institutions can be restricted. The interaction among agencies holding the data, research communities, policymakers and users requires ongoing, iterative communication. However, this communication is often limited and data from government meteorological departments are not always accessible to local universities, research institutes and other users due to restrictive sharing policies (World Wide Web Foundation, 2016[153]). Researchers therefore struggle to validate research, even at local scales. Likewise, other stakeholders, such as research institutions or private companies, who would provide W&CSs are unable to do so.

Weather and climate modelling and forecasting requires significant computational capacity, a good technical infrastructure and high expertise by designated personnel. Datasets continue to improve and grow, and must be adequately processed to produce readily accessible and useful information. This also requires computational capacity and adequate technical infrastructure. Weather and climate sciences and W&CS-related research

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[144] https://openknowledge.worldbank.org/bitstream/handle/10986/33474/9781464815003.pdf?sequence=2&isAllowed=y.

[145] https://www.unido.org/news/us23-million-pledged-support-technology-transfer-address-climate-change-developing-countries.

[146] https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/NAD_EBG/54b3b39e25b84f96aeada52180215ade/b8ce50e79b574690886602169f4f479b.pdf.

[147] https://www.ctc-n.org/.

[148] https://www.gawtec.de.

[149] https://www.international-climate-initiative.com/en/about-iki.

[150] https://www.thegef.org/sites/default/files/publications/TechTransfer-FS-June2009_2.pdf.

[151] https://seors.unfccc.int/applications/seors/attachments/get_attachment?code=F4DS5MM353N1VASDPK4K6JBDKVBI0KNT.

[152] https://library.wmo.int/doc_num.php?explnum_id=10421.

[153] https://opendatabarometer.org/3rdedition/regional-report/africa/#overview; https://datascience.codata.org/article/10.5334/dsj-2020-031.

are new fields in many LDCs. Access to computational capacity and e-infrastructure is limited, especially when it comes to the high demand of supercomputers/clusters and sufficient storage for big data. The ratio between the number of usable computers and users (World Bank, 2015[154]) is low in most African universities, and research institutions dispose of limited budgets to acquire those facilities. In addition, some universities are not able to afford to pay for access to closed-access journals.

Examining **procedural capacity**, renewable energy generation such as that of wind power, solar power and hydropower, as well as energy demand, are highly dependent on atmospheric conditions. Accurate generation forecasts for renewable energy – short and long term, centralized and decentralized – are valuable to system operators and renewable energy generators. Accurate weather forecasting is crucial for integrating wind and solar power into the grid, especially at high penetration levels, and for open-source systems for weather data collection and sharing. Advanced meteorological devices can help improve system delivery. Meteorological technology can capture real-time, site-specific weather data. Algorithms can produce advanced forecasts for solar and wind output (IRENA, 2020[155]). Thus, it is key to build procedural and infrastructural capacities (for example, see Box 6.3). In addition, building capacity for the uptake of co-production processes is crucial, as also discussed in Chapter 4. Effective communication is important to enhance procedural capacity and increase productivity, and should be incorporated into the policies and work of NMHSs and other relevant organizations. Although procedural guidelines for W&CSs for energy are at an early stage of development, there have been some recommendations made by international agencies (Möhrlen, 2022[156]). Strengthening communication with all relevant stakeholders is key to this level of capacity development.

With regards to the **human resources capacity level**, there are several capacity gaps that need to be addressed. For researchers, the availability of research facilities and national research funding is fundamental for building their capacity to implement W&CSs. The limited funding allocated to scientific research and development in general, and to weather and climate research in particular, is slowing the progress of W&CS delivery in Africa. For example, World Bank indicators mention that Africa's research and development funding was only 0.42% of the gross domestic product and still limited in most sub-Saharan Africa countries (World Bank, 2022[157]).

Mentorship of early career scientists and early career researchers is crucial for individual capacity development. These professionals are a positive driving force to developing sustainability pathways. Providing efficient mentorship helps them gain relevant experience that increases their chances to access fellowships, and leads to higher research productivity and better career opportunities. Even though some universities provide mentorship programmes, collaboration with international universities and institutes through intracontinental and intercontinental collaboration (for example, in Africa) remains limited. As a result, knowledge transfer remains limited, and it becomes challenging to align with international scientific agendas and initiatives. Brain drain is also a problem in Africa. For example, in the Maghreb region, 33% of Tunisian-born and 44% of Algerian-born physicians moved abroad in 2000 (African Development Bank Group, 2011). The result of the brain drain is a dramatic reduction in the skilled labour force, which has hindered the development of high-knowledge industries and new initiatives for the climate sciences.

6.3 Capacity-building: From gaps to action

There are various ways that capacity gaps can be filled across scales and via different actors. However, providers, intermediaries and users of W&CSs or energy management information are diverse in terms of their technical background and scientific education. For example, researchers or consumers of model outputs or data analyses require a different level of learning to a decision maker in a government ministry. In particular, with regard to climate change impacts and adaptation, there is a need for a simpler translation of science for some users, including through long-term learning versus single training activities (Knoedler, 2018; Reis and Ballinger, 2020). Capacity-development activities should always consider the technical level,

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[154] https://blogs.worldbank.org/edutech/surveying-ict-use-education-africa.

[155] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Advanced_weather_forecasting_2020.pdf_20_20%20la=en&hash=8384431B56569C0D8786C9A4FDD56864443D10AF.

[156] https://www.sciencedirect.com/book/9780443186813/iea-wind-recommended-practice-for-the-implementation-of-renewable-energy-forecasting-solutions.

[157] https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?locations=ZG.

Box 6.3. Supporting the uptake of a hybrid renewable energy system in South Africa

Eastern Cape Province in South Africa has been engaging in several renewable energy initiatives to improve access to electricity, create jobs and alleviate poverty. The Upper Blinkwater Smart Project is one of the initiatives developed to provide a decentralized, sustainable and hybrid minigrid system (GIZ, 2020). The system is based on renewable energies and diesel backup. It provides electricity access for poor rural households, who are also vulnerable to extreme weather events. Provision of renewable energy has facilitated community development and job opportunities within the community, and reduced the consumption of fossil fuels.

The project was made possible by collaboration between Eastern Cape Province, Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH and the German federal state of Saxony. Other key partners included the community of Upper Blinkwater, the South African Department of Mineral Resources and Energy, the Department of Economic Development, the Department of Environmental Affairs and Tourism, the Council for Scientific and Industrial Research, the South African National Energy Development Institute and the universities of Fort Hare and Nelson Mandela.

The project demonstrates that renewable technologies can play an important role in enabling energy access to off-grid communities, improving living conditions, enhancing economic opportunities and slowing down rural-to-urban migration. Challenges encountered during the project included delays due to administrative and procurement processes, as well as policy requirements to obtain licences as determined by the National Energy Regulator of South Africa. Cooperation and participation of various stakeholders in project design and implementation were critical success factors that helped overcome these barriers. Figure 6.5 provides a schematic of the project.

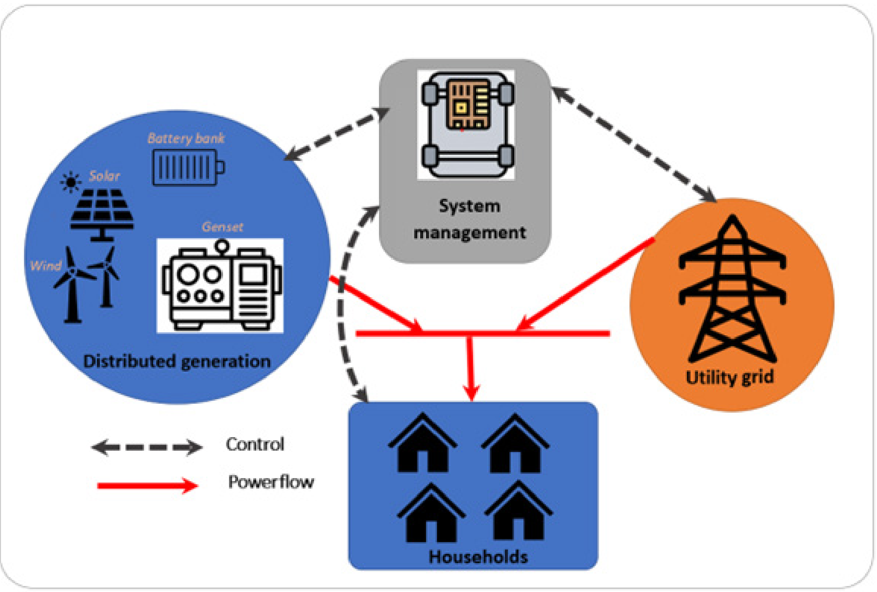

Figure 6.5. Upper Blinkwater minigrid project schematic

Source: SAWS

Benefits from the hybrid energy system include community access to clean and affordable energy, which is used for economic activities such as goat cheese production and processing of fruit and vegetables. Households saved between 30 and 800 rand per month, which was previously used to purchase paraffin and candles. Other benefits include reduced deforestation and reduced health risks associated with the use of firewood. The use of renewable energy also relieves women and children from the burden of spending valuable time collecting firewood, which can then be converted into other productive activities and education.

decision-making needs, data usage (and familiarity) and analysis activities when designing programmes and trainings. Especially for individual capacity development, learning should be tailored to particular users to ensure specific and varied needs are met.

To enable appropriate capacity-development activities to be identified and put in place, this section builds upon and modifies the capacity-development process already suggested by WMO (2020b[158]), as illustrated in Figure 6.6. This process is iterative and is adapted from the United Nations Development Programme's capacity-development process (UNDP, 2015[159]). There are also some overlaps here with the co-production process outlined in Chapter 4. Initially, there is a need to define baseline and capacity-development requirements for selected stakeholders. This should be done together with relevant stakeholders and especially those whose capacity needs are to be addressed. Based on this initial analysis, specific capacity needs can be identified, and a capacity-development plan developed and implemented. Monitoring and evaluation of the capacity-development activities can take place before, during or after implementation of the capacity-development activities.

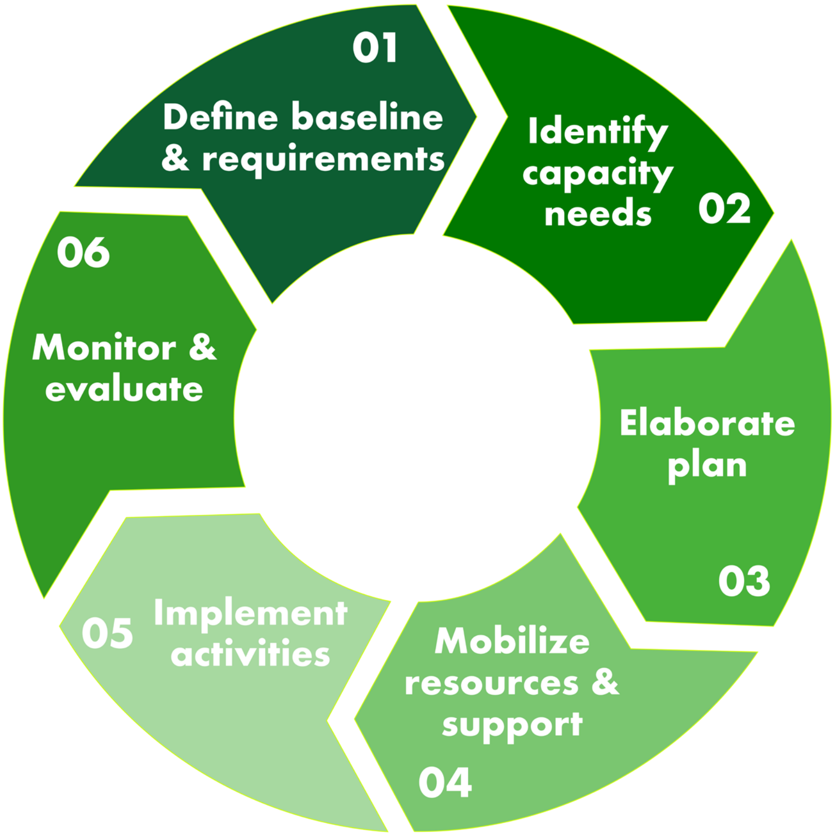

Figure 6.6. Capacity-development process

Source: Adapted from WMO (2020b)

Figure 6.7 presents a provisional toolbox of capacity-development activities to enable uptake of W&CSs in support of the energy transition. This toolbox is divided according to the levels of capacity-development presented in Figure 6.1. The toolbox includes some provisional, streamlined activities that can be adapted to the local context and stakeholder requirements.

For monitoring and evaluation of capacity-development activities, the capacity-development learning outcomes framework outlined by the World Bank are built upon (Otoo et al., 2009). To do this, additional outcomes relating to infrastructural and institutional capacity are added, in line with the capacity-development framework already presented in Figure 6.1 (see Figure 6.8).

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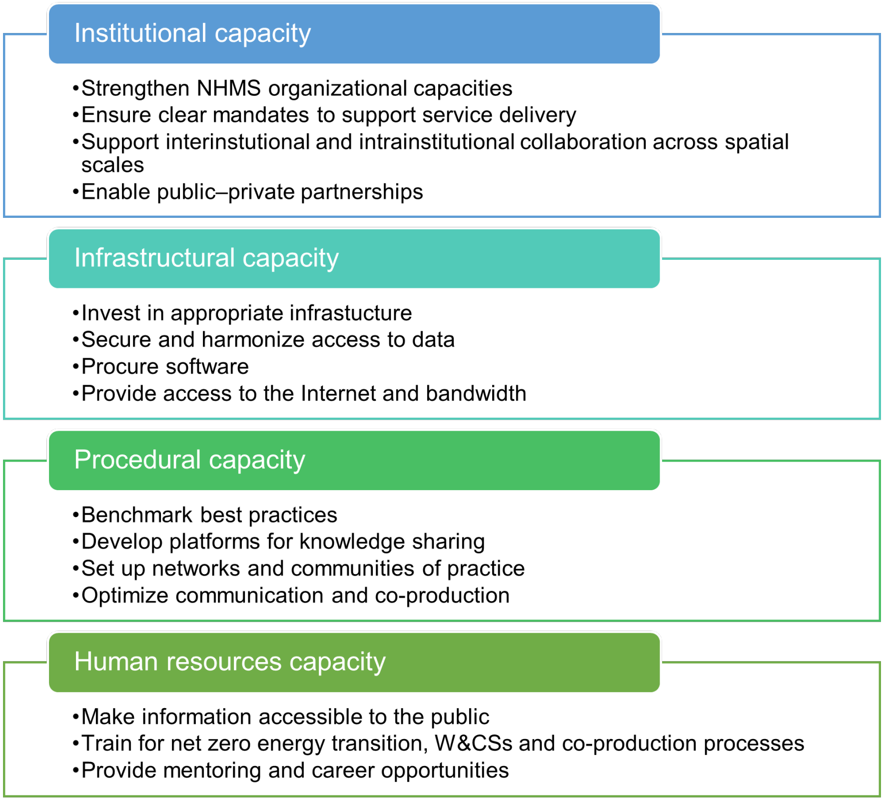
[158] https://library.wmo.int/doc_num.php?explnum_id=10272.

[159] https://www.undp.org/sites/g/files/zskgke326/files/publications/CDG_PrimerReport_final_web.pdf.



Institutional capacity

- Strengthen NHMS organizational capacities
- Ensure clear mandates to support service delivery
- Support interinstutional and intrainstitutional collaboration across spatial scales
- Enable public–private partnerships

Infrastructural capacity

- Invest in appropriate infrastucture
- Secure and harmonize access to data
- Procure software
- Provide access to the Internet and bandwidth

Procedural capacity

- Benchmark best practices
- Develop platforms for knowledge sharing
- Set up networks and communities of practice
- Optimize communication and co-production

Human resources capacity

- Make information accessible to the public
- Train for net zero energy transition, W&CSs and co-production processes
- Provide mentoring and career opportunities

Figure 6.7. Capacity-development toolbox

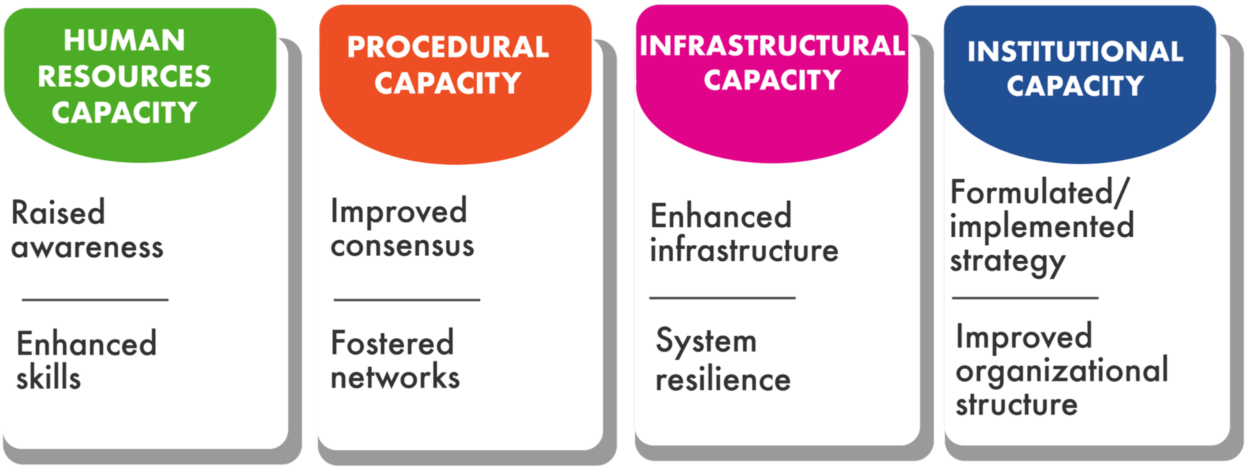


Figure 6.8. Framework for monitoring and evaluating capacity-development outcomes
Source: Adapted from Otoo et al. (2009)[160]

Based on this framework, a set of indicators and measures for monitoring and evaluating capacity-development outcomes can be developed in a context-specific manner. Table 6.3 presents a generic suggestion for such a framework.

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[160] https://openknowledge.worldbank.org/handle/10986/23037.

Table 6.3. Capacity-development evaluation indicators

Capacity-development outcome	*Generic result indicator*	*Measure of indicator*	*Possible evidence*
Raised awareness	Participant motivation increased	Number of participants and changes in attitude	Feedback from participants, surveys, website forums and so forth
Enhanced skills	New/improved skills or knowledge	Share/number of trained staff/individuals who use new skills or knowledge	Self-reporting and direct monitoring
Improved consensus	Stakeholder agreement reached	Share of participants who agree with project outcomes	Surveys and interviews
Fostered networks	Partnerships and networks created at various spatial scales	Share of respondents using the network	Response to surveys and website usage analysis
Enhanced infrastructure	Improvement in infrastructure for W&CSs, net zero energy transition and user interface	Improvement in data access, information provision, energy and data management and so forth	Additional infrastructure investment, number of people with improved data access and so forth
System resilience	Ability to respond to climate change mitigation and adaptation, and equity considerations	Project-specific indicators such as increased renewable capabilities, improved resilience to climate impacts/extreme weather events, gender consideration, information access and so forth	Expert evaluation (ex ante and ex post)
Formulated policy/strategy	Strategy proposed/implemented	Strategy document submitted and consultation process established	Information from relevant institutions/organizations
Improved organizational structure	Institutional and organizational changes to accommodate for uptake of W&CSs in support of net zero energy transition	Changes in institutional and organizational arrangements, including communication and collaboration	Information from relevant institutions/organizations

Source: Adapted from Otoo et al. (2009)[161]

In the WMO SG-ENE survey introduced in Chapter 1 (see Figure 1.8), NMHSs were also asked to indicate what they view as the most relevant approaches to improving uptake of W&CSs for the energy sector. Developing individual capacity through training courses and workshops was given as the most sought after solution (Figure 6.9). Evaluating the results over the six WMO regions, it emerged that the need for building and developing capacity in developing services for the energy sector is not limited to developing countries, but it is a global need raised uniformly across the world. Enabling cross-sectoral collaboration and promoting co-creation of W&CSs are indicated as the next two top potential solutions.

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[161] https://openknowledge.worldbank.org/handle/10986/23037.

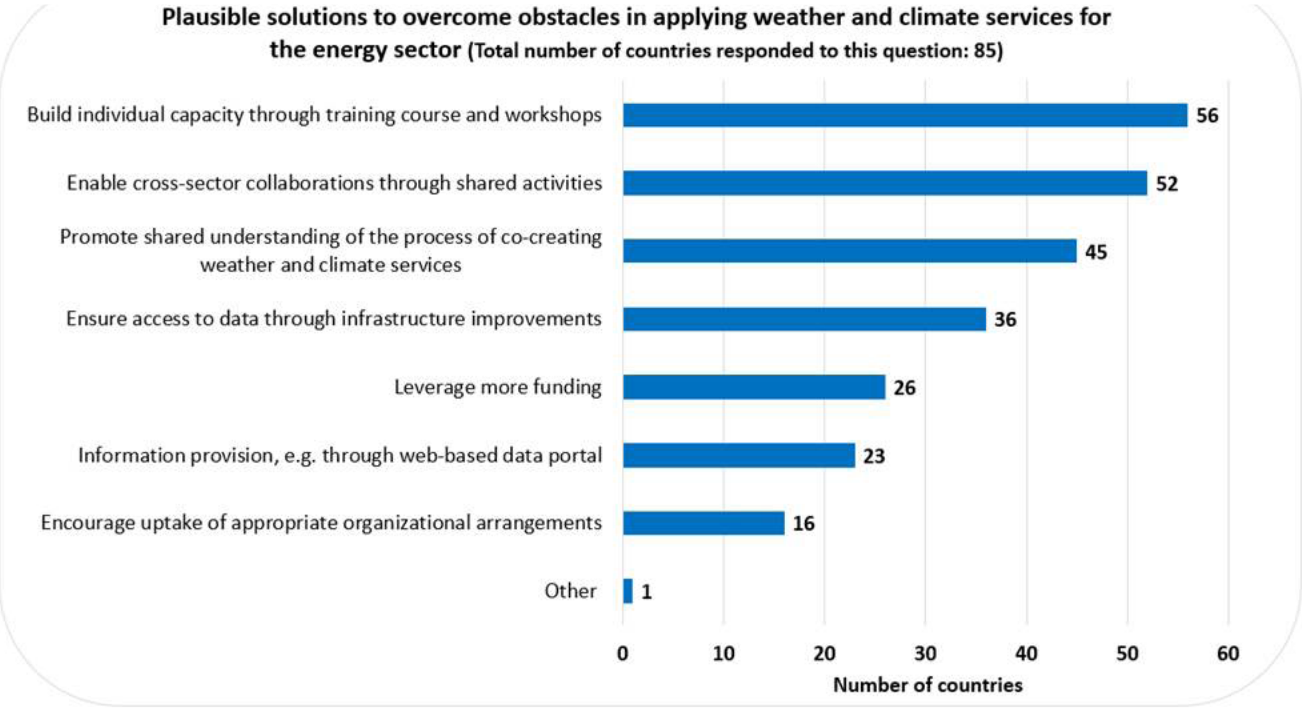

Figure 6.9. Analysis of the responses from NMHSs of the survey question: "Select the three most plausible solutions to overcome obstacles in applying weather and climate services for the energy sector"

As illustrated in this chapter, capacity-development needs can be understood at individual, procedural, infrastructural and institutional levels. Importantly, capacity-development needs vary significantly among stakeholders and across geographies. Many stakeholders in LDCs, who are most adversely affected by climate change and energy considerations, lack basic capacities that need to be prioritized. In devising capacity-development activities and programmes, the above-mentioned four levels of capacity-development can also help in devising context-specific capacity-development actions and appropriate monitoring and evaluation schedules.

To address some of the issues mentioned in this chapter, a capacity-development comprehensive plan for W&CSs for the energy sector is being developed under SG-ENE. It is designed to address the training needs of the public and private sectors, including NMHSs and TSOs. This capacity development plan aims to fill gaps in technical knowledge while promoting good service delivery practices and communication skills, and is directed to all those involved in the energy sector (meteorological organizations, policymakers, energy company practitioners, NGOs, academics and other interested stakeholders). The purpose is to foster an overall understanding of the close interlinkages between renewable energy and weather variability and climate change, and to enhance technical and product co-production skills.

The plan includes the delivery of regional training courses, summer schools, webinars, seminars and conferences (see Box 6.4 as an example for conferences), initially spanning the period 2022–2024. This plan is in response to energy sector user needs, and is based on past related events. Regional courses are exclusively designed to address that capacity-development needs vary geographically and among stakeholders.

Additionally, the plan includes the WMO Weather and Climate Services for Energy Portal, which will be launched in 2023. The portal is intended to be an initiative that will have a permanent online presence, where past courses, webinars, news, key publications and other relevant information can be found, shared and discussed. It will also provide access to historical and climate projections data through the Global Energy Resilience Atlas, which will also be hosted in the portal.

The next and concluding chapter provides some recommendations for further action.

Box 6.4. International Conference Energy and Meteorology (ICEM) – World Energy and Meteorology Council (WEMC)

In 2011, a group of weather and climate scientists, with support from some energy experts, undertook to launch the first ICEM (https://www.wemcouncil.org/wp/icem). The intention was to provide a unique platform where meteorologists and energy industry specialists could share the substantial amount of expertise and knowledge that exists across both sectors. The conference format offered an exciting, convivial and productive environment in which to explore opportunities for collaboration. The conference committee was also keen to promote ICEM core values of targeted and positive transition (of the energy system) in the face of climate change and inclusivity – for example, through its broad organizing committee or the awards given to young specialists for best presentation.

The inaugural conference at the Gold Coast in Australia was a great success, attracting over 170 energy and meteorology specialists from 50 countries, proving the need for a collaborative, knowledge-sharing platform that spans both sectors and setting in place a blueprint for future biennial ICEMs (in odd years, with one exception – the additional ICEM in 2018) in France (2013), the United States (2015), Italy (2017), China (2018) and Denmark (2019) (see Figure 6.10). With the support of WEMC collaborators, and many more colleagues and peers from the science and energy communities (too many to name!), ICEM has grown and developed. It is now an established global platform for world-leading research organizations, meteorological service providers, energy companies and energy policy experts to come together for active discussion and sharing of expertise on innovation and action on climate and energy issues.

Figure 6.10. Locations of past ICEMs

Source: WEMC

Scientists and energy sector experts are in a unique position to help lead the targeted and positive transition (for the energy system) in the face of climate change using the combined expertise available within the science and energy communities. The unique interactions taking place at ICEMs provide directions on what is really critical in the pathway towards more sustainable and renewable energy systems.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Concluding remarks

The international goal to achieve net zero carbon emissions by the middle of the twenty-first century, as implied by the most ambitious target of the COP 21 Paris Agreement (in 2015) first, and cemented with the COP 26 Glasgow Climate Pact (in 2021) later, requires rapid decarbonization of the energy system (e.g. in generation, infrastructure and transport). Given the significant exposure of the energy sector to weather and climate variability, which affects demand and supply, but also other components of the energy supply chain at all timescales (e.g. generation, transmission, distribution and delivery), a key element in support of the ensuing infrastructure, technological and societal transformation in the energy sector is the development of robust and effective W&CSs.

As presented in this publication, W&CSs for the energy sector are, in many ways, well developed, particularly in terms of weather services. However, despite the energy sector being one of the most advanced users of weather and climate information, its rapid evolution constantly creates new needs, which require new paradigms for a more effective exchange of information between service providers (for example, NMHSs) and energy sector users. This is even more so now, given that over the next decades, climate change mitigation and adaptation will lead to an overhaul in energy systems.

Information gaps relating to the type, level of accuracy and frequency of delivery of specific weather and climate information therefore exist. These are also accompanied by advances in weather and climate science and technology, which do not translate quickly enough into usable W&CSs (as, for example, with the rapid development of machine learning algorithms, see Chapters 2 and 3). Ongoing technical and scientific interactions between W&CS providers and the energy sector, supported by input from the information and communication technologies, can help bridge these gaps as well as integrate W&CSs into decision-support systems.

However, scientific progress on its own is not sufficient to increase the value of W&CSs for energy. Improving decision-making processes, based on tailored meteorological information, also demands improved communication and mutual understanding between energy and meteorology experts (Dubus et al., 2018a; Gundasekera, 2018), through the co-production processes discussed above (see mainly Chapters 1 and 4).

To enable the uptake of W&CSs, it is also important to evaluate their SEBs, and to harness appropriate sustainable business models (as seen in Chapter 5), and to develop and implement targeted and ongoing capacity-development programmes (as discussed in Chapter 6). It is on this basis that the recommendations below are framed.

7.2 Recommendations

The recommendations presented here are the result of numerous threads that revolve around SG-ENE[162] activities. Thus, they draw on this publication's content as well as on the output and outcomes of many projects and activities, especially those involving co-production of W&CSs for the energy sector, over the past few decades. Incidentally, several of the recommendations made here have close similarities with those formulated more than a decade ago, following the workshop on weather and climate risk management in the energy sector held in October 2008 (Troccoli et al., 2010a, 2010b, 2013). The main updates regard those related to the co-production and socioeconomic evaluation, as well as technological developments such as greater use of machine learning algorithms.

The target audience for these recommendations is all NMHSs, and any other entity whose focus is the improvement of W&CSs for the energy sector, be they institutional, research or commercial actors. The recommendations broadly follow the co-production framework (Figure 1.9).

Recommendation 1: Improve mapping of user requirements

User requirements are the foundation for useful and usable W&CSs. Collecting such information may be time-consuming as it involves close engagement with sometimes many users. Nevertheless, specific requirements from energy sector users globally should be collected in databases and ideally widely shared, to minimize duplication of effort and at the same time allow action in a timely way. The collection of user requirements is a continuous process. Production of a W&CS needs to be adapted to specific users, and therefore requirements must be adjusted to the circumstances. Therefore, it is important to regularly update the list of requirements, while also reducing overlaps (for example, the same requirement could be expressed

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[162] https://community.wmo.int/activity-areas/sercom/SG-Energy.

in different ways in separate entries). In addition, the way user requirements are structured is critical – ideally, they should be provided as actionable entries.

The European Union's C3S provides an example of user requirements. It has developed its own operational User Requirements Database that stores thousands of user requirements from many sectors and covering various elements of the C3S infrastructure (C3S, n.d.d[163]). The user requirements are regularly clustered and analysed, and presented in user requirements analysis documents, which include actionable recommendations to guide the evolution of C3S (see Figure 7.1).

Recommendation 2: Improve the science and technology supporting W&CSs for the energy sector

The science and technology behind W&CSs, used for weather and climate forecasts, climate projections, collection of observations and so forth, should be improved continuously. There should be a close link to entities guiding weather and climate research, for example, WMO RB, WWRP and WCRP.

While a wealth of data is already being used to create effective W&CSs, some limitations are evident. The science and technology are at different levels of development, with weather forecasts more advanced than climate forecasts. However, there is room for improvement in each of these areas. For instance, in weather forecasts, work could be done to improve parametrizations relevant for wind and solar power. In seasonal climate forecasts, improvements could come from the dynamics of climate anomalies, which may involve improving model resolution, increased observation coverage (particularly in oceans and sea ice) and enhancements in the understanding of physical processes of the different components of the climate system.

Limits of predictability and uncertainties should also be better quantified, while clearly stating the limitations of the experimentation adopted to evaluate them. At the same time, experimentation using high-resolution model outputs, especially in terms of temporal resolution, should be expanded to better understand the information content potentially extractable from these data.

It is important to try to estimate the effects of specific science and technology improvements for applications in the energy sector, and also more broadly for other sectors, noting that it is generally not possible to target ameliorations in a weather or climate model that is beneficial to a specific sector. An example that applies mainly to energy could be improvement of the simulation and forecast of direct solar radiation, which is a critical variable for concentrating solar power generation.

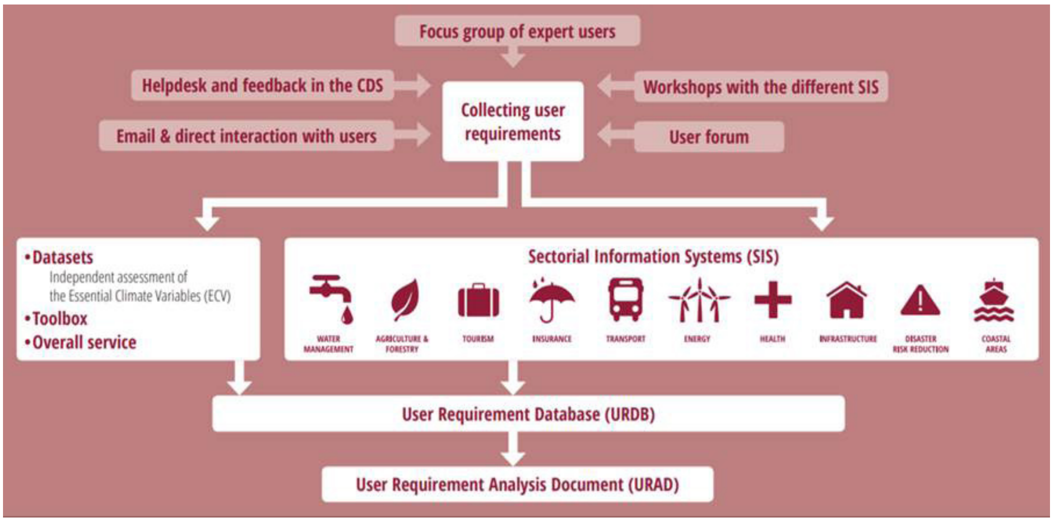

Figure 7.1. Sources of user requirements and analysis process for a variety of sectors, including energy

Source: C3S (n.d.d)

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[163] https://climate.copernicus.eu/user-requirements-gathering-and-analysis.

Recommendation 3: Improve postprocessing methods and energy conversion models

Weather and climate data should increasingly be used with energy applications as targets. This means that metrics should measure integrated application performance rather than the quality of weather and climate data themselves, even if the latter is typically a fundamental input in the production chain of the service.

While this approach makes the processing more specific to the application being considered, and therefore less transferable to other W&CSs, it will provide a much better estimate of the effectiveness of the weather and climate data through the energy applications production chain. Sensitivity experiments should also be conducted to gain a better appreciation of the role of weather and climate in the final weather and/or climate service solution (linked to Recommendation 2).

Postprocessing tasks to be considered include tailoring (for example, through physical or statistical models to derive variables required for energy applications, such as wind at a specific height), downscaling (dynamical or statistical, for example, to increase the temporal resolution of time series to suit energy models) and calibration (for example, of probabilistic information, by adjusting the reliability of the forecasts). Machine learning methods should also be increasingly tested and implemented, especially in cases when a sufficiently high amount of data is available for training these statistical models.

Recommendation 4: Improve data access, exchange and policy

Data availability and access for meteorological and energy data should be significantly improved. While data policy varies considerably at the international level, and notwithstanding the evolving supportive WMO resolutions on data access, data collection is still a major component of the creation of W&CSs. Even where data are freely available (for example, in the United States, where there is a free data policy for meteorological data), the ways in which the data are distributed are highly technical and involved (for example, through ftp of large files that contain numerous variables, from which useful ones need to be extracted). This is particularly the case when it comes to hourly data, which are key, for example, in power grid modelling.

The situation is markedly worse for energy data, for which it is generally a challenge to collect consistent plant locations and characteristics, particularly for solar power and hydropower, and even more so in the case of actual power generation, and demand. Incentives to make data available, particularly meteorological and energy measurements, should urgently be explored, tested and implemented. Incentives could, for example, be in the form of economic and/or institutional knowledge creation.

Certified data quality assurance must also be a high priority. Data that do not pass quality checks substantially increase inefficiencies in W&CS workflows, especially when these data must be discarded in the end. In addition, it is not unusual for measurements to degrade over time due to factors such as lack of maintenance of instrumentation, deteriorating conditions of the site and changes in software programmes used to handle the data.

Despite efforts towards the adoption of common conventions and interoperability of datasets, much work still needs to be done in this regard. C3S, with its CDS, is perhaps the best example of common data conventions (based on the CF convention used for NetCDF files, see also Chapter 2) and interoperability through a relatively simple, though highly technical, interactive platform (including providing access via Python scripts).

Critically, user-friendly and, ideally, free data access, including the adoption of common conventions and interoperability principles, would reduce barriers to entry. This is particularly the case for start-up companies, which cannot afford to pay for highly expensive datasets or invest time to retrieve and process them. This is also valid for energy organizations, which often find it daunting to approach complex meteorological data, or even understand the terminologies used.

Among other things, integrated tools should be developed that allow the retrieval and conversion of data into useful weather and climate information and derived services. In addition, common metadata conventions, which allow unambiguous interpretation of the data characteristics, including their measurement errors and uncertainties, should be defined and shared with intermediaries and users of W&CSs.

Recommendation 5: Refine co-production approaches, including data visualization, support and guidance, and use of delivery channels

The dialogue among providers, intermediaries and users of W&CSs should be enhanced, through, for instance, novel participatory approaches, both in person and online. Great advances have been made in the co-production of W&CSs in the last decade. These have been through the involvement of users in most, if not all, steps of the co-creation process (design, development and so forth) and by experimenting with stakeholder engagement methodologies (for example, user stories and online discussion boards).

Key to a stronger uptake of W&CSs by the energy sector is further demonstration (so as to instil increased confidence), that they can reduce volatility in energy demand and generation. This is particularly notable in the context of the increasingly high penetration of renewable energy in the grid, which is still viewed by some energy practitioners as a major obstacle to the expansion of variable generation from, for example, wind and solar power.

More should also be done to improve ways in which users proactively interact with producers to achieve a better weather and/or climate service. One such way could be through effective visualization tools, in the form of standard graphics or online web applications, as they can provide a key common focal point for discussion. Such tools should adopt a user-centred design approach, thereby requesting continuous user feedback, and by keeping the visual aspects and terminology as approachable as possible. In this context, it is also critical to involve experts with different backgrounds such as social scientists, user experience designers, communication specialists, software developers, weather and climate data engineers, and, of course, energy sector users (Terrado et al., 2021).

Recommendation 6: Explore new energy sector applications using W&CSs

Research into new areas and/or advanced applications should be explored. Research developments in the W&CS space are already broad and thriving (see, for example, Chapters 2 and 3), but new opportunities regularly emerge. An immediate area of extension in current work is the link with energy modelling, especially in the research community. An increasing number of collaborations are being established in this area, but institutional support, as provided for instance by WMO, would be required to accelerate this important process.

In addition, several specific topics, some of which relate to new technology developments, are emerging. These include: (i) the use of weather and climate information in energy storage (electric, hydro or even hydrogen) management, (ii) the sensitivity of existing or new technologies to weather and climate conditions as in the case of DLR or bifacial solar PV panels and (iii) the computation of climate risk to energy systems by properly accounting for vulnerabilities, exposure and likelihood of impacts. It is therefore important to identify appropriate funding and/or lobby funding agencies to invest in recognized critical new areas of research that can support innovation in W&CSs for the energy sector.

Recommendation 7: Refine business models for sustainable W&CSs

Business models for W&CSs that account for the peculiarities of these services (as discussed in Chapter 5) should be refined. While there is a strong projected market growth for W&CSs over the coming years, as climate change increasingly affects energy systems operations, management and planning, the W&CS enterprise is not yet taking advantage of the (potential) opportunities.

Two main factors contribute to the W&CS enterprise’s slow progress, particularly for climate services: (i) the perceived, and real in some cases, high level of uncertainty in climate forecasts and projections and (ii) the short-sightedness in the investment cycle for these services, particularly for larger organizations for which the end of external project funds determines the termination of the development of the climate service (on which they perhaps worked for the prior 3–5 years) if no follow-ups are immediately available.

Therefore, a two-pronged approach should be adopted whereby WMO, or other relevant agencies, could, on the one hand, set up a task force composed of environmental economists, W&CS managers and energy sector users to provide recommendations for possible business models for sustainable W&CSs. On the other hand, they could assist in identifying appropriate funding bodies and/or investors interested to accelerate the growth of W&CSs, including through public–private partnerships.

Recommendation 8: Implement capacity-building activities

As requirements for weather and climate data for the energy sector expand, there is an increasing number of users who find it necessary to learn about the main features of these data and information, and how they can be harnessed to achieve effective W&CSs. It is therefore critical to create a network of producers, intermediaries and users who have a good understanding of the close interlinkages among weather, climate and renewable energy systems, with a clear idea of the challenges and opportunities of a W&CS.

Capacity-building can and should be achieved in multiple ways, to allow recipients to choose the learning method most suitable to them. Thus, capacity-building should include targeted training courses, summer schools, masters programmes, webinars, conferences, open discussion forums and so forth. For instance, a specific module could be developed to form an elective for Master of Business Administration programmes. Crucially, the learning should be intended as a two-way process, with producers learning from intermediaries and users, and vice versa. This two-way process allows for a more targeted and efficient interaction towards the co-creation of a weather and/or climate service.

Depending on the type of learning opportunity, the successful completion and application of learning should be evidenced by some form of recognized certification. While WMO is not set up to be a certification body, it should look to develop the underpinning knowledge and skills frameworks in coordination with an energy agency, for example, IEA or the International Renewable Energy Agency (IRENA), and with other relevant organizations such as NMHSs and universities.

Recommendation 9: Enhance communication activities

Communication activities should be at the core of interaction among producers, intermediaries and users of W&CSs for the energy sector. While communication is essential in most of the other recommendations presented here, but especially for co-production approaches (Recommendation 5) and capacity-building (Recommendation 8), it must have a scope of its own. In this context, the main objectives of the communication activities are to: (i) inform all community actors about the latest developments and main achievements in W&CSs for the energy sector and (ii) raise awareness among users of the benefits of W&CSs and how they can be used for real-life decision-making and risk management in the energy industry.

Implementing these objectives will involve a number of activities. One of these is the set-up and maintenance of the portal for W&CSs under SG-ENE. The portal, which is already under way, is planned to become the credible "go-to" technical and informational reference point for users of energy sector services and climate science, complementing existing institutional resources. Its three main functions are: (i) to provide a knowledge gateway, (ii) to promote networking and connecting and (iii) to provide a global action-oriented energy resilience atlas. As with all web portals, support and effort will be needed to maintain and sustain it over many years to come. Therefore, efforts should be made towards identifying appropriate resources.

Other communication activities should include standard social media posts, blogs and interviews, to inform and raise awareness about W&CS progress and achievements. In addition, regular updates of this publication could be made, for instance biennially, similar to the annual REN21 *Global Status Report* or the IEA *World Energy Outlook*. To do so, specific KPIs of the W&CS evolution should be identified, and these KPIs could be the main targets of the publication updates. Organization of a major conference, also biennially and possibly based on the existing ICEMs[164] (see Chapter 6), should be another key communication (as well as capacity-building) opportunity for SG-ENE.

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[164] Apart from the pause due to COVID-19, ICEM is the only sustained process within the last more than 10 years, run biennially, aiming at bringing meteorology and energy experts together, with the goal to cover weather, water and climate sciences and services, and all the fields of activity in the energy value chain. The last ICEM was in 2019, and the next is planned for 2023, organized by WEMC and supported by WMO.

Recommendation 10: Strengthen existing and create new collaborations across organizations and sectors

Collaborations at a high institutional level across meteorology and energy organizations should be enhanced. The importance of expanding the dialogue between the two sectors at the top organizational and policy level was raised at the first ICEM (Troccoli et al., 2013) and in the Energy Exemplar (WMO, 2017). Specifically, a suggestion was made to create a framework at national and international levels for collaboration between energy and meteorology to provide an essential bridge between the two sectors for the sustainability of energy sector W&CSs.

Much work has been done in this direction since the initial implementation of the Energy Exemplar, when links between WMO and relevant energy agencies (for example, UN-Energy, IEA, IRENA, the World Energy Council and the World Bank's Energy Sector Management Assistant Program) were fostered. However, there is now a renewed need to increase collaborations with energy sector users.

Such a framework should also have as one of its mandates to lobby for sustained support from national and continental funding agencies (such as the United States Department of Energy, NASA, and the European Union Directorates for Energy and for Climate), as well as aid agencies (such as the United States Agency for International Development and the World Bank), and regional development and/or investment banks (such as the African Development Bank, the Asian Development Bank, the Inter-American Development Bank, the European Investment Bank and the European Bank for Reconstruction and Development).

Regardless of the size and focus of interactions between energy and meteorology, it is crucial that the energy sector finds value in these interactions and that they play an active role in formulating an effective network/framework to exchange information. It is also important that the larger energy companies lobby governments to invest properly in public good observation networks, serving all sectors of the community (Troccoli et al., 2013).

In addition, the increased cross-sectoral socioeconomic interplay of the energy sector, especially with the water and agriculture sectors, means that it is becoming crucial to establish and/or strengthen collaborations with an even larger number of organizations, such as UN-Water and the Food and Agriculture Organization of the United Nations. While this broadening of the network certainly adds complexity and potentially makes progress slower, it is essential to ensure energy develops and is manged in balance with other socioeconomic sectors.

For example, this will help to avoid conflict in the use of resources as in the case of water, which is a common resource for human consumption, agricultural irrigation and power production. Some of these interactions were already established with the GFCS Partnership Advisory Committee in climate services; however, they now need to be strengthened and broadened to include weather services. WMO Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM) could be a natural initiator of such a collaboration, given these connected sectors are already represented within it.

Overall, such a framework and/or collaborations should play an important role in facilitating the development of science-based and user-driven solutions. This will result in effective integration of high-quality weather, climate and other environmental information into energy sector policy formulation, planning, risk management and operational activities to better manage power systems on all timescales and strengthen climate change mitigation and adaptation (Dubus et al., 2018b).

ABBREVIATIONS AND ACRONYMS

API	application programming interface
ARWF	automatic regional weather forecast
CDF	cumulative distribution function
CDS	Climate Data Store
CEM	capacity expansion model
CGCM	coupled general circulation model
CMIP	Climate Model Intercomparison Project
COP	Conference of the Parties
CORDEX	Coordinated Regional Downscaling Experiment
C3S	Copernicus Climate Change Service
CSIS	Climate Services Information System
CST	Climate Services Toolkit
DMP	data management plan
DSO	distribution system operator
ECEM	European Climatic Energy Mixes
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
ESA	European Space Agency
EU-MACS	European Market for Climate Services
GCM	general circulation model
GFCS	Global Framework for Climate Services
GHG	greenhouse gas
GPC	global producing centre
GPCLRF	Global Producing Centre for Long-Range Forecasts
ICEM	International Conference Energy and Meteorology
IEA	International Energy Agency

IG^{3}IS	Integrated Global Greenhouse Gas Information System
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LDC	least developed country
MARCO	MArket Research for a Climate Services Observatory
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form
NMHS	National Meteorological and Hydrological Service
NMME	North American Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction
OECD	Organisation for Economic Co-operation and Development
PPE	public–private engagement
PV	photovoltaic
RCC	Regional Climate Centre
RCM	regional climate model
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SERCOM	Commission for Weather, Climate, Water and Related Environmental Services and Applications
SEB	socioeconomic benefit
SG-ENE	Study Group on Integrated Energy Services
S2S	sub-seasonal to seasonal
SSP	Shared Socioeconomic Pathway
SST	sea-surface temperature
STLF	short-term load forecasting
TSO	transmission system operator
UNFCCC	United Nations Framework Convention on Climate Change

WCRP	World Climate Research Programme
W&CS	weather and climate service
WEMC	World Energy & Meteorology Council
WFIP	Wind Forecast Improvement Project
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting
WWRP	World Weather Research Programme

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