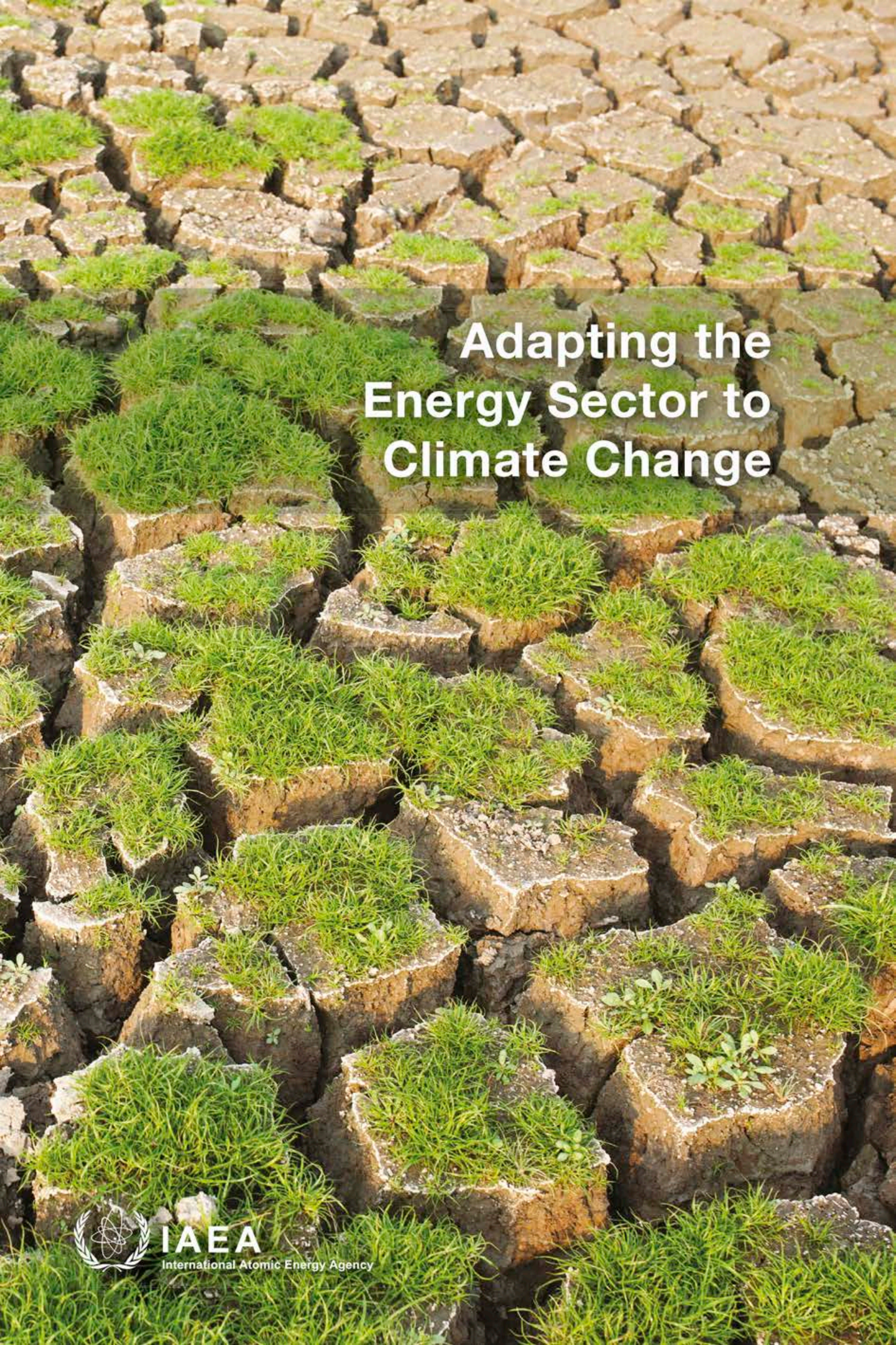

Adapting the Energy Sector to Climate Change

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ADAPTING THE ENERGY SECTOR TO CLIMATE CHANGE

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ADAPTING THE ENERGY SECTOR TO CLIMATE CHANGE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
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FOREWORD

Anthropogenic climate change is one of the greatest environmental challenges facing the world, accelerating the rise in the global mean temperature and affecting most other attributes of the Earth's climate. Although a considerable degree of uncertainty persists both in the magnitude of projected global changes and regional patterns, changes in global and regional temperatures, precipitation amounts and seasonal distribution, a sea level rise, and various extreme events are forecast by most global and regional climate models. These changes have already had an impact on nuclear energy installations and the energy sector in general, and the effects are expected to be amplified as the continued rise in greenhouse gas emissions results in further global warming and associated changes to the climate.

Since 2010, there has been a growing interest in impact studies that explore options and their associated costs to reduce the vulnerability of the energy sector to climate change, and the longer term impacts and adaptation options. Indeed, the global energy sector faces a double challenge in the next 20–30 years. Not only does the sector need to be fundamentally transformed into a low carbon energy supply system in response to climate change mitigation and related policies (e.g. the Paris Agreement under the United Nations Framework Convention on Climate Change), it also needs to adapt to climate change and its effects to ensure that energy supplies remain secure and reliable.

This publication explores the diverse range of impacts on the energy sector resulting from gradual climate change and extreme weather events, and the potential ways to counter them. All elements of the supply chain are explored: resource base, extraction and transport of depletable energy sources, power generation, transmission and distribution. This publication includes three case studies which assess the energy sector vulnerability of Argentina, Pakistan and Slovenia. The studies were prepared as part of the IAEA Coordinated Research Project on Technoeconomic Evaluation of Options for Adapting Nuclear and Other Energy Infrastructure to Long Term Climate Change and Extreme Weather. This publication presents the topics explored, methods adopted and insights gained from the Coordinated Research Project and will be useful to States interested in evaluating climate related risks to the energy sector. The IAEA officer responsible for this publication was L. Stankeviciute of the Division of Planning, Information and Knowledge Management.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

For many years, vulnerability to climate change, its potential impacts and resultant adaptation options have been explored less extensively for the energy system than they have for many other climate sensitive natural systems and economic sectors, like ecosystems, agriculture, water resources, human health and tourism. The bulk of the climate impact assessments in the energy sector have focused on energy demand. This bias is reflected in pertinent chapters of subsequent reports of the Intergovernmental Panel on Climate Change (IPCC) that assess the literature available at the time of their preparation. Studies conducted since the Fourth Assessment Report [1] of the IPCC generally confirm the main insights about the impacts of climate change on energy demand that were initially identified by the Second Assessment [2] and reinforced by the Third [3] and Fourth [4] Assessments: other things being equal, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographical, socioeconomic and technological conditions. However, there are many other drivers of change in energy demand besides climate and weather. The relative importance of changes in long term climatic and short term weather conditions among the drivers varies across regions and keeps changing over time.

In the last decade or so, in addition to the increasing abundance of energy demand studies, a growing interest has been observed in assessing the vulnerability of different energy sources and technologies under present and future climatic conditions, and current and possibly changing future patterns of extreme weather situations; the options and costs to reduce vulnerability, and the longer term impacts and adaptation options in various energy systems (e.g. see Refs [5–12]) have also been increasingly assessed. The emerging picture indicates that the global energy system will face a double challenge over the coming decades: it will be transformed by climate change mitigation requirements and related policies, and it will need to adapt to impacts of emerging changes in climate and weather. Adequate responses to these challenges will be crucial for a secure and reliable energy supply.

1.2. OBJECTIVE

The objective of this publication is to explore the diverse range of impacts on the energy sector resulting from gradual climate change (GCC) and the related shifts in extreme weather events (EWEs), as well as potential adaptation options. This publication presents three national case studies to show various possible framing and analytical techniques to tackle the challenges posed by these events in the energy sector.

1.3. SCOPE

This publication focuses on the supply side and presents a systematic overview of the diverse range of impacts on the energy sector resulting from GCC and related shifts in EWEs. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

Following the IPCC definition of climate change as a “change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer” (Ref. [13], p. 557), GCC attributes relevant for the energy sector and considered here include gradual changes in mean temperature, precipitation, windiness, cloudiness and sea level. In the same source, an EWE is defined as the “occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable” (Ref. [13], p. 557). The EWEs most relevant to the energy sector include changing patterns (frequency, intensity, duration, timing and/or spatial extent) of extreme high and low temperature and precipitation; extreme high wind; storms (tropical and extratropical cyclones, hurricanes, typhoons, or tornadoes) and storm surges; hail; and lightning (see also Ref. [8]).

For the purposes of this publication, three types of combined climate and weather attribute are also considered as possible climatic hazards for the energy sector. The first is the superimposition of changing patterns of EWEs on GCC that would exacerbate the impacts of the latter. An example is hot spells added to higher average temperature, which would make impacts more severe and require greater adaptation efforts. The second type of combination involves cumulative impacts of weather conditions (not necessarily EWEs) persisting for a longer period. Examples include droughts (resulting from a longer period of low precipitation) and floods (caused by high intensity and/or long duration precipitation). The third type of combination includes simultaneous occurrences of several EWEs, such as drought due to low precipitation exacerbated by high temperature, resulting in dry conditions, plus extreme wind leading to dust storms or sandstorms, or high precipitation and low temperature resulting in freezing rain and the buildup of snow and ice.

In all climate trends, extreme events and the above combinations, it is important to distinguish and keep track of direct impacts (affecting a given facility or infrastructure component of the energy sector directly) and indirect impacts (caused by climate or weather phenomena affecting another component of the energy system or the environment at large and imposing impacts on the energy system). For example, icy rain would damage solar panels directly. In contrast, low precipitation and the resulting low water level in a river may lead to the shutdown of a coal power plant indirectly, because coal delivery would be disrupted (although the power plant could operate). Another example of indirect effect is when a snowstorm disrupts power transmission lines and forces an otherwise intact nuclear power plant to shut down because it cannot export electricity to the grid system. The distinction between direct and indirect impacts is important for assessing and implementing options to reduce the exposure and increase the adaptive capacity in specific components of the energy sector and to make the energy supply more secure.

1.4. STRUCTURE

The publication is organized as follows: this introduction is followed by a short discussion of the general principles of climate change adaptation stipulated in the Paris Agreement; these principles provide the broader context for efforts to reduce the vulnerability of energy systems and increase their adaptation to climate change (Section 2). The latest assessments and projections of changes in climate attributes of particular relevance for the energy sector are summarized in Section 3.

The technology sections (Sections 4–6) are organized into the framework of the supply chain in the energy sector. The starting point of the energy chain is the exploration and extraction of depletable energy resources: coal, oil, gas and uranium. This is also the proper context for evaluating the impacts of climate change on the resource potential of renewable energy sources like hydropower, wind and solar. Accordingly, the energy technology sections start with the impacts on energy resources: the extraction and treatment of depletable energy sources (fossil fuels and uranium) and the resource base of the most important renewables (hydro, wind and solar) except bioenergy. This is followed by the assessment of impacts and adaptation options in the transport of primary energy resources.

Primary energy resources are converted into various forms of secondary energy: into electricity at fossil and nuclear power plants, gasoline and other liquid fuels at refineries, and appropriate quality of gas at gas treatment plants. Hydro and wind resources are converted into electricity, and energy from insolation is transformed into electricity and heat. The conversion technologies applied today are based on a range of physical and chemical processes. They are affected by current and future climate and weather attributes very differently. The main focus is on conversion of these resources into electricity. A separate section (Section 7) is devoted to the transmission and distribution of electricity for end use as final energy. For each stage of the supply chain, direct and indirect impacts of GCC, EWEs and different types of combination are explored.

The energy technology sections focus on the most significant impacts on key energy sources and technologies rather than attempting an all-encompassing list of climate change effects on the whole energy sector. Bioenergy is not considered explicitly because climate mostly affects the production of the primary material in agriculture and forestry, and the transport, conversion (into liquid fuels or electricity) and distribution steps in the bioenergy chain are affected by the same climate and weather attributes as those in the fossil fuel chains. Similarly, geothermal energy is omitted because, given the nature of the technology, it is not particularly affected by changing climate and extreme weather. This assessment framework and the large number of examples are intended to put the climate–energy supply linkages in context and foster more in-depth studies on the linkages between climate impacts and the energy sector in the future at reginal, national and international levels.

Three national assessments of energy sector vulnerability and adaptation are presented in Sections 8–10. They present short summaries of national case studies prepared as part of the IAEA coordinated research project Technoeconomic Evaluation of Options for Adapting Nuclear and Other Energy Infrastructure to Long Term Climate Change and Extreme Weather. The scope (the technologies, climate and weather aspects considered), the assessment methods (energy systems models and spatial information system) and other features of these case studies vary extensively and thus present a large diversity of possible framing and analytical techniques to tackle the challenges posed by climate change for the energy sector.

1.5. SUMMARY

The impacts of GCC will mostly affect the resource base of renewable energy sources: changes in water availability for hydropower, windiness for wind energy and insolation/cloudiness for solar energy. The extraction and transport of depletable energy sources are relatively less affected by gradual changes in climate attributes. The direction and magnitude of changes in the relevant climate features are somewhat uncertain and are likely to vary regionally.

The impacts of GCC on most components of the energy supply chain are expected to be modest and easy to cope with in the investment and renewal cycles of several energy technologies. Important exceptions are thermal and nuclear power plants and energy infrastructure elements with economic lifetimes of 50–60 years or more.

Present and future impacts of EWEs can be more severe, and reducing vulnerability to them can be much more expensive. EWEs plague vulnerable components of energy systems under the current climate regime. EWEs overlaid on GCC tend to make related impacts worse. Simultaneous occurrences of several EWEs amplify single impacts and can lead to severe outcomes. Changes in EWEs in adverse directions (greater frequency and intensity, longer duration) superimposed on GCC will exacerbate impacts further.

Investments are being implemented worldwide to reduce the vulnerability of existing energy facilities and infrastructure to EWEs. These investments should also consider projected future changes in climate and weather, especially for long lived assets. New facilities should be designed to be ‘climate proof’ with a view to projected future climate and weather characteristics and should obey the ensuing new design requirements.

Technological development and management improvement efforts are also underway to reduce vulnerability to EWEs under the current climate. Planned adaptation can reduce the exposure and vulnerability of energy systems to increasing future vagaries of climate and weather, but projections of plausible directions and magnitudes of changes are needed to implement these adaptation measures effectively and efficiently. Yet a robust, climate proof energy system will not be one that performs optimally under one climate change scenario but rather one that performs reliably across a plausible range of climate futures. It would probably be economically unaffordable to make each single element of an energy system 100% climate and weather proof. Finding the balance between the costs and security of energy supply involves balancing the energy system by deploying capacities that are vulnerable to different types of EWE and can provide backup if one system component is damaged by a given type of event.

2. ADAPTATION TO CLIMATE CHANGE IN THE PARIS AGREEMENT

In December 2015, the 21st session of the Conference of the Parties adopted the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) [14]. The agreement has been widely celebrated as a historical breakthrough in global climate policy because it is the first universal and legally binding accord to mitigate climate change. (The Kyoto Protocol is also a global and legally binding climate accord, but its mitigation provisions are valid only for countries listed in Annex I of the UNFCCC.) The mitigation target of the Paris Agreement is specified in Art. 2 as (Ref. [14], p. 3):

> "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change".

As a low carbon technology, nuclear energy has been demonstrated to be able to contribute to reducing energy related greenhouse gas (GHG) emissions, which account for three quarters of the total GHG emissions [15]. The IAEA highlighted the potential contribution of nuclear power to achieving the mitigation target specified in the Paris Agreement [16] while also fostering the implementation of several Sustainable Development Goals adopted by the United Nations [17].

Much less public and media attention has been paid to other components that make the Paris Agreement unique: it is truly comprehensive and involves a range of issues on which progressive action will be required to implement environmentally effective, economically efficient and socially just climate protection strategies. Beyond mitigation, these components include adaptation, loss and damage, finance, technology development and transfer, capacity building, and transparency of action and support. Given the bottom-up, voluntary nature of targets and actions in these areas and the yet unspecified rules and modalities of implementation, tangible outcomes are difficult to foresee.

Next to the mitigation target, Art. 2 of the Paris Agreement also specifies adaptation as a prominent objective of the agreement: "Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production" (Ref. [14], p. 3). Article 7 on adaptation links adaptation needs to the temperature target (Ref. [14], p. 9):

> "Parties hereby establish the global goal on adaptation of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal referred to in Article 2."

Article 7 mostly regulates the international aspects of adaptation and emphasizes the importance of international support for developing countries in their adaptation efforts. The "nationally determined" nature of adaptation planning and implementation includes, among other aspects, “The assessment of climate change impacts and vulnerability, with a view to formulating nationally determined prioritized actions, taking into account vulnerable people, places and ecosystems” (Ref. [14], p. 10). This publication intends to support IAEA Member States and any interested groups and organizations in undertaking such impacts and vulnerability assessments in the energy sector and in formulating adaptation strategies to respond to them. As such, this publication is also a response to para. 8 of Art. 7 of the Paris Agreement [14] encouraging the United Nations specialized organizations and agencies to support Parties in implementing their adaptation related activities.

Adaptation is also a key element of the nationally determined contributions (NDCs) and will have to be regularly reported as adaptation communication to the UNFCCC as a part of or together with other communications, such as national adaptation plans (NAPs) or national communications. Adaptation plans and actions will be reviewed in the periodic assessments of the collective progress towards the objectives of the Paris Agreement [14] (referred to as ‘global stocktake’). How to operationalize these provisions is somewhat vague at this point. One of the adaptation related tasks in taking the agreement forward is to develop modalities to recognize the adaptation efforts of developing counties and get them adopted by the first session of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement [18]. The systematic assessments of vulnerabilities and adaptation options in the energy sector presented in this publication may also help Parties in compiling the energy component of the adaptation actions for the reports mentioned above.

All vulnerability and adaptation related provisions are presented in the Paris Agreement at a generic level. Except the principle cited above that adaptation and low GHG development should not threaten food production, no economic sector or activity is mentioned in conjunction with adaptation. Consequently, climate related risks and countermeasures are not discussed in sector specific terms, but the principles, procedures, guidelines and provisions are also applicable for the energy sector.

Several organizations have published guidance documents, particularly for developing countries, on implementing the Paris Agreement. The Pocket Guide to the Paris Agreement [19] by the European Capacity Building Initiative explains in non-technical language what the agreement involves for national level implementation. The report elaborates on the provisions in the article on adaptation, but going into sectoral details is beyond its scope. Together with other organizations, the Climate and Development Knowledge Network prepared a quick start guide and a reference manual [20] to support developing countries in preparing and implementing their NDCs. The adaptation section provides very useful guidance and a detailed procedure for implementing the adaptation component of NDCs, but again at a rather generic level.

Many least developed countries have prepared national adaptation programmes of action since 2008 and submitted them to the UNFCCC. These programmes focus on urgent and immediate adaptation needs and include syntheses of available information: assessments of vulnerability to current climate variability and EWEs as well as assessments of areas where risks would increase owing to climate change. The programmes also deal with searching for key adaptation measures, specifying criteria for prioritizing implementation activities and selecting the most urgent activities.

The NAP process was established in 2011 to help countries to conduct comprehensive medium and long term climate vulnerability assessment and adaptation planning. It can be used to prepare and implement the adaptation part of a State's NDCs by focusing on the following objectives (Ref. [21], p. 11):

> "(a) To reduce vulnerability to the impacts of climate change, by building adaptive capacity and resilience;
>
> (b) To facilitate the integration of climate change adaptation, in a coherent manner, into relevant new and existing policies, programmes and activities, in particular development planning processes and strategies, within all relevant sectors and at different levels, as appropriate."

This publication is intended to help interested countries, companies and other stakeholders in the design and implementation of the energy part of the NAP process as well.

3. ENERGY RELEVANT CHANGES IN CLIMATE AND WEATHER

3.1. INTRODUCTION

This section presents the projected changes in climate attributes, EWEs and their combinations introduced in Section 1 that are most important for the energy sector. The impacts of these climate trends and weather phenomena on various energy technologies are discussed in Sections 4–7.

The contribution of Working Group 1 to the IPCC Fifth Assessment Report [22] is the main source of the climate change projections presented in this section. Unless indicated otherwise, all statements, projections and uncertainty specifications are based on that report. The IPCC special report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [13], published in 2012, is another important resource, especially about trends and projections of EWEs.

Recent publications reinforce the observations and statements of these IPCC reports. For example, the latest State of the Climate report coordinated by the National Centers for Environmental Information of the National Oceanic and Atmospheric Administration [23] confirms that 2016 was the warmest year since instrumental records started more than 130 years ago. The 2016 record heat was due to the combination of long term global warming and a strong El Niño event early in the year. The report finds that all key climate indicators reflect trends consistent with a warming climate, including land and ocean temperatures, sea level and GHG concentrations in the atmosphere, which all surpassed the records set just in the preceding year.

Despite major advances in scientific knowledge about human influences on the Earth's climate, considerable uncertainties remain in: interpreting and attributing past changes in climate; understanding and modelling atmospheric, oceanic and biospheric processes and their interactions; and, especially, projecting how climate will change in the future in response to different magnitudes of anthropogenic forcing. The IPCC reports [13, 22] cited in this section use two metrics to characterize the degree of uncertainty in their key findings, based on the evaluations of underlying scientific understanding by the author teams:

(1) The first metric is the confidence in the validity of a finding, expressed in qualitative terms on the basis of the author team's evaluation of the associated evidence and its consistency. The level of confidence is presented by using five qualifiers: *very low*, *low*, *medium*, *high* and *very high*, and is indicated in italics in this section.

(2) The second metric is a quantified measure of uncertainty indicating the assessed likelihood of a finding, outcome or result, expressed in probabilistic terms across the following probability scale (shown in italics in this section):
- — *Virtually certain*: 99–100%;
- — *Extremely likely*: 95–100%;
- — *Very likely*: 90–100%;
- — *Likely*: 66–100%;
- — *More likely than not*: >50–100%;
- — *About as likely as not*: 33–66%;
- — *Unlikely*: 0–33%;
- — *Very unlikely*: 0–10%;
- — *Extremely unlikely*: 0–5%;
- — *Exceptionally unlikely*: 0–1%.

These uncertainty measures provide important information when the evaluation of the climate change vulnerability of energy systems is formulated in a formal risk assessment framework (risk = probability × consequence).

This section starts with a short summary of past climate developments and the four IPCC scenarios driving the calculations of future climate change in global climate models, mostly general circulation models. It then presents recent projections of GCC attributes and the evolution of selected large scale climate phenomena. This is followed by an overview of projected changes in the patterns of EWEs. The most important changes for the energy sector are briefly summarized at the end of the section.

3.2. PAST AND PROJECTED CLIMATE CHANGE

In its contribution to the Fifth Assessment Report, Working Group 1 of the IPCC confirmed at a higher level of confidence than ever before that the climate of the Earth is changing as a result of anthropogenic GHG emissions: “Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia” (Ref. [22], p. 4). Over the period 1880–2012, globally averaged surface temperature increased by 0.85°C. The upper layer of the ocean is warming, the Greenland and Antarctic ice sheets are losing mass, glaciers continue to shrink and the global mean sea level rose by 0.19 m between 1901 and 2010.

Patterns of EWEs have been changing in recent decades as well. The Emergency Events Database [24] was launched in 1988 by the Centre for Research on the Epidemiology of Disasters with the help of the World Health Organization and the Government of Belgium. The Emergency Events Database contains essential core data on the occurrence and effects of over 22 000 mass disasters in the world from 1900 to the present day. The database is compiled from various sources, including United Nations agencies, non-governmental organizations, insurance companies, research institutes and press agencies. Figure 1 shows the decadal trends of drought and floods in five continents since 1977.

The Fifth Assessment Report [22] adopted a new approach to projecting anthropogenic climate change for the next few decades to the next few centuries. Abandoning the traditional pathway of tracking changes from scenarios of socioeconomic development and associated GHG emissions from energy use and land use changes through atmospheric GHG concentrations and radiative forcing to climate attributes such as temperature and precipitation, as was the case in the IPCC Special Report on Emissions Scenarios [25], the Fifth Assessment Report bases new projections on alternative assumptions about radiative forcing values for the year 2100.

The new IPCC scenarios consist of four so-called representative concentration pathways (RCPs) for exploring the near and long term climate change implications of different paths of anthropogenic emissions of all GHGs, aerosols and other climate drivers. The four RCPs present approximate total radiative forcing values for the year 2100 relative to 1750, ranging from 2.6 W/m^2 to 8.5 W/m^2. RCP2.6 assumes strong GHG mitigation actions resulting from stringent but unspecified climate policies. Radiative forcing along this pathway peaks and declines during the twenty-first century and leads to a low forcing level of 2.6 W/m^2 by 2100. In RCP4.5, radiative forcing stabilizes by 2100 at a significantly higher level. The other two concentration pathways (RCP6.0 and RCP8.5) indicate increasing emissions throughout the twenty-first century and lead to stabilizing radiative forcing beyond 2100 at 6.0 W/m^2 and 8.5 W/m^2, respectively. The RCPs were converted into corresponding GHG concentrations and emissions that served as inputs to more than 50 global climate models used in the Coupled Model Intercomparison Project (CMIP) Phase 5 to assess the changes they would trigger in the climate system globally and regionally [22].

Figure 2 shows the projected global annual mean surface air temperature change — or simply, the triggered global warming — relative to the 1986–2005 mean values from the CMIP5 concentration driven experiments for all RCPs. Relative to the 1850–1900 period, the increase in global surface temperature is *likely* to exceed 1.5°C by the end of this century for all but the RCP2.6 scenario. Relative to the IPCC Fifth Assessment Report reference period (1986–2005), global surface temperature by the end of the twenty-first century is expected to rise between 0.3°C and 1.7°C (RCP2.6) at the low end and between 2.6°C

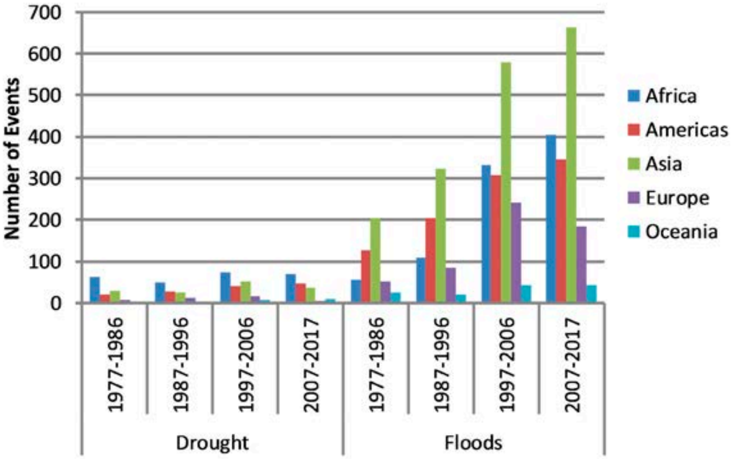

FIG. 1. Registered occurrence of droughts and floods [24].

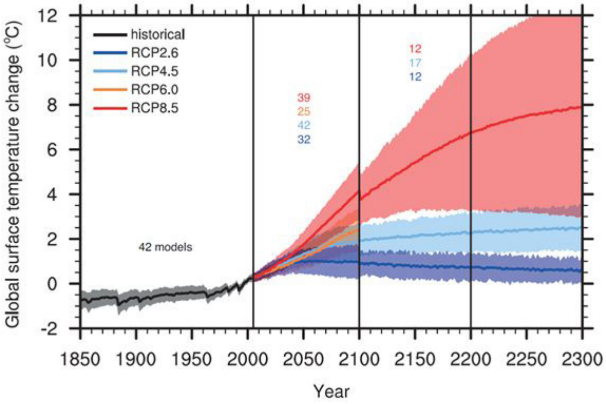

FIG. 2. Global annual mean surface air temperature change until 2300 relative to the 1986–2005 mean values from the CMIP5 concentration driven experiment. (Reproduced courtesy of IPCC.) Source: Figure 12.5 of Ref. [22]. Note: CMIP — Coupled Model Intercomparison Project; RCP — representative concentration pathway. Solid lines indicate multimodel means; shaded areas represent 95% ranges. Numbers in colour indicate the number of models that provided input to CMIP5 for a given RCP. Discontinuities at 2100 are due to the smaller set of models running beyond 2100.

and 4.8°C (RCP8.5) at the high end of the scenario spectrum. The low end of the spectrum is associated with limiting the global mean temperature increase to less than 2°C above the pre-industrial level, corresponding to the target of the Paris Agreement (see Section 2).

3.3. GRADUAL CLIMATE CHANGE

3.3.1. Mean annual surface temperature

Changes in mean temperatures will affect several energy technologies. The most important impact is on nuclear and fossil thermal generation, in which higher ambient temperatures reduce the efficiency of thermal conversion (Carnot's rule) and, by warming ambient water bodies, the efficiency of cooling. Higher mean temperatures also increase the evaporation rates in hydropower reservoirs, thereby reducing the resource base for power generation. Increasing temperatures in permafrost regions can destabilize energy infrastructure such as wells and pipelines.

In the near term, the global mean surface temperature is *likely* to rise by 0.3–0.7°C in the period 2016–2035 relative to 1986–2005 (*medium* confidence). This projection is based on various types of evidence and assumes no major perturbations in total solar irradiance and no major volcanic eruptions. It is *very likely* that the increase in mean temperature in the next two decades will be more rapid over land areas than over the oceans. Relative to their natural internal variability, both seasonal and annual mean temperature increases are expected to be larger in the tropics and subtropics than in midlatitude regions in this time frame (*high* confidence).

Over the long term (2081–2100), however, a rather different picture emerges: as a *likely* span, 0.3°C (the low end of the RCP2.6 range) to 4.8°C (the high end of RCP8.5) increases are foreseen in the global mean surface temperatures. The spatial patterns are the same as in the near term: faster warming over land areas than over the oceans. The magnitude of warming is projected to be much greater in the high latitude regions, especially in the north, than around the equator.

Figure 3 shows the projected changes in the annual mean surface air temperatures relative to the 1986–2005 mean values from the CMIP5 modelling work for the two extreme RCPs. Even under stringent climate policies (RCP2.6), the average surface warming is projected to reach 1.5°C in most terrestrial areas and 2°C in the middle and high latitude regions of the northern hemisphere by the end of this century. Fast increasing GHG emissions and atmospheric concentrations driving the high scenario (RCP8.5) are projected to lead to mean temperature increases of 4–5°C in continental areas of the already hot tropical regions and 5–7°C in most of the middle and high latitude regions of the northern hemisphere.

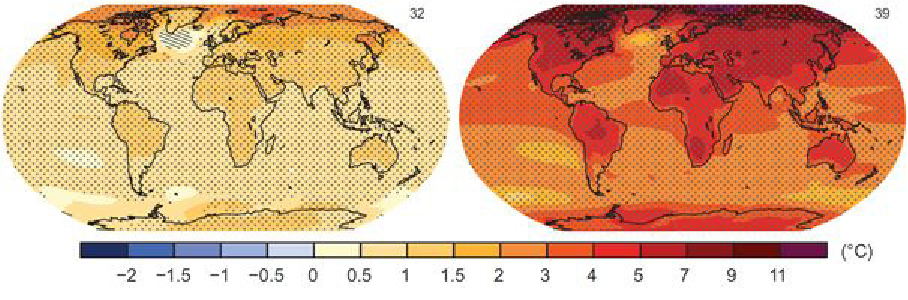

FIG. 3. Annual mean surface air temperature change in 2081–2100 relative to the 1986–2005 mean values from the CMIP5 concentration driven experiment for scenarios RCP2.6 (left) and RCP8.5 (right). (Reproduced courtesy of IPCC.) Source: Figure SPM.8 of Ref. [22]. Note: CMIP — Coupled Model Intercomparison Project; RCP — representative concentration pathway. Numbers in the upper right corners indicate the number of models used to calculate the multimodel mean.

3.3.2. Precipitation

Precipitation in catchment regions of hydropower plants is the main factor determining the amount of water resources available for power generation. Changes in the amount and timing of precipitation are also important for nuclear and other thermal generation that depend on water for cooling. Large amounts of energy resources (coal, oil, uranium) are transported by rivers that can be disrupted by low water levels.

Over the next few decades, it is *very likely* that zonal mean precipitation will increase in high and some midlatitude regions, and will *more likely than not* decrease in the subtropics. Precipitation changes may be dominated by a combination of natural internal variability, volcanic forcing and anthropogenic aerosol effects and vary accordingly at subzonal scales. Near surface specific humidity is *very likely* to increase over the next few decades. It is *likely* that there will be increases in evaporation in many regions. Projections of changes in soil moisture and surface runoff have *low* confidence.

In the long term, it is *virtually certain* that in a gradually warming world, global precipitation will increase. In the most modest climate change scenario (RCP2.6), the rate of *likely* increase is projected in the range of 1–3%/°C with a sensitivity range across the CMIP5 models between 0.5 and 4%/°C at the end of the twenty-first century. Nonetheless, substantial spatial variations are expected in how average precipitation will change in all scenarios, most markedly under RCP8.5. Regions will see increases, decreases or no significant changes at all (see Fig. 4). There is *high* confidence that the annual mean precipitation in wet regions will increase, while in dry regions it will decrease. Similarly, the contrast between wet and dry seasons will increase in most regions. By the end of this century under the RCP8.5 scenario, high latitudes are *very likely* to see more precipitation, many midlatitude and subtropical arid and semi-arid regions will *likely* get less precipitation, and many moist midlatitude regions will *likely* experience more precipitation.

3.3.3. Windiness

Wind is the energy source for wind power generation, which is therefore sensitive to changes in mean wind speed. Other energy technologies are not as much affected by changes in mean wind velocity but can be subject and vulnerable to extreme wind conditions (see Section 4.3).

Shifts in energy and water cycles in a warming world are closely linked with changes in atmospheric circulation and mass distribution. In extratropical regions of the northern hemisphere, anthropogenic drivers will shift the jet streams and related zonal mean storm tracks poleward and will strengthen the

Atlantic storm track. Yet climate modellers suggest caution over these near term projections owing to imperfect formulation of the underlying forces in their models. Figure 5 shows the projected annual mean zonal wind change for the next two decades under the RCP4.5 scenario, which involves modest climate policies to reduce GHG emissions.

As indicators of surface changes in atmospheric circulation, sea level pressures decrease in high latitudes and increase in midlatitudes. This trend is connected with the poleward shift of the southern hemisphere midlatitude storm tracks and other large scale atmospheric processes. Changes in annual mean zonal winds are projected throughout the atmosphere, and their magnitudes are greater in higher RCPs. Figure 6 shows large increases in winds in the tropical stratosphere. Under the considerably warming but relatively modest RCP4.5 and in the very high RCP8.5 climate change scenarios, there is a marked poleward shift and intensification of the southern hemisphere tropospheric jet.

3.3.4. Cloudiness

Clouds are an important component of the climate system. Cloud processes and feedback, and the interactions between aerosols and clouds, are important

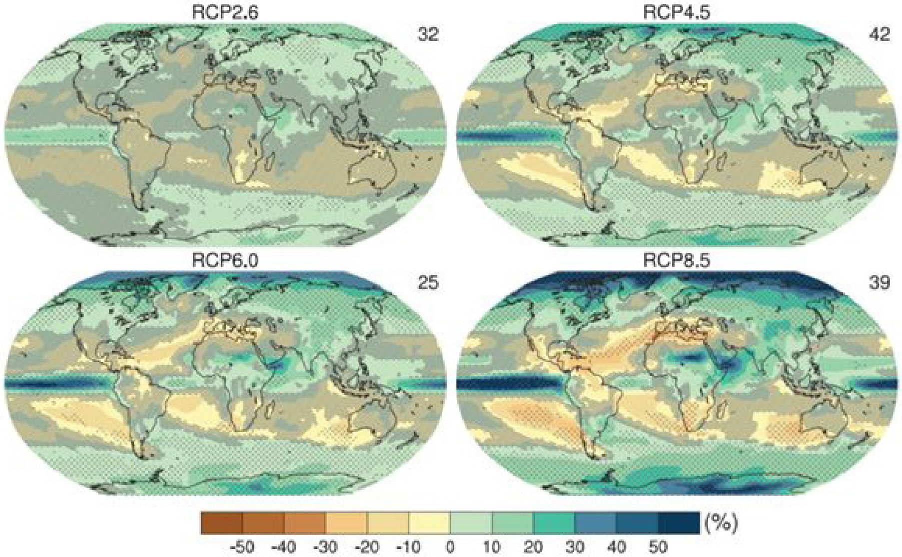

FIG. 4. Annual mean precipitation change for four scenarios (2081–2100). (Reproduced courtesy of IPCC.) Source: Figure TS.16 of Ref. [22]. Note: RCP — representative concentration pathway. Numbers in the upper right corners indicate the number of models used to calculate the multimodel mean.

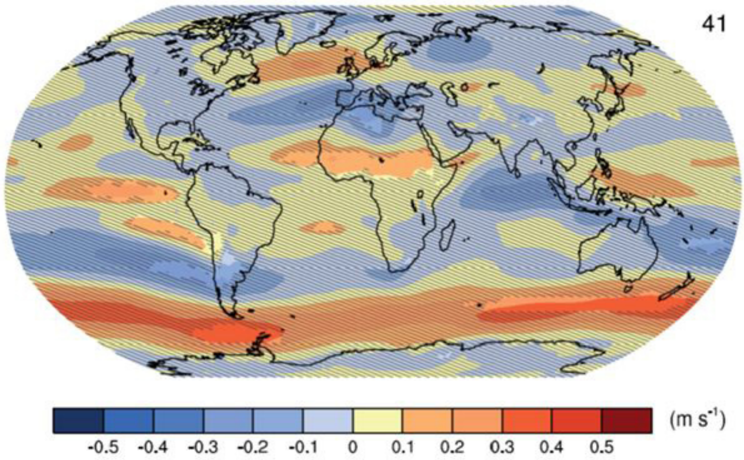

FIG. 5. Annual mean zonal wind change in 2016–2035 under the RCP4.5 scenario. (Reproduced courtesy of IPCC.) Source: Figure 11.15 of Ref. [22]. Note: RCP — representative concentration pathway. The number in the upper right corner indicates the number of models used to calculate the multimodel mean.

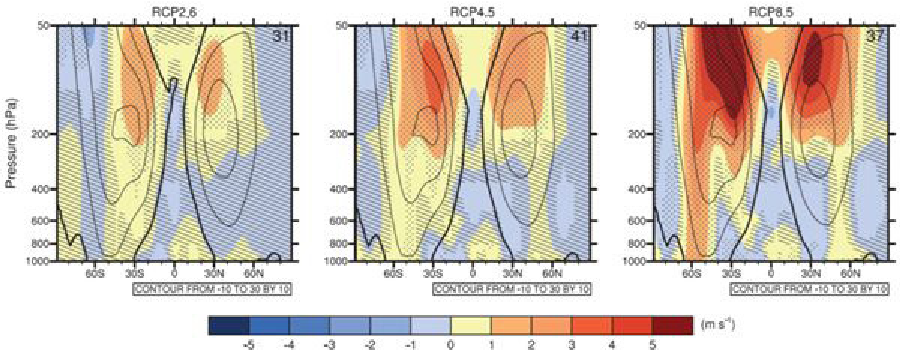

FIG. 6. Annual mean zonal wind change in tropical stratosphere (2081–2100) relative to 1986–2005 under three climate change scenarios. (Reproduced courtesy of IPCC.) Source: Figure 12.19 in Ref. [22]. Note: RCP — representative concentration pathway. Black contours represent the multimodel average for the 1986–2005 base period. Numbers in the upper right corners indicate the number of models used to calculate the multimodel mean.

in determining climate sensitivity (the equilibrium change in the annual global mean surface temperature in response to the doubling of atmospheric equivalent CO_2 concentration) and other climate attributes. From the perspectives of energy supply, cloudiness is a proxy indicator of sunshine hours, although the effect of cloud cover on the duration of solar radiation is rather complicated.

Future projections of total cloud amount indicate consistent decreases in the subtropics and increases in high latitudes. In average conditions, low and midlatitude areas are projected to become less cloudy and drier. The projected changes in annual mean cloud fractions by the end of this century are presented in Fig. 7.

3.3.5. Sea level rise

A large fraction of the global population lives in coastal areas; hence, a considerable amount of energy related facilities and infrastructure is located there. Sea level rise can directly affect (inundate) all types of power plant located in low lying coastal areas and indirectly influence their resource supply anywhere by affecting harbours and coastal transport infrastructure. Offshore wind, oil and gas facilities will also be affected by rising mean sea levels.

Global mean sea level is projected to rise throughout this century under all RCP scenarios, driven by continued ocean warming and additional loss of mass from glaciers and ice sheets. Relative to 1986–2005, the rise in global mean sea level for 2081–2100 will *likely* reach 0.26–0.55 m under RCP2.6, 0.32–0.63 m under RCP4.5, 0.33–0.63 m under RCP6.0 and 0.45–0.82 m under RCP8.5 (*medium* confidence) (see Fig. 8).

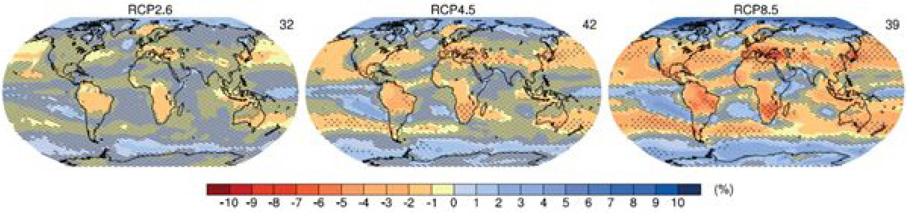

FIG. 7. Annual mean cloud fraction change (in %) in 2081–2100 relative to 1986–2005 under three climate change scenarios. (Reproduced courtesy of IPCC.) Source: Figure 12.17 in Ref. [22]. Note: RCP — representative concentration pathway. Numbers in the upper right corners indicate the number of models used to calculate the multimodel mean.

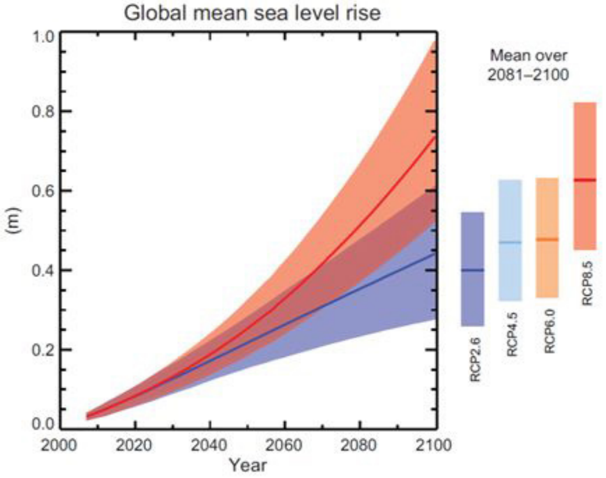

FIG. 8. Global mean sea level rise until 2100 relative to 1986–2005 under four climate change scenarios. (Reproduced courtesy of IPCC.) Source: Figure SPM.9 in Ref. [22]. Note: RCP — representative concentration pathway. The likely ranges and median values for 2081–2100 are shown by the vertical side bars and the horizontal lines in them, respectively.

3.3.6. Large scale climate patterns

The future evolution of large scale climate phenomena will modify current vulnerabilities of energy systems and might spawn new ones in various regions. Projected changes in monsoon systems, El Niño events and some tropical phenomena are summarized in this section.

Although the global monsoon circulation is projected to weaken, global measures of area and summer precipitation of monsoon are *likely* to increase. It is also *likely* that monsoon onset dates will commence earlier or will change only slightly, and monsoon withdrawal dates are *likely* to begin later. This implies a lengthening of the monsoon season in several regions. Seasonal mean precipitation is projected to increase noticeably in East and South Asian summer monsoons, whereas large uncertainties surround projected changes in other monsoon regions. Total monsoon related precipitation is projected to increase in the Asian–Australian monsoon somewhat unevenly: increasing in India and only slightly changing in the Australian summer monsoon (*medium* confidence). The Indian summer monsoon circulation is expected to weaken, although this is expected to be compensated by higher atmospheric moisture content, resulting in more rainfall (*medium* confidence). In East Asia, summer monsoon circulation and rainfall are projected to increase. Monsoon related interannual rainfall variability is anticipated to increase (*medium* confidence), and it is *very likely* that precipitation extremes will increase in many regions [22].

The El Niño–Southern Oscillation (ENSO) is a warming of the tropical Pacific Ocean basin east of the 180th meridian, connected with a fluctuation of a global scale tropical and subtropical surface pressure pattern with time scales of two to seven years. The prevailing trade winds weaken during an ENSO event, thereby reducing upwelling, altering ocean currents and warming sea surface temperatures that further weaken the trade winds. The event has wide ranging impacts on wind, sea surface temperature and precipitation in the tropical Pacific and climatic effects throughout the Pacific region and in many other parts of the world. The cold phase of ENSO is called La Niña.

It is projected that ENSO will remain the dominant mode of natural climate variability with global influences in the twenty-first century and will *likely* increase the intensity of induced regional rainfall variability (*high* confidence). Given the large natural variations of the amplitude and spatial pattern of ENSO, however, confidence in any other projected changes for this century remains *low*. Relative to the wide spread of foreseen changes across climate models, the projected change in El Niño amplitude is small for both the RCP4.5 and RCP8.5 scenarios. Patterns of temperature and precipitation anomalies over the North Pacific and North America are likely to move eastwards (*medium* confidence), but projections of climate impacts on ENSO changes in regions have *low* confidence. In general, the increase in atmospheric moisture intensifies the temporal variability of precipitation in a warming world, even if atmospheric circulation variability remains constant. This also applies to precipitation variability induced by ENSO, although the possibility of changes in ENSO teleconnections can make this general conclusion regionally somewhat varied [22].

Precipitation patterns in the tropical zone are another climate phenomenon of importance for energy systems in that region. Projections of change in precipitation vary across tropical regions, showing increases in some regions and decreases in others. Two drivers are likely to shape the spatial distribution of tropical rainfall changes: current climatology and the ocean warming pattern. The first will increase rainfall near the currently rainy regions, while the second will increase rainfall in areas where the ocean warming exceeds the tropical mean value. Tropical rainfall projections seem to be more reliable for the seasonal than for the annual mean changes (*medium* confidence).

The tropical Indian Ocean is projected to show a zonal pattern with less warming and less rainfall in the eastern zone (including Indonesia), and more warming and more rainfall in the western part (including East Africa). The dipole mode of interannual variability in the Indian Ocean is *very likely* to stay active, and this will affect climate extremes in Australia, East Africa and Indonesia [22].

3.4. EXTREME WEATHER EVENTS

3.4.1. Temperature extremes

As global mean temperatures increase, there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales (*virtually certain*). Heatwaves will be more intense, occur more frequently, last longer and affect larger areas than in recent decades (*very likely*). Nonetheless, occasionally cold winter extremes will occur even in an on average warming world.

Figure 9 shows projected changes in extreme temperatures by the end of this century. The changes depicted in this figure are calculated as fractions or percentages in the 2081–2100 period (based on simulations for the A2 emissions scenario of the IPCC's Special Report on Emissions Scenarios [25]), minus the fractions or percentages of the 1980–1999 period. Warm day and cold day changes are expressed in units of standard deviations, derived from detrended per year estimates from the three 20 year periods 1980–1999, 2046–2065 and 2081–2100 pooled together. Changes in maximum temperatures greater than 30°C are given directly as differences in percentage points.

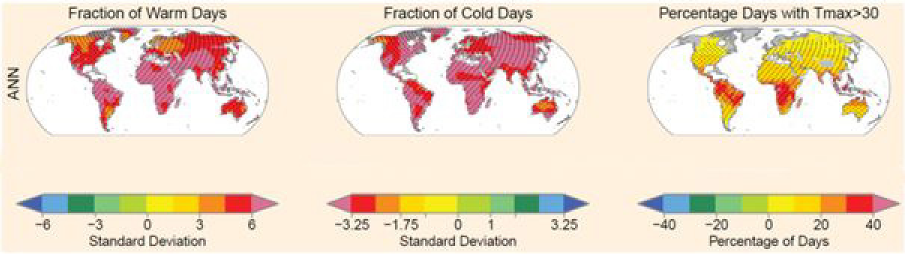

FIG. 9. Projected annual changes in three indices for daily maximum temperatures for 2081–2100 relative to 1980–1999, based on 14 general circulation models contributing to the CMIP3. (Reproduced courtesy of IPCC.) Source: Based on figs 3 and 4 of Ref. [13]. Note: ANN — annual; CMIP — Coupled Model Intercomparison Project. Left (and middle): fraction of warm (and cold) days when the highest temperature exceeds the 90th percentile (remains below the 10th percentile) of that day of the year, calculated from the 1961–1990 reference period. Right: percentage of days with maximum temperature (T_{max}) > 30°C. Colour shading is only added for areas where at least 66% (i.e. 10 out of 14) of the general circulation models agree on the direction of the change.

3.4.2. Precipitation extremes

It is *likely* that the frequency and intensity of heavy precipitation events will increase over land in the coming decades, mostly driven by increases in atmospheric water vapour content and partially influenced by changes in atmospheric circulation. Regional scale changes are greatly shaped by natural variability and are also influenced by trends in future aerosol emissions, volcanic activity and land use changes in the given region; therefore, the combined outcome of anthropogenic forcing at regional scales is more difficult to project.

Towards the end of this century, short duration precipitation events (storms) are *likely* to become more intense, whereas weak storms are *likely* to become fewer. Extreme precipitation events will *very likely* become more intense and more frequent over most of the midlatitude land areas and over wet tropical regions. The global average sensitivity of the 20 year return value of the annual maximum daily precipitation ranges moves together with a local temperature increase at the rate of 5.3%/°C in the average of CMIP5 models, but large regional variations prevail.

Figure 10 shows projected changes in extreme precipitation by the end of this century. The changes depicted are calculated as fractions or percentages in the 2081–2100 period (based on simulations under the A2 emissions scenario of the IPCC's Special Report on Emissions Scenarios [25]), minus the fractions or percentages of the 1980–1999 period (from corresponding simulations for the twentieth century). Changes in wet day intensity and in the fraction of days with precipitation greater than 10 mm are expressed in units of standard deviations, derived from detrended per year estimates from the three 20 year periods 1980–1999, 2046–2065 and 2081–2100 pooled together. Changes in the percentage of days with precipitation above the 95% quantile are given directly as differences in percentage points.

3.4.3. Wind extremes

Confidence is *low* in wind trends in general and also in the relationship between past trends in observed mean wind speed and trends in extreme wind events. Several factors (few studies about future extreme winds, shortcomings in models) explain why confidence is also *low* in projections of changes in extreme winds, except the more extensively studied but highly complex issue of tropical cyclones.

Near term projections of tropical cyclone activities indicate reduced frequency globally as well as in the northern and southern hemispheres for the period 2016–2035 relative to 1986–2005. However, these short term projections vary widely across global climate models and scenarios. Over this period, the

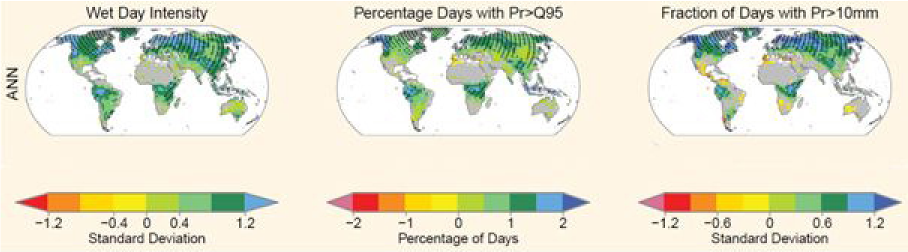

FIG. 10. Projected annual changes in three indices for daily precipitation for 2081–2100 with respect to 1980–1999, based on 17 general circulation models contributing to the CMIP3. (Reproduced courtesy of IPCC.) Source: Based on figs 3–6 of Ref. [13]. Note: ANN — annual; CMIP — Coupled Model Intercomparison Project. Left: wet day intensity; middle: percentage of days with precipitation (Pr) above the 95% quantile of daily wet day precipitation for that day of the year, calculated from the 1961–1990 reference period; right: fraction of days with precipitation greater than 10 mm. Colour shading is only added for areas where at least 66% (i.e. 12 out of 17) of the general circulation models agree on the sign of the change.

CMIP5 ensemble range of projected change in tropical cyclone frequency across the RCP2.6, RCP4.5 and RCP8.5 scenarios for the North Atlantic spans from –30 to 27%.

Long term projections indicate that the annual frequency of tropical cyclones will decrease or remain basically unchanged in most regions. Some assessments [26] project that the maximum wind speed (intensity) and the rainfall rates in the vicinity of cyclone centres will slightly increase. Yet the number of modelling experiments is too low to make assertive forecasts.

3.4.4. Sea level extremes

Driven primarily by an increase in mean sea level and by the drastically decreasing return periods of extreme events, a significant increase in the occurrence of future sea level extremes is projected by the end of the twenty-first century. This trend is *likely* to start in the coming decades. Here again, confidence in region specific projections of storminess and associated sea storm surges is *low*.

3.5. SUMMARY

During the twenty-first century, many attributes of global and regional climate, as well as patterns of EWEs, of particular importance for the energy sector are projected to change significantly owing to anthropogenic GHG emissions.

The emerging trends will be noticeable in the next few decades (i.e. during the economic lifetime of many energy installations and infrastructure).

The most pronounced feature of climate change will be the increase in mean temperatures and the greater frequency, intensity and duration of hot spells. The degree of warming will depend on the level of anthropogenic forcing and is projected to be in the range of 0.3–4.8°C by the last decades of this century. The temperature increase will vary across regions, and its variability over interannual to decadal scales will remain.

Changes in mean precipitation will be more varied across regions. Most high latitude regions and the equatorial Pacific will receive more precipitation on average, while many midlatitude and subtropical dry areas will get less. Similarly to temperature extremes, extreme precipitation events are very likely to become more intense and more frequent in midlatitude terrestrial and wet tropical regions by 2081–2100.

Changes in other energy relevant climate and weather attributes are subject to greater uncertainties and are more difficult to forecast. Nonetheless, sufficient information is available about the possible directions and magnitudes of changes to assess the related vulnerabilities and initiate forward looking adaptation measures as part of energy sector planning and development.

4. NUCLEAR POWER

4.1. INTRODUCTION

Many impacts of GCC and EWEs on nuclear power plants are similar to those on fossil fuel fired thermal power plants. These impacts are presented in detail in Section 5. This section focuses mainly on impacts and vulnerabilities of special importance for nuclear plants. Resource extraction and transport is discussed first, followed by the power generation and operation of nuclear power plants. Disruptive impacts of weather events in the past are presented to identify lessons learned from them. Various aspects of adaptation in nuclear power plants are also reviewed. The section ends with a short summary of the key points.

Nuclear power plants are built to withstand EWEs on the basis of past experience, typically the worst expected event at the plant site over a 50 or 100 year period or much longer (e.g. 500 year floods) [27, 28]. However, as climate changes, past events are becoming an increasingly inappropriate basis for the prediction of the severity of future events. Existing nuclear power plants may become vulnerable to EWEs, and the siting and design of future nuclear power plants need to account for a changing climate. Nuclear plants are exposed to an additional level of vulnerability beyond those that other types of generating plant face. Various types of EWE can affect critical safety systems and increase the risk to human health and the environment, making adaptation more than an economic calculus for plant owners. Ensuring that external events do not lead to safety system failures is the highest priority for adaptation to EWEs.

Generally speaking, many acute safety threats from EWEs can be minimized by shutting down nuclear reactors until an event has passed, but this strategy leads to increasing outages as climate change and EWEs become increasingly unfavourable. Moreover, a shutdown state during an EWE may not be the safe state. Adapting plants so that reactor shutdowns become less frequent would minimize outages as well as avoid costly plant related damages that would have occurred without plant adaptation.

Although the accident at the Fukushima Daiichi nuclear power plant was caused by a tsunami, which is unrelated to climate change, this tragic event underscores the vulnerability of nuclear power plants to extreme flooding. In the aftermath of the Fukushima Daiichi accident, the nuclear power industry and its regulators reassessed nuclear plant safety against extreme natural hazards, including flooding, wind, ice storms and extreme temperatures.

4.2. RESOURCE EXTRACTION AND TRANSPORT

Increased precipitation may have some effects on uranium mining, though no more so than on any other heavy metal mining operation. Open pit mining for uranium is subject to threats of flooding. For example, in 2001 and 2012, the flooding of Toro Energy Mines in Australia affected the price of uranium. Fortunately, unprocessed uranium as it occurs naturally in uranium mines is relatively harmless compared with enriched uranium. Uranium mining operations, therefore, can take the same sort of precautions against flooding that any other heavy metal mining operation takes. The extraction of uranium will be most affected by EWEs. The extent of the vulnerability of uranium mining will depend on the mining method. Open cast mining might be particularly affected by high precipitation extremes and related floods and erosion. These events can increase the amount of trace elements leached from the overburden and thus their environmental impacts on water bodies. Temperature extremes, especially extreme cold, might also encumber extraction.

Transporting uranium, nuclear fuel and radioactive waste always carries some risk, but GCC is expected to affect the transport of nuclear material only modestly. In regions with declining mean annual precipitation levels, ship and barge transport on rivers will be affected by low water levels. Port and dock facilities as well as coastal roads and rail tracks will need to be adapted to gradually rising mean sea level to avoid or at least reduce damage caused by flooding. The increasing frequency and intensity of EWEs will bring more severe and potentially costly impacts for the transport sector. For instance, sustained periods of extreme heat can lead to deformities in rail tracks and eventually derailment, softening of road surfaces in general, and rutting and bleeding of asphalt surfaces [6, 29].

The most sensitive steps in the nuclear fuel cycle (enrichment and reprocessing) are done indoors in well protected facilities. The threat posed by extreme weather is no different than the threat to any other industrial processes involving hazardous material. Buildings housing the machinery and equipment for these processes are constructed with a high margin of safety.

Perhaps the most severe threat of extreme weather with respect to the nuclear fuel cycle is the threat of flooding of temporary high level radioactive waste storage at nuclear plants. Once waste is permanently disposed of in geologically inactive underground repositories, there is virtually no risk from climate change. But while waste is stored on the site before permanent disposal facilities are prepared, there is a risk that floods could disturb or dislodge radioactive waste and release radioactive material to the environment. As part of the probabilistic safety assessment (PSA) (see Section 4.5.2), on-site storage should be carefully assessed with respect to the threat of flooding due to climate change, and appropriate measures, such as additional protective earthworks surrounding waste storage areas, should be implemented if flooding is deemed a risk. A PSA could also cover other events, such as extreme wind. For other parts of the nuclear fuel cycle, appropriate measures should be taken that are comparable with those adopted in other industries that deal with hazardous materials.

4.3. POWER GENERATION

4.3.1. Gradual climate change

Higher ambient mean temperatures reduce the thermal efficiency of all thermoelectric plants, including that of nuclear power plants. As discussed in Section 3, IPCC scenarios project global mean surface temperature increases between 0.3°C (low end of the lowest scenario) and 4.8°C (high end of the highest scenario) by 2100; near term increases are expected to be in the range of 0.3–0.7°C in the period 2016–2035 [22].

According to recent estimates, with every increase of 1°C in global mean temperature, nuclear plant generation output declines by 0.4–0.7% at low temperatures and by 2.3% at high temperatures [30]. If global mean temperatures rise by 0.4°C in 20 years, consistent with IPCC scenarios, average nuclear generation would decline by 0.16–0.28% at low temperatures and 0.92% at high temperatures [30]. Assuming a linear increase in temperature, a 90% capacity factor, a 5% discount rate and a constant €0.05/kW·h value of generation, these estimates imply that a 1 GW(e) nuclear power plant would lose generation owing to reduced thermal efficiency valued at approximately €4–6 million net present value over the next 20 years at low temperatures and around €21 million net present value at high temperatures. If current nuclear generation is projected for 20 years for all current nuclear plants, the global cost of rising temperature is on the order of €1–6 billion (using the assumptions as above, a linear increase in temperature and a constant projection of 2224 TW·h of nuclear generation) [31]. Net economic losses to operators will depend on their locations and the selling price of electricity.

Other than siting new plants in areas expected to have lower than average temperature increases, which may not be an option for many countries, no choices are available to avoid reductions in thermal efficiency due to higher temperatures. Furthermore, even if siting in a cooler area is an option, the ambient temperature is only one of dozens of factors that affect siting, many of which would have greater influence on the final siting decision.

Climate change will also alter precipitation patterns in most regions. Impacts of gradually increasing mean annual precipitation would be positive because more water would be available for cooling. However, significantly higher levels of precipitation can lead to flooding, which can have serious implications (see Section 4.3.2).

In contrast, decreasing annual precipitation would lead to long term reductions in the water levels in rivers or lakes that provide cooling water for existing nuclear plants, and this reduction could pose serious problems. In areas where long term rainfall patterns will reduce water availability, nuclear plants must compete with many other vital uses of scarce water. In some circumstances, generation may need to be curtailed or even halted if water levels are too low.

Higher average wind speeds brought on by changing climate can have some impact on nuclear plants. For plants near the coast, more persistent wind and fog can, over time, carry additional salt spray to those plants. Salt deposited in this way on exposed cables and metal parts will lead to faster corrosion and, potentially, to short circuits if the deposits are not cleaned regularly. For plants in dry areas, higher average wind speeds might deposit more dust and dirt. Such dust can cause problems with mechanical devices, electronic circuit boards, and so on. For both salt and dust, increased maintenance, appropriate shielding, and seals are effective solutions.

Although sea level rise has not yet affected nuclear plants, it threatens to be one of the most economically damaging climate change events. Any flooding can be problematic for a nuclear plant, but sea level rise in combination with storms could lead to site inundation. Table 1 summarizes the most important impacts of GCC on nuclear energy, together with the related adaptation options.

4.3.2. Extreme weather events

A nuclear power plant is one of the most complex electricity generating technologies and requires a large number of systems to operate safely and properly. Key components vulnerable to EWEs include water cooling, electronic control and monitoring, physical plant access, structural integrity, ventilation, and systems needed to ensure access to the electric grid.

Access to water for the cooling system is as important as the electricity needed to pump it. Long term climate change can lead to more extreme cold in winter and more extreme heat in summer. Ice can block the cooling water intake system, reducing the flow of cooling water to unsafe levels. Hot weather can facilitate algae blooms or rampant growth in seaweed and other plant materials, which can also block cooling water intake. If cooling water is too hot because of high ambient temperatures, the cooling capacity can be diminished and safety

TABLE 1. IMPACTS OF GRADUAL CLIMATE CHANGE ON AND ADAPTATION OPTIONS FOR NUCLEAR ENERGY

Impact	Potential vulnerabilities	Examples of adaptation options
Higher mean temperatures	Decreasing thermal efficiency Decreasing cooling efficiency	Select sites in cooler local climates when possible Design different cooling systems
Lower mean precipitation	Less and warmer cooling water, leading to potential reductions in output or even short term shutdown	Reuse wastewater, recover evaporated water in recirculating systems Improve wet cooling; install dry cooling
Increased windiness near coasts and dry areas	Salt sprays from sea leading to long term corrosion and short circuit of exposed electrical equipment; dust and sand carried by wind, leading to equipment malfunction	Weather seal critical equipment
Sea level rise	Flooding of low lying coastal sites	Raise dykes and other protective embankments

jeopardized. If discharging used cooling water into a river or lake would raise the temperature above the limit allowed by heat pollution standards, a nuclear plant must reduce its operation level or shut down altogether until ambient temperatures decline. Long term droughts can lead to water rationing, which would limit water intake for cooling. To maintain performance, generation output could be reduced or even temporarily halted, depending on the severity of the drought.

Most EWEs tend to exacerbate the impacts on nuclear power plants of gradual changes in the related climate attribute. The increasing frequency of extreme hot temperatures and low precipitation periods aggravates the impacts of already warmer conditions: reduced thermal and cooling efficiency, overheated buildings and water availability problems. Cooling of buildings, especially those housing key instrumentation and control equipment, is crucial for nuclear power plants. On the positive side, less frequent extreme cold and frost events will mean less corrosion. High temperature extremes increase the need for adaptation measures beyond those intended to mitigate impacts under GCC. As a secondary impact, heat can foster the rapid growth of biological material, which can clog cooling water intake, leading to reduced generation or shutdown. Indirect biological impacts are simple to manage by increasing the maintenance of screens to ensure that biological matter does not clog water intake systems.

Local high precipitation events can cause floods directly at the site of power plants and can damage buildings, equipment and downstream fuel cycle components, such as spent fuel storage (e.g. on-site dry casks). Floods upstream in the river basin may carry large amounts of debris and items accumulated on the riverbank, which would necessitate precautionary measures to be taken to protect cooling water intake (see Fig. 11). Adaptation options include hard measures — such as flood protection by dams, embankments, flood control reservoirs, ponds, channels, drainage improvement, and the rerouting and isolation of water pipes — and soft measures, such as the zoning and restricting of activities in flood prone areas.

Structures and building related systems, such as ventilation, must also withstand EWEs. Integrity of the reactor containment vessel and surrounding structures is critical to ensure safety, as is integrity of structures protecting spent fuel and radioactive waste storage. Buildings that house diesel generators, control equipment, and so on, must also be able to withstand high winds, projectiles driven by high winds, floods and heavy loads due to rain or snow. Extreme pressure differentials accompanied by high winds, as well as smoke and ash, can impair ventilation systems, without which personnel would be unable to continue to operate in affected buildings.

High winds and lightning (see below) have always been a threat to nuclear plants, and the threat will rise as these EWEs become more intense with climate change. Generally speaking, critical safety systems are well protected by reinforced structures designed to withstand extreme winds. Typically, the greatest threat from wind is its ability to disrupt power from the grid system, either off the site or via the plant's internal power connections. Without connection to the grid system for any length of time, a nuclear plant's reactors must sometimes be tripped to stop generating electricity. Yet the plant's safety systems must continue to operate and need power to do so. Diesel generators fill this gap.

Extreme winds and storms (tornadoes and other rare events) can damage buildings, cooling towers and storage tanks. Upgrading construction standards can reduce the risk of structural damage. Storm surges, superimposed on sea level rise, increase the flood risk for all facilities in low lying coastal areas.

Electronic control and monitoring systems consist of sensitive electronic equipment and miles of cables and sensors, all of which can be damaged by lightning strikes or corroded by moisture, dust, sand and salt. Climate change can increase the intensity of storms that result in lightning strikes [32] as well as bolster the underlying causes of corrosion [33], which can lead to short circuiting. Although the probability is low that multiple systems will fail simultaneously, the threat is there and needs to be considered. Lightning can short circuit or create false signals in instrumentation and can also short circuit on-site power connections, backup diesel connections and controls at nuclear power plant sites.

FIG. 11. Floods around the Slovenian nuclear power plant Krško in 1990. (Reproduced with permission courtesy of the Slovenian Nuclear Safety Administration.)

Exposure would be reduced by ensuring that circuits are insulated and grounded, key circuits are buried underground and diesel generator controls are shielded.

Landslides, forest fires and wildfires (possibly started by lightning) are not EWEs, but they can be triggered by extreme weather. Climate change can intensify storms and rainfall patterns that lead to landslides. Climate change can also intensify drought, which creates the conditions for a wildfire. Nuclear plant siting takes into consideration the potential for increased probability of landslides, forest fires and wildfires, so there is little direct threat from these events. However, such events can disrupt transmission lines connecting a nuclear plant with the grid system. They can also disrupt emergency access to and from a nuclear plant. Nearby landslides and fires can potentially inhibit nuclear plant personnel from entering or exiting the plant. Another indirect combined impact is smoke blown from wildfires to power plants, which may damage sensitive equipment and hinder the access of critical personnel, supply deliveries and emergency response workers. The most important impacts of EWEs on nuclear power plants are summarized in Table 2.

4.4. VULNERABILITIES OF NUCLEAR POWER TO EXTREME WEATHER IN THE PAST

Since 1980, the IAEA has maintained a database of events at nuclear plants, as reported by Member States, called the International Reporting System for Operating Experience (IRS) [34]. The purpose of the IRS is to act as a clearinghouse for Member States to share information and learn from everyone’s operating experience. Certain Member States may report a particular type of event and others may not. Therefore, broad conclusions from analysis of the data must be made with caution. Nevertheless, the IRS is the best single source of information on weather related events at nuclear facilities worldwide over the last 30 years. As such, the IRS can provide insight into the most reported EWE vulnerabilities facing nuclear power plants, how those vulnerabilities may be changing over time, and how nuclear plants have been adapting.

Of the 3665 reports in the IRS between 1980 and 2010, only a small fraction (74 cases, about 2%) involved weather or climate events. The overwhelming majority (88%) of the reported EWEs primarily affected only three major systems: water cooling systems (28%), electrical control systems (27%) and transmission grid systems (32%). The remainder of the events were general (e.g. flooding) or affected other systems (e.g. frozen water line to boiler) [34].

Because of the interconnectedness of systems within a nuclear facility, outside events like extreme weather have tended to reveal design, construction or maintenance errors that may have otherwise gone unnoticed. For example, a

TABLE 2. IMPACTS OF EXTREME WEATHER EVENTS ON AND ADAPTATION OPTIONS FOR NUCLEAR ENERGY

Impact	Potential vulnerabilities	Examples of adaptation options
Extreme heat	Heat can limit water discharge if temperatures are too high for water quality regulations, which can in turn reduce generation or force a shutdown	Reduce generation to avoid raising stream temperatures from discharged water above regulation
	Heat can further reduce the effectiveness of cooling	Switch from once through cooling to recirculating to reduce temperature of discharged water Switch from wet cooling to dry cooling
	Heat can foster the rapid growth of biological material that can clog cooling water intake, leading to reduced generation or shutdown	Increase maintenance of screens to ensure that biological matter does not clog water intake system
Extreme cold	Ice can clog water cooling systems, leading to reduced generation or automatic shutdown Ice can inhibit plant access Freezing pipes can lead to internal flooding Ice can damage the grid system	Route heated water from cooling system to inlet area Insulate critical piping
Precipitation	Excessive rain or snow can collapse unreinforced structures Excessive rain or snow can inhibit plant access to critical personnel and supply deliveries	Ensure that all buildings housing critical systems are reinforced Develop emergency weather plans Establish special procedures for removal of snow and ice
Drought	Low water levels can force plants to reduce generation output or shut down	Implement alternative cooling options: reuse wastewater Recover evaporated water in recirculating systems Switch to dry cooling systems
High winds	Wind generated missiles can damage buildings and backup generators High winds can knock out grid system interconnection	Install tornado missile shields

TABLE 2. IMPACTS OF EXTREME WEATHER EVENTS ON AND ADAPTATION OPTIONS FOR NUCLEAR ENERGY (cont.)

Impact	Potential vulnerabilities	Examples of adaptation options
Floods or sea level rise	Some coastal plants are increasingly vulnerable to storm surges as sea level rises and storms become more intense, whereas other plants may be vulnerable to river floods, both of which can force an automatic shutdown but can also damage critical safety systems and grid system interconnections and threaten spent fuel storage	Consider flood risks in site selection for new plants Build earthworks to minimize risk of flooding Upgrade flood resistant doors Raise elevation of backup diesel generators
Lightning	Lightning can short circuit or create false signals in instrumentation Lightning can short circuit on-site power connection and backup diesel connections and controls	Ensure that circuits are insulated and grounded Bury key circuits underground Shield diesel generator controls
Forest fire and wildfire	Forest fires and wildfires can disrupt plant access to critical personnel, supply deliveries and emergency responders	Develop emergency access and response plans in case of nearby forest fires and wildfires

lightning strike may not be deemed an event had proper grounding been in place. Extreme cold may not have led to an event if a water intake system had been designed to heat the area of intake, preventing ice formation. A loss of off-site power may not have been an event if a transmission interconnection bus had been properly shielded.

From 1980 to 1999, the events were remarkably balanced between lightning (33%), winds (33%) and freezing (30%), with a few flooding events (4%). The first half of the 2000s saw two new types of event: heat and corrosion. In the second half of the 2000s, over half of the reports were heat related. Five reports were related to freezing, the most since the second half of the 1980s (see Fig. 12). Obviously, new heat related events suggest that climate change may already be having an impact on nuclear plants. The fact that freezing events had steadily declined from the latter half of the 1980s (presumably because plants historically subject to freezing successfully adapted) and suddenly rose again also suggests

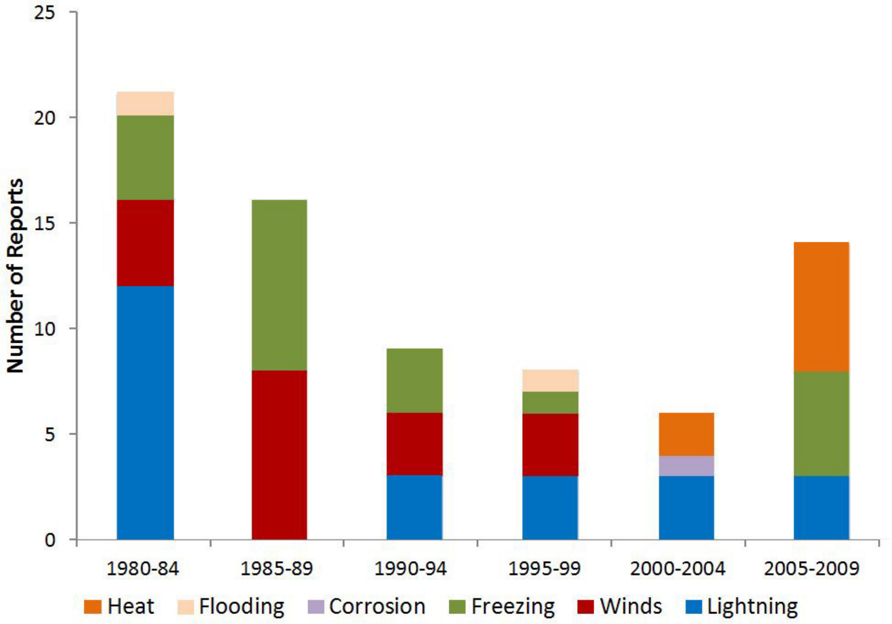

FIG. 12. International Reporting System for Operating Experience reports by climate or weather event between 1980 and 2009 [34].

that these incidents may also be climate related (plants with no history of cold related reports that had been in operation for an average of 17 years were now experiencing sufficient cold to lead to an event).

Heatwaves in the 2000s led to low water levels and/or high water temperatures that forced nuclear plants in Europe to curtail output, and in some cases to shut down altogether, for an extended period. In the summer of 2003, Europe experienced a severe heatwave that led to power reductions and outages because ambient water temperatures in many places were too high for power plants to discharge heated water from cooling systems. France lost 5.3 TW·h [35] from 17 nuclear plants operating at reduced capacity as a direct result of the heatwave [36]. Ultimately, the Government of France granted waivers to 13 thermal plants to violate thermal discharge limits; four nuclear plants and one fossil fuel plant used the waivers [37]. The state owned utility, Électricité de France, estimated that the heatwave cost the company €300 million; the price for electricity at the peak of the heatwave was €1000/MW·h, whereas as typical summer peak prices are €95/MW·h [36]. Another heatwave struck in 2006, and France again allowed nuclear plants to discharge water above thermal limits to avoid outages [38]. As climate change becomes increasingly severe, more generation capacity will likely be lost to heatwaves and drought.

4.5. ADAPTATION

4.5.1. Direct and indirect costs of not adapting

Without adaptation, in the worst case scenario significant plant damage and potential release of radioactive material can occur. Typical costs, however, will come in the form of lost revenue while the plant is shut down as a result of an EWE. Every 24 hours that a 1 GW nuclear plant is shut down (assuming €0.05/kW·h) costs the plant owner €1.2 million in lost revenue. Outages also lead to indirect costs. When a nuclear plant is shut down owing to an EWE, electricity customers must either experience a power outage or pay more for electricity from alternative sources to fill the gap.

In some circumstances, especially when a region is highly dependent on electricity supply from a nuclear plant (e.g. in small developing countries), an unexpected outage can lead to a wider blackout and impose substantial indirect economic costs. These costs vary considerably from country to country, as they are based fundamentally on the economic structure of a particular country. The value of lost load in the Netherlands is estimated at €8.6/kW·h [39] and around €4–€18/kW·h in Ireland [40]. If a 1 GW nuclear plant were to shut down for 24 hours (disregarding a wider blackout that could be triggered by the shutdown), the value of the lost load in the Netherlands would be €206 million (assuming that the customers of the nuclear plant do not have power from other sources) [39].

Many developing countries have less value added from electricity generation than the Netherlands and would also have lower values of lost load, but the loss would be no less significant to the economies of those countries. The cost of lost load in Shanghai, China, is estimated at €1/kW·h, so the above shutdown example applied to Shanghai would cost the economy €24 million [41]. Regardless of the location, the indirect economic cost of a nuclear outage can be sizeable. While an outage of one plant in most countries would not actually lead to a blackout, meaning the indirect costs would be far less if other generating resources could meet demand during the outage, the potential for costly blackouts warrants careful consideration of adaptation options at nuclear power plants.

4.5.2. Probabilistic safety assessment

The nuclear industry has developed successful mechanisms to adapt to many types of threat. These tools can be applied to reduce vulnerability and enhance adaptation to climate change. Sharing experience is an important tool. PSA is another key tool for ensuring persistent adaptation [42, 43]. PSA is a method for evaluating the many potential risks facing a particular nuclear power plant. Analysts determine the probability for events (and combinations of events) that could have implications for safety. Plant owners then implement plans to avoid or mitigate the effects of events that have risks above a certain tolerance threshold, thus applying resources to the threats that are most likely to occur and have severe implications. Although analysts have always factored external weather related events into PSAs, they have not typically considered changing climate.

In 1988, the United States Nuclear Regulatory Commission requested that all licensees conduct individual plant examinations of external events, including EWEs. Even though climate change was not specifically considered, the types of action taken are comparable to the types of action that would likely be taken if nuclear plant owners re-examined plants with climate change in mind. High winds accounted for 27% of improvements, external flooding 50%, transport 8% and other events 15% [44]. Owners revised procedures (e.g. arranging timely delivery of additional diesel generator fuel before storms and increasing maintenance of drainage structures) and improved facilities (e.g. protecting diesel generator exhaust systems from tornado strength winds and upgrading flood resistant doors).

4.5.3. Basic adaptation options

The IRS database reveals that for most plants built to a high margin of safety with respect to external events, increased maintenance, new procedures and minor physical changes are sufficient to adapt to many climate threats. For example, stopping plant materials from clogging the water intake can be as simple as more frequent inspection and cleaning by maintenance crews. Other nuclear plants may need minor alterations in some water intake systems. For instance, ice blockage of water intake can be avoided by diverting some hot water discharged from the cooling system back to the area around the intake. Frozen pipes can be prevented by adding heat tracing. Lightning damage can be prevented by maintaining proper grounding and burying certain outside cables.

The marginal costs of adapting to these types of EWE do not appear to be significant when compared with the costs of plant outages. Other adaptation measures can be costlier, such as raising the height of dykes surrounding a plant to protect against storm surges. Adapting water cooling to lower water levels and hotter temperatures may be very costly, as discussed in Section 4.5.4.

4.5.4. Adaptation to heat and drought and implications for cooling

Thermoelectric plants, including nuclear plants, withdraw large volumes of water. In the United States of America, for example, thermoelectric generation accounts for 41% of all freshwater withdrawals [45], and is responsible for 3% of water consumption, equal to 11.356 million m^3/day [46]. Nuclear plants typically use wet cooling systems, which are either once through or recirculating. Once through systems withdraw a large volume of water and then discharge the warmed water back to the source. Even though withdrawal rates are high, water consumption is only about 15% of the diverted water [47]. However, the sheer volume of water withdrawn can be disruptive when low water levels are brought on by heat and drought. In addition, once through systems discharge warmer water than recirculating systems, which can lead to violations of water temperature regulations. Coastal sites that can access sea water for cooling typically opt for once through systems because the cost is lower and the high withdrawal and discharge rates have a relatively small impact on oceans. Yet the advantage of low water consumption for these sites is largely irrelevant since their use of sea water for cooling insulates them from constraints imposed by heat and drought in the first place.

Nuclear plants at inland sites are most susceptible to limitations brought on by heat and drought. Because high water withdrawal and discharge could disrupt environmental quality, more recently built nuclear plants near rivers and lakes typically use recirculating systems with large natural or mechanical draft cooling towers, cooling ponds, cooling lakes or cooling canals. Recirculating systems withdraw much less water (about 96.5% less) but actually consume over 4.5 times more than once through systems because they employ evaporation as a means to facilitate cooling [46]. The evaporated water must be continually replenished. Thus, this water consumption must compete with other demands, such as drinking, irrigation, environmental quality and recreation.

Foerster and Lilliestam [48] model the effects of increased water temperature and reduced water flow (based on 28 years of daily temperature and stream flow data) on a hypothetical 1400 MW nuclear plant with once through cooling located in central Europe. The model accounts for the various regulatory constraints, such as the maximum allowable temperature at the mixing point where water is discharged, the maximum difference between unaffected water and mixed water, and the minimal water flow near the plant. The constraints force a reduction or temporary halt in output with high temperatures and low water flow. The model is used to examine scenarios in which actual observed temperatures are increased by 0, 1, 2, 3, 4 and 5 K and in which water flow is reduced by 0, 10, 20, 30, 40 and 50%. Foerster and Lilliestam [48] find that, even under current climatic conditions (i.e. without any additional increases in temperature beyond the current temperature profile), average yearly production losses are 87 GW·h. The +5 K scenario results in average yearly losses of 1350 GW·h. This reduction in output amounts to average annual financial losses between €5.2 million (no temperature increase) and €81 million (+5 K scenario) for the hypothetical plant. In an extreme year of heatwave like 2003, the hypothetical plant would have to reduce production for 32.8% of all days and stop production for 11.5% of days, resulting in a loss of 2150 GW·h and €130 million [48].

As the climate changes, nuclear plant owners facing water restrictions may consider alternatives. In places where water temperature regulations are likely to be constrained and where absolute withdrawal rates are an issue, wet recirculating systems may be an option to consider in place of once through systems. If further withdrawal and consumption reductions are needed, advanced wet recirculating technologies and the use of alternative water sources can be pursued. In places where the least consumption of water is a critical priority, dry cooling may be the best option. Dry cooling consumes only 5% of the water compared with wet recirculating cooling [47].

Alternatives to once through cooling systems can be costly, both in energy and economic terms. The energy used to operate a wet recirculating system reduces plant generation output by 1.9% during summer peak demand and by 1.7% annually compared with once through systems [49]. This added energy cost, plus the considerable cost for the construction of cooling towers, leads to a 40% cost premium for recirculating systems over once through systems [50]. A study by the Electric Power Research Institute (EPRI) estimated the costs of replacing once through cooling with wet recirculating retrofits at thermal plants in the United States of America [51, 52]. The study found that the average cost calculated at net present value for a nuclear plant (average size 1538 MW) would be US $1.9 billion or US $1239/kW, including capital costs, extended outage revenue losses, and heat rate and energy penalties. However, the EPRI study did not account for the effects of climate change. Recirculating cooling systems may reduce forced outages and related costs for existing once through plants that discharge water into bodies that may reach thermal limits with a changing climate. These potential cost reductions are ignored in the EPRI study.

The US National Energy Technology Laboratory is developing water reducing cooling technologies under its Innovations for Existing Plants Program. By using (i) alternative water sources such as wastewater, (ii) increased effectiveness of cooling towers through greater intensity of water usage and (iii) recovery of evaporated water, the National Energy Technology Laboratory aspires to reduce the freshwater withdrawal and consumption of wet recirculating systems by 50% at a levelized cost of less than US $0.63/m^3 conserved by 2015 and by 70% for less than US $0.42/m^3 conserved by 2020 [46]. On the basis of the 2020 goal and a withdrawal rate of 4 L/kW·h for a wet recirculating system, a

1 GW nuclear power plant operating at a 90% capacity factor would spend about US $10 million per year to reduce water withdrawal from 32.55 million m^3/year to 9.84 million m^3/year [46].

Dry cooling is the other major option for reducing water withdrawal and consumption in cooling systems. The energy penalty for dry cooling systems depends on the prevailing weather. In colder climates, the average annual energy penalty is in the range of 5.5–7.8% compared with once through cooling. In hotter climates, the average annual energy penalty is around 12%. During peak summer periods, the energy penalty is greater at 10–11.9% in cooler climates and 12.3% in hotter climates [49]. The much greater energy penalty for dry systems stems from their inherent design. Rather than allow cooling water to evaporate as with wet recirculating systems, dry systems keep exhaust steam enclosed. Thin metal fins surrounding the exhaust steam dissipate heat to passing air in much the same way as a car radiator works. Heat dissipation via air is much less efficient than via water. This lesser cooling efficiency translates into a greater energy penalty and higher costs. Similarly to wet recirculating systems, dry cooling also uses natural or mechanical draft cooling towers, although larger or more in number owing to the lesser efficiency of heat transfer via air.

The need for larger cooling towers translates into much higher construction costs. The cost of building dry cooling for a new power plant is estimated at 3–4 times the cost of a wet recirculating system and 4–5.5 times the cost of a once through wet system [50]. If dry cooling retrofits are also 3–4 times the cost of wet recirculating retrofits, then, on the basis of the EPRI cost study, the cost for dry retrofits would be on the order of US $3600–4800/kW. Dry cooling retrofits would approach the cost of building an entirely new nuclear plant.

An owner of an existing plant or a prospective owner of a new plant must carefully weigh the added costs of dry cooling against the expected lost revenue from future reduced output and outages stemming from heat and drought that accompany wet systems. With much higher construction costs and more severe energy penalties than wet cooling, dry cooling is an expensive option for new nuclear plants and is almost certainly not economically feasible as a retrofit for most existing plants. For dry cooling to be economically viable at a prospective new site, water resources need be severely limited and other generation options relatively expensive. Other cooling options, such as advanced technologies being developed by the National Energy Technology Laboratory, promise to be much lower cost alternatives to dry cooling.

4.6. SUMMARY

Nuclear power plants and other nuclear facilities in general are designed and built to withstand many kinds of external event, including EWEs recorded in the past [53]. The regular application of PSAs, hazard analyses, plant vulnerability assessments and deterministic evaluations for expected EWEs and the implementation of basic adaptation measures as climate and patterns of EWEs are changing should be sufficient to ensure the safe operation of nuclear power plants.

The most significant impacts of GCC on nuclear power plants are the degradation of thermal efficiency and the volume and temperature of water in adjacent water bodies affecting cooling water availability. Alternative cooling options are available or increasingly considered to deal with water deficiency, ranging from reusing wastewater and recovering evaporated water [46] to installing dry cooling [49].

The implications of EWEs for nuclear plants can be severe owing to the nature of the technology. Reliable interconnection (on-site electric power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, backup generators) are indispensable for the safe operation or shutdown of a nuclear reactor. A reliable connection to the grid system for power to run cooling systems and control instruments in emergency situations is another crucial item. Several EWEs can damage critical components or disrupt their interconnections. Preventive and protective measures include implementing technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown).

5. THERMAL POWER

5.1. INTRODUCTION

According to the New Policies Scenario of the International Energy Agency, US $60 trillion in investment will be needed in global energy supply up to 2040 [54]. Nearly 40% of this capital will go to the extraction and supply of oil, gas and coal as well as to building power plants fuelled by these resources. Despite the significant shift in capital allocation in the energy sector (almost 70% of total supply investment went to fossil fuels in the period 2000–2015), it will be very important to make these investments climate proof by reducing the vulnerability of the new assets to the extent physically possible and economically rational.

This section provides an overview of climate change impacts and the vulnerabilities of fossil fuel supply chains and power generation in thermal power plants. As noted in Section 4, many impacts of GCC and EWEs in this sector are similar to those impacting nuclear power plants. Hence, a large part of Section 5.3 is also relevant for those interested in impacts on and adaptation options for nuclear power plants.

Temperatures will not rise uniformly around the world. Some areas will experience modest increases in temperature, while other areas will face higher than average warming. The vulnerability and potential losses in the energy sector will vary with regions and regional climates. This assessment starts with the extraction and transport of fossil fuel resources, followed by the electricity generation and operation of thermal power plants. The section closes with a short summary of the main conclusions.

5.2. RESOURCE EXTRACTION AND TRANSPORT

5.2.1. Gradual climate change

Slow changes in key climate attributes do not affect the extraction of coal in any significant way, either from underground or open pit mines. On average, a wetter climate may lead to the accumulation of water and thus necessitate changes in drainage and runoff regulation for on-site coal storage, and the higher moisture content of coal will require more energy for coal handling and drying before transport, but these adaptation measures are straightforward and not particularly costly [55]. Impacts are more significant downstream of open pit mines in a wetter climate (especially in already wet regions). The waste (or spoil) material, called ‘overburden’, that lies above a coal seam is removed to get access to the underlying resource and piled up. Trace elements from this overburden could be mobilized by rain and washed into nearby water bodies [56].

A large volume of oil and gas extraction capacity operates in cold regions and that volume is expected to increase. Access to and operation in many cold regions are fostered by permafrost (i.e. ground (rock and soil together with ice and organic material) that remains at or below 0°C for at least two consecutive years). Higher mean temperatures can melt the frozen ground. The thawing of permafrost will severely affect oil and gas facilities by destabilizing their foundations, thereby breaking pillars and pipes. Access to extraction sites will be more difficult, and maintenance and repair more expensive. Melting permafrost has already decreased the time period during which Alaska, United

States of America, can be reached across the tundra from over 200 days/year to fewer than 120 days/year over the past few decades [57]. On the positive side, a reduction in sea ice will allow the extension of offshore exploration and extraction in cold regions [56, 57]. Gradually increasing mean sea level will affect offshore platforms, but adjustment to even relatively high rates of sea level rise (5.2–9.8 cm/decade by 2100 under the RCP8.5 scenario [22]) is likely to be manageable.

Primary fossil energy sources (coal, oil, gas) are transported in diverse ways to distances ranging from a few kilometres to thousands of kilometres. Using the same infrastructure, the transport of energy related material by ocean and inland waters, rail and road are exposed to the same impacts of climate change as the rest of the transport sector [10]; therefore, only some key aspects are mentioned here. Gradual shifts in climatic attributes will affect rail and road transport infrastructure and operation only modestly. Nevertheless, the implications for rail shipment of coal could be critical. A 1000 MW coal fired plant needs 8600 t of black coal delivered every day. If the rail infrastructure were damaged, coal plants would quickly run out of fuel.

In regions inside or at the boundary of cold and temperate zones, changing freeze–thaw cycles (especially more frequent passing of the threshold point) might cause increasing damage to roads and rail tracks [58]. Adjustments in infrastructure can be made as part of the regular maintenance–repair cycles. In regions with declining mean annual precipitation levels, ship and barge transport in rivers will be affected by declining water levels [59]. Reducing the payload or dredging riverbeds would mitigate this impact somewhat [60, 61]; building and operating additional water storage capacities to increase the dependability of water flow required for navigation might be a more expensive but also more effective option. Port and dock facilities as well as coastal roads and rail tracks will need to be amended to gradually rising mean sea level to avoid or at least reduce damage and disruption caused by flooding.

An important issue here is the impacts on transport infrastructure predominantly used by the energy sector (i.e. pipelines). Pipelines play a central role in the energy sector by transporting oil and gas (and occasionally coal slurry) from wells to processing and distributing centres, over distances ranging from small regions to intercontinental connections. With the advent of CO_2 capture and geological disposal, a new application will be to transport CO_2 from the capture site (typically fossil, mainly coal fired power plants) to disposal sites onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land, from hot deserts to permafrost areas, and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet changing climate and weather conditions may require adjustments in existing pipelines and improvements in the design and deployment of new ones.

Higher mean temperatures will change the conditions for transporting resources from cold regions. For example, ship transport in some northern routes might be open to operate for longer time periods. Sea level rise in coastal regions and melting permafrost in cold regions might also affect pipelines. For example, pipelines running through current permafrost regions will become vulnerable as their supporting structures destabilize. Reinforcing all pipeline elements will be necessary to reduce this vulnerability [57].

5.2.2. Extreme weather events

The vulnerability of coal mining to EWEs depends on the mining method. Open cast mining might be particularly affected by high precipitation extremes and related floods and erosion. Extreme precipitation events can increase the amount of trace elements leached from the overburden and thus their environmental impacts on water bodies [55]. Temperature extremes, especially extreme cold, might encumber extraction. Impacts on coal cleaning and the operation of underground mines will probably be less severe. Several types of EWE affect oil and gas extraction facilities, depending on their location. Extreme wind conditions and tornadoes can severely damage oil and gas wells, while sea storms and cyclones threaten offshore platforms [57].

As noted in relation to uranium transport in Section 4, more frequent and more intense EWEs will trigger increasingly severe and possibly detrimental impacts on the transport sector. Extremes in temperature and precipitation affect rail and road transport infrastructure: air temperatures higher than 43–45°C can lead to increasing deformities of rail tracks (thermal misalignment, track buckle) and derailment [62]. Extreme heat can soften road surfaces in general and cause rutting and bleeding of asphalt surfaces [58]. Extreme cold may freeze railroad switches and cause track breaks, and would also damage road surfaces. Extreme rain events may inundate short segments or flood large stretches of rail tracks and roads, weakening the integrity of the track foundations and the road base; extreme snow events can block rail tracks and roads for days. For example, flooding after a typhoon in 2011 disrupted rail traffic and forced coal ports to close in Queensland, Australia [55].

River transport would be blocked during cold spells by the formation of thick ice and by floods caused by longer periods and/or extreme high episodes of precipitation. For example, high storm surge and debris carried by the storm led to the complete closure of the Mississippi River to navigation after Hurricane Katrina in 2005 [57]. Low water levels preventing navigation may result from long lasting precipitation periods and impede coal delivery.

Above ground sections of pipelines are affected by extreme high and low temperatures through material damage and thermal expansion or contraction, or through the scouring of base areas. Extreme rain events would damage underground pipelines by unearthing them. In 1994, a severe flood near Houston, Texas, United States of America, caused pipeline ruptures and undermined pipes at river crossings [57]. High wind and storms can damage offshore and onshore pipelines and related equipment and can lift and blow heavy objects against pipelines, causing structural damage. Lightning can pierce pipelines, causing fires or explosions. All these EWEs may lead to severe spills of the transported material, which is particularly problematic in the case of oil. Enhanced design criteria and updated disaster preparedness are but two options to deal with these impacts [57].

5.2.3. Combinations of changing climate and extreme events

Worsening patterns of EWEs under changing climate will amplify the impacts on coal extraction discussed above: more flooding and more trace elements washed out, more dust blown from dry coal stockpiles. Increasing the scale of known adaptation measures to mitigate these impacts will be proportionally more expensive, but not insurmountable.

The impacts of higher and stronger waves from an anyway increasing sea level could make simple adjustments insufficient to protect offshore platforms from inundation. Stronger winds amplify these impacts and may necessitate major structural upgrades even within the lifespan of existing facilities, which can turn out to be an expensive endeavour. Adaptation over the medium term, especially by adopting upgraded design standards for newly built equipment in the future, is likely to be less expensive.

Increasing EWEs superimposed on GCC will worsen the impacts on most of the affected constituents of the transport sector. The outcome of simultaneous occurrences of several EWEs would often be synergetic. Coastal roads and rail lines will be particularly exposed to the combination of sea level rise, high precipitation events and coastal storms. The frequency and cumulative severity of these EWEs may make simple adjustments (like enhancing road foundations and rail beds or increasing flood protection) ineffective or overly expensive so that full relocation (abandoning current tracks and building new ones across less flood prone areas) may be necessary. Indirect events, like forest or bush fire caused by combinations of hot spells and low precipitation or drought conditions, can also disrupt the operation of road, rail and pipelines and inflict severe damage on the infrastructure in the affected area.

Erosion, landslide or avalanche caused by heavy rain or snow can expose and rupture underground pipelines; damage valves, pumping stations and river crossings; and lead to spills, ignition of spilt oil, fire and air pollution [57, 63].

5.3. POWER GENERATION

5.3.1. Gradual climate change

In 2016, fossil fired power plants generated the bulk of global electricity (almost 65%). Although decreasing, their share is projected to remain high (nearly 52%) in 2040 under the main scenario of the International Energy Agency — the ‘New Policies Scenario’ [54]. Thermal plants are operated under diverse climatic conditions, from cold Arctic to hot tropical regions, and are well adapted to prevailing weather conditions. However, thermal plants might face new challenges to which they will need to respond with hard (design or structural) or soft (operating procedure) measures as a result of climate change [64].

Rising mean temperatures in general will decrease the efficiency of thermal conversion by 0.1–0.2% in the United States of America and by 0.1–0.5% in Europe [65]. This follows from Carnot’s rule and will work against efficiency improvements of innovative technologies, such as coal fired supercritical and ultra-supercritical steam cycle plants. Higher mean air temperature will also increase the mean temperature of water used for cooling. Accounting for decreasing cooling efficiency and reduced operation level, capacity loss in Europe is estimated in the range of 1–2%/°C average temperature increase [66].

Decreasing mean precipitation will reduce the volume and increase the temperature of cooling water. These trends may lead to operation at reduced capacity and even the temporary shutdown of power plants [64, 67, 68]. Adaptation possibilities include relatively simple and low cost options, like exploiting non-traditional water sources and reusing process water. For example, recycled water from condensed flue gases can cover 25–37% of the water requirement of a power plant [5]. More drastic and expensive measures include installing dry cooling towers, heat pipe exchangers and regenerative cooling [67, 69]. EPRI [52] estimates the cost of closed cycle cooling retrofits at more than US $95 billion (net present value, 30 year plant life) for a generation capacity of 312 000 MW (252 000 MW fossil and 60 000 MW nuclear), potentially subject to retrofit requirements in the United States of America. Planning for gradual changes in climatic conditions and selecting the pertinent cost efficient cooling technology for new builds is easier and cheaper than refurbishing existing power plants, especially those towards the end of their economic life. The cost effective strategy for the operator also depends on the prevailing regulation: income losses due to shutdown might be more acceptable for the operator than making expensive investments to ensure continuous operation under any condition, but this option is less attractive if undelivered power leads to penalties or compensations for unserved customers.

Increased windiness near coasts and in dry areas would increase salt sprays from the sea and lead to enhanced corrosion in thermal power plants, and can short circuit exposed electrical equipment. Dust and sand carried by wind can lead to equipment malfunction. Sealing critical equipment would reduce the exposure to such events.

Many conversion facilities (fossil power plants, refineries, gas treatment plants) are located in low lying coastal areas for which earthworks to protect against flooding from sea level rise, taking into account the impacts of changing patterns of coastal storms (see Section 5.3.2), would be needed. Site selection accounting for sea level rise is the obvious solution for new plants. Table 3 summarizes the most important impacts of GCC on thermal power generation, together with the related adaptation options.

5.3.2. Extreme weather events

Most EWEs tend to exacerbate the impacts of gradual changes in the related climate attribute on thermal power plants. The increasing frequency of extreme hot temperatures aggravates the impacts of anyway warmer conditions: reduced thermal and cooling efficiency [30, 65] and overheated buildings. In 2006, high water temperatures forced 11 German thermal power plants to reduce output equivalent to 1741 MW [70]. Temperature control in buildings with critical control equipment is imperative in all power plants and conversion facilities. On the positive side, less frequent extreme cold or frost events will mean less corrosion. More frequent hot spells and low precipitation periods further increase water availability problems prevailing under on average warmer and drier conditions, and may severely limit cooling water discharge if temperatures are too high relative to water quality regulations. This would boost the need for finding hard or soft measures for cooling to avoid reduced operation or shutdown. Heat can also accelerate the growth of aquatic biomass, which can obstruct cooling water intake and thus lead to reduced generation or even full shutdown.

High temperature extremes increase the need for more potent and cost effective adaptation measures relative to adaptation needs under GCC, such as switching from once through cooling to recirculating to reduce the temperature of discharged water or switching from wet to dry cooling [46]. Indirect biological impacts are simple to manage by increasing the maintenance of screens to ensure that biological matter does not clog water intake systems.

TABLE 3. IMPACTS OF GRADUAL CLIMATE CHANGE ON AND ADAPTATION OPTIONS FOR THERMAL POWER

Impact	Potential vulnerabilities	Examples of adaptation options
Higher mean air temperatures	Warmer ambient temperatures reduce the efficiency of thermal conversion everywhere The rate is 0.1–0.2% in the United States of America and 0.1–0.5% in Europe, where capacity loss can reach 1–2%/°C temperature increase, accounting for decreased cooling efficiency and reduced operation level and shutdown Warmer ambient temperatures also increase the temperature and reduce the availability of water for cooling, causing less power generation and an annual average load reduction of 0.1–5.6%, depending on the climate change scenario	Select sites in cooler areas to the extent possible Use non-traditional water sources (e.g. from oil and gas fields, coal mines and treatment or treated sewage) Reuse process water from flue gases (can cover 25–37% of cooling needs) Apply coal drying or condensers (dryer coal has higher heating value; cooler water enters cooling tower) Use ice to cool air before entering the gas turbine (increases efficiency and output; melted ice can be used in cooling tower) Use condenser at the outlet of cooling tower to reduce evaporation losses by up to 20%
Lower mean precipitation	Less precipitation means less and warmer water for cooling, which reduces cooling efficiency and may reduce power generation	Consider alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers The costs of retrofitting cooling options depend on the features of existing systems, the distance to water and the required additional equipment
Increased windiness near coasts and dry areas	Airborne salty material from sea can cause corrosion and short circuit electrical equipment Dust and sand blown by wind may cause equipment malfunction	Enclose or cover sensitive equipment
Sea level rise	Rising sea levels can result in inundation of coastal power plants and related infrastructure	Build new or raise existing dykes and sea walls Relocate existing plants to, and build new plants at, safe sites

In coal fired thermal plants, heavy precipitation events can lead to coal drenching and reduce boiler efficiency by about 1% per 10% increase in moisture [64]. More frequent hot spells or longer dry periods may lead to self-ignition of coal stockpiles (more cooling is needed to prevent it) and to drying and dust blown away from storage of incoming coal stocks and from waste products stored after combustion. In contrast, less extreme cold periods mean less freezing of coal stockpiles. However, during extreme cold conditions, ice can clog water cooling systems, leading to reduced generation or automatic shutdown. Ice can also inhibit plant access. Freezing pipes can break and lead to internal flooding. Routing heated water from the cooling system to the inlet area, developing emergency weather plans and insulating critical piping are simple and low cost adaptation options in fossil power plants.

High precipitation events hitting power plants, oil refineries and other energy installations can cause floods on the site (see Fig. 13). Intense rainfall upstream can lead to flooding of supply routes and plant sites from the nearby water body, most typically a river. Excessive snowfall can collapse unreinforced structures and inhibit plant access by critical personnel and supply deliveries [55]. Floods can damage buildings, equipment and upstream (e.g. coal stockpile drenching, gas and oil storage tanks) and downstream (fly ash and bottom ash storage) fuel cycle components. Adaptation options include hard measures like flood protection by dams, embankments, flood control reservoirs, ponds, channels [71], drainage improvements, and the rerouting and isolation of water pipes [72], while soft measures comprise zoning and restricting activities in flood prone areas, building codes and flood insurance [73].

Similarly to nuclear power plants, lightning can short circuit or trigger false signals in monitoring and control instruments at thermal power plants. It can also short circuit on-site power connection and related equipment, such as transformers and switchyards. Exposure can be reduced by insulating and grounding key circuits and connections outdoors or putting them underground altogether. Extreme winds and storms (tropical cyclones, tornadoes and other stormy events) can damage buildings (accommodating turbines, conversion machinery, electrical components and control rooms), cooling towers and storage tanks, as well as mobilize dust from coal and fly ash storage. The obvious adaptation measures include upgrading construction standards to prevent structural damage and watering coal storage areas to mitigate dust blow. Indirect effects can also hit all power generation technologies. Storms even far away from thermal plants may disrupt transmission and distribution lines and related electric equipment, and this would force reduced operation or full shutdown because electricity cannot be transferred to the grid system. Table 4 summarizes the most important impacts of EWEs on thermal power generation, together with the related adaptation options.

5.3.3. Combinations of climate trends and weather events

Extreme hot periods added to on average warmer temperatures or drought periods will lead to very dry conditions and thus to releasing more dust from coal stockpiles and post-combustion waste storage sites, especially during high wind episodes. The deployment and operation of current CO_2 capture technologies would almost double water consumption per unit of electricity generated from coal fired plants, exacerbating water supply problems in water stressed regions and seasons. At the back end of the fuel cycle, the management of fly ash, bottom ash and boiler slag may need to be modified in response to changes in combined EWE patterns, like high temperatures and winds or high precipitation episodes leading to floods. An indirect combined impact is that drought may trigger forest and wildfire from which smoke blown to power plants may damage sensitive instrumentation and equipment, and may hinder access to critical personnel, supply deliveries and emergency response workers. Storms surges superimposed on sea level rise increase the flood risk for conversion facilities of all sorts in low lying coastal areas.

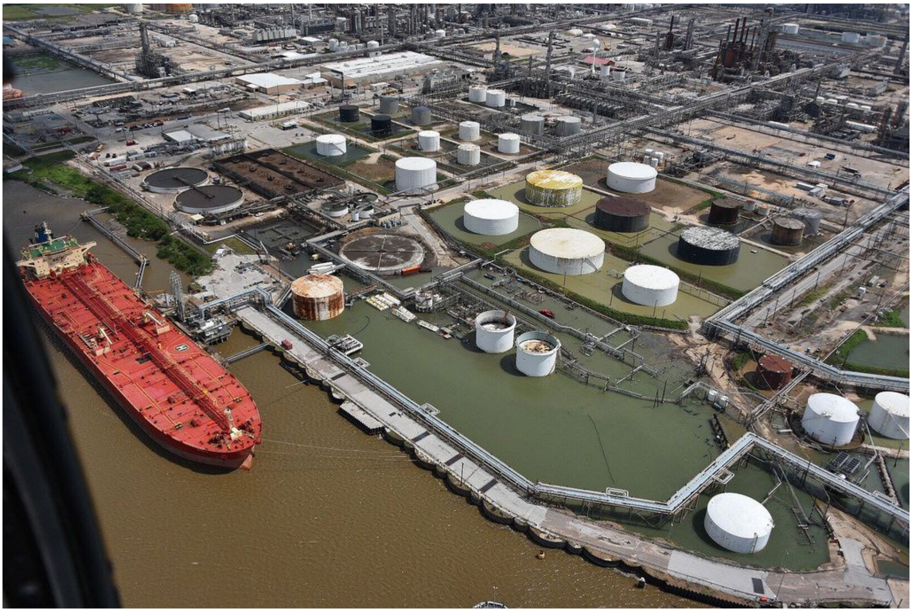

FIG. 13. Flooded oil refinery in Texas, United States of America, caused by Hurricane Harvey in August 2017. (Courtesy of Coast Guard News.)

TABLE 4. IMPACTS OF EXTREME WEATHER EVENTS ON AND ADAPTATION OPTIONS FOR THERMAL POWER

Impact	Potential vulnerabilities	Examples of adaptation options
More frequent and intense hot temperatures	Hot spells aggravate the impacts of on average warmer conditions Less conversion and cooling efficiency Overheated buildings Self-ignition of coal stockpiles	Locate new plants at cooler sites when possible Install air-conditioning in buildings Cool coal stockpiles by water spraying
Less frequent extreme cold or frost	Accumulating ice can block water intake for cooling Frozen pipes can break and inundate parts of the power plant site Potentially less freezing of cold stockpiles and less corrosion due to frost	Use warm cooling water to heat inlet area Insulate critical piping
More frequent and more intense high precipitation events	Extreme high rainfall in a short time can inundate plant site and can lead to coal stockpile drenching (higher coal moisture reduces boiler efficiency by 1% per 10% increase in moisture content) Excessive snow can cause weak structures to subside and hinder access to the plant	Change reference climate for drainage design Build proper water management facilities (dams, water pumps) Spray coal to create crusting surface or put plant or grass cover on top Reinforce buildings and structures Prepare emergency plans for snow and ice removal
More frequent and longer periods of low precipitation or drought conditions	Low precipitation leads to reduced water availability and more competition for water Less and warmer cooling water leads to potential reductions in output or even shutdown	Consider alternative cooling options: reuse wastewater and recover evaporated water in recirculating systems Consider dry cooling
More frequent and intense extreme wind conditions (storms, tornadoes, hurricanes)	Wind storms can damage buildings, cooling towers and storage tanks and can disrupt connection to the grid system	Adjust construction standards to changing conditions Reinforce sensitive buildings and structures Build barriers and windbreaks

TABLE 4. IMPACTS OF EXTREME WEATHER EVENTS ON AND ADAPTATION OPTIONS FOR THERMAL POWER (cont.)

Impact	Potential vulnerabilities	Examples of adaptation options
Floods in river basins; sea storms in coastal areas	Floods can inundate plant sites, damage buildings and equipment and lead to shutdown, as well as deluge coal stockpiles and oil and gas storage tanks	Adopt hard measures — Flood protection by dams, embankments — Flood control reservoirs, ponds or channels — Drainage improvements and rerouting and isolation of water pipes Adopt soft measures — Zoning — Construction restrictions in flood prone areas — Adjusting building codes and flood insurance
Lightning	Lightning can pierce pipelines, damage storage tanks and short circuit electric components and connections	Apply enhanced lightning protection Insulate and ground sensitive components Install key components in protected structures or underground

5.4. SUMMARY

The most significant impacts of GCC on thermal power plants are similar to those for nuclear power plants: the reduction of thermal efficiency due to warmer average temperatures, and the lesser volume and higher temperature of water in nearby rivers and lakes, which affects cooling efficiency and water availability for cooling. Various alternative cooling options are available for planners of future and operators of existing thermal plants to manage the risk of water shortage. They range from simple and conservative options like using non-traditional water sources, reusing process water from flue gases, coal drying and using condensers, to more radical and more expensive technologies such as dry cooling.

The implications of EWEs for thermal power plants are diverse and can lead to severe structural damage and financial losses. Protecting fossil fuel stockpiles (coal, oil, gas) from overheating, flooding, extreme winds and lightning is of major importance to ensuring the uninterrupted operation of the plants even under severe weather conditions. The flood protection and reinforcement of buildings, cooling towers and other structures is also key for safe and reliable operation. A robust, possibly multiple connection to the grid system is a precondition for offloading the generated electricity. Precautionary and defence measures range from hard engineering options, like civil engineering or technological changes, to soft measures such as modifying legislative or regulatory directives and changing operating regulations.

6. RENEWABLE ENERGY TECHNOLOGIES

6.1. INTRODUCTION

Renewable energy technologies are the main actors in the global energy transition towards mitigating anthropogenic climate change. Their total contribution to global electricity generation was 24% in 2016. Hydropower had by far the largest share (16%), followed by wind energy (4%) and solar photovoltaic (1%); all other renewable sources contributed about 3% in total [54]. Under the most ambitious mitigation scenario of the International Energy Agency (Sustainable Development Scenario), renewable sources will provide the bulk of global electricity in 2040 (66%). The proportions will change drastically: the share of hydropower grows only modestly to 19%; wind energy increases sevenfold to 21%; solar photovoltaic energy provides 17% and other renewables contribute 8% to the world's power generation [54]. This immense output growth will require large increases in generation capacities and thus massive investments in site exploration, design and construction. Similarly to other investments, these capacity expansions will need to consider changing climatic conditions and weather patterns to avoid technical failures and economic losses.

This section presents the most important vulnerabilities of the three main renewable energy technologies to impacts of GCC and EWEs. Section 6.2 discusses hydropower, Section 6.3 examines wind energy and Section 6.4 explores solar energy. In each section, impacts and adaptation options for the given technology are presented. Section 6.5 concludes with a short summary.

6.2. HYDROPOWER

6.2.1. Resource base

Hydropower potentials are generally estimated on the basis of 90% dependable river flow (i.e. the amount of water available 90% of the time in a given period, typically a year). The economic lifetime of storage based hydropower plants may well exceed 100 years. They are designed on the basis of average historical climate, including the observed fluctuation of rainfall within a range of variability, and their generation capacity and output are rated accordingly. However, observed historical means and variability patterns might not be the appropriate guidance for future water resource assessments and capacity planning owing to climate change. Therefore, planners and managers of hydropower plants need to consider changes in climatic trends and shifts in variability when selecting sites for and designing the storage and generation capacities of future plants. Run-of-river plants do not have expensive storage dams, hence their capital costs are lower and the capital return period is shorter. They are sensitive to different types of climate and weather factor than their dam based counterparts.

The most important climate attribute affecting the resource base of hydropower is the mean annual amount as well as the seasonal and interannual variability of precipitation. However, runoff perturbs the impact of precipitation on river flow considerably: the degree of runoff reduction can be two to four times greater than the decline in precipitation [74] owing to changes in moisture levels in soils and the evapotranspiration of the prevailing vegetation cover in the river catchment.

Gradual alterations in precipitation patterns will affect the resource base of hydropower by leading to changes in the volume and timing of water availability [75–77]. The global hydropower potential is projected to increase slightly [78], but water resources available for hydropower will be reduced by higher mean temperature, increasing the evaporation losses from rivers and dams. Changes in seasonal and interannual variation in inflows (water availability) will lead to shifts in seasonal and annual power output [79].

6.2.2. Power generation

6.2.2.1. Changes in precipitation

Lower average precipitation obviously leads to a decline in runoff, reduced river flows and decreased power generation. The magnitude of these changes depends on the climatic and geographical characteristics of the affected region and varies significantly across regions. For example, in Europe, hydropower potential is projected to increase by 15–20% in Scandinavia and northern Russian Federation; it is expected to decrease by 20–50% in the south-west and south-east regions. The gross hydropower potential in Europe is projected to decrease by about 6% by 2070 [80]. In California, United States of America, a small percentage change in rainfall can produce a much larger percentage change in runoff. A temperature increase of 2°C together with a 10% decrease in precipitation is projected to reduce runoff by 40% in the Colorado River [81], while total hydropower production in Brazil is estimated to decline by 7% by the end of the twenty-first century under medium climate change scenarios [82].

Higher average precipitation is unlikely to affect hydropower generation negatively. Some regions can expect a slight increase in potential generation capacity, depending on the catchment properties and the location of hydropower plants. In northern Quebec, Canada, for example, up to 15% more electricity may be generated annually with existing plants on the basis of the projected 20% increase in annual precipitation [83]. Average precipitation is projected to increase in many regions of the world under the RCP scenarios (see Section 3), and hydropower generation could be enlarged if average runoff also increases in proportion. However, an increase in river flow due to climate change will not necessarily increase hydropower generation potential in real terms because hydropower facilities are designed according to an observed river flow. The generation capacity of a given plant is determined by its storage and turbine capacity, and this limits the amount of additional power that can be generated from higher flows. The emerging new flow patterns can make plant operation suboptimal in many cases [84].

6.2.2.2. Higher average temperatures

Enormous amounts of water resources are lost from hydroelectric facilities owing to evaporation of water from reservoirs. This water could otherwise be used for power generation and made available for downstream uses. Higher mean temperatures in a warming world will increase the evaporation from hydropower dams, but changes in other climate attributes will also influence or even balance out this impact. For example, changes in humidity will considerably affect the rate of evaporation, higher atmospheric moisture content in humid regions will limit evaporation [22], and more and swifter winds will likely enhance evaporation. Deeper reservoirs with smaller surface areas are relatively less affected by evaporation losses than are those with large surface areas. Current annual average evaporation losses are estimated on the order of 1.1 m of depth, but the actual amount heavily depends on the temperature in a given region. The depth of loss for the Aswan High Dam on the Nile River is calculated at 2.7 m, or about 11%

of the reservoir capacity [85]. Average evaporative losses in hydropower plants in California are about 0.54 m^3/MW·h of electricity generated [85].

Higher average temperatures in a region can also affect the runoff potential in various ways. In river catchments that depend on snowfalls, increasing temperatures will shift the balance of rain and snow towards more rain, resulting in higher winter flows and lower summer flows from ice thaws [86]. Regions where runoff depends on glacial melt will be particularly affected. In the Andes, warmer temperatures are accelerating the retreat of tropical glaciers [9]. Glaciers in the Eastern Rockies of Canada are forecast to melt considerably owing to projected warmer temperatures. This may cause higher stream flows in the next two to three decades, but lower flows thereafter because the glacial mass will decline [83]. Since natural water storage in the form of snow and ice will decline, additional storage capacities will need to be constructed in the catchment to preserve the current level of hydropower generation potential.

Glacial retreat affects negatively the amount of snow falling in winter as well, thereby reducing potential runoff. A particular hazard caused by glacial retreat is the formation of glacial lakes that can eventually result in glacial lake outburst floods, inundating downstream valleys and damaging settlements and infrastructure, including dam based and run-of-river hydropower plants [87].

Higher average temperatures and/or extreme hot episodes tend to reduce the moisture content of soils in the catchment. Soil moisture functions as water storage and regulates runoff. A combination of precipitation changes and temperature increases will modify these processes. Drier soils take up rain and thus reduce the amount of runoff. In contrast, more saturated soils absorb less water and increase the risk of flooding [84]. Both cases affect storage levels, and hence the generation potential, and require operative interventions.

Adjusting water management is a cheap soft adaptation option; more expensive hard options include building additional storage capacities, improving turbine runner capacity and implementing other engineering measures. An indirect impact of warmer conditions in many regions will involve increasing demand for water for other uses, especially irrigation, leaving less water in rivers for hydropower generation. Hydropower planners will need to account for these competing demands for water when assessing available resources.

6.2.2.3. Extreme precipitation related events

The main source of exposure of hydropower to EWEs is high precipitation in the catchment area, causing floods. The impacts of sudden increases in runoff due to high precipitation extremes depend on the actual conditions. If dams have unfilled storage capacities, it is possible to capture and store the additional water for later use in low precipitation periods. However, dams are generally designed to cope with historical fluctuations and would usually see little benefit from the abrupt boost in river flow. In the absence of unused storage capacities, dam based plants would usually discharge extra water through bypass channels without benefitting from the additional resource by generating electricity. Run-of-river plants do not have the turbine capacity to harvest abrupt and erratic surges in runoff anyway. More serious direct impacts include floods that may wash away dam walls in the worst case or severely damage water storage facilities.

In some cases, more frequent and intense extreme precipitation events, storms and floods can severely damage hydropower plants [88]. Unexpected floods can be destructive for large dams if erosion in the river basin loads large amounts of sediments into the river that are then carried by the streams and settle in dams and lakes. Bulky logs, large volumes of vegetation and other large objects can also damage or block up run-of-river plants. Improving tools to forecast regional EWEs and adjusting water management are examples of soft adaptation. Increasing storage capacity and facilities for debris removal is an example of a hard response measure [79].

Low precipitation extremes reduce runoff and the amount of water stored in dams if operation is continued at the usual rate. How long dam based plants can manage their water reserves and keep up regular operation depends on the magnitude and duration of low precipitation episodes. In the absence of buffering storage, run-of-river plants are more vulnerable to low precipitation and low flow events and may need to reduce power generation in such cases.

6.2.2.4. Extreme temperature related events

Extreme high temperatures have similar impacts to those of low precipitation extremes because they remove water from the catchment and water bodies by evaporation and evapotranspiration. Implications for generation and adaptation options are also similar to the low precipitation case for both types of hydropower technology. At the other end, extreme cold conditions can lead to ice formation that may block turbine inlets. Management strategies to reduce flow and measures to prevent ice cover formation are the easiest adaptation options. Furthermore, in most cold regions of the world, extreme cold conditions are likely to decrease. Table 5 summarizes the most important impacts of GCC and EWEs on hydropower generation, together with the related adaptation options.

TABLE 5. IMPACTS OF CLIMATE CHANGE AND EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR HYDROPOWER

Impact	Potential vulnerabilities	Examples of adaptation options
Change in precipitation	Amplified by runoff conditions, the resulting change in water availability determines whether power output is reduced or increased	Increase storage capacity Adjust water release schedule to maximize generation
Changes in seasonal and interannual variability of precipitation	Higher precipitation variability leads to greater fluctuations in inflows (water availability), which may modify seasonal and annual power output; higher peak flows can cause floods and output losses	Improve short term water flow forecasts Adjust water management strategies Build additional storage capacity Enhance turbine runner capacity
Extreme high precipitation events	The resulting floods can damage dam walls and turbines directly and indirectly by mobilizing debris in flooded areas upstream Floods lead to output losses due to releasing water through bypass channels	Increase storage capacity and enhance defence structures for dams and turbines Adjust water management to retain surplus storage for excess water Organize debris removal
Low precipitation/ high temperature	Both events reduce the amount of water stored	Increase storage capacity, if possible, to retain more water from high flow yields
Extreme cold conditions	Ice can damage dam walls and block turbine inlets	Adopt operational strategies to reduce flow and manage ice cover formation

6.3. WIND ENERGY

6.3.1. Resource base

The resource base of wind power will also be affected by gradual changes in temperature, leading to changes in pressure differences and thus in windiness, and by lower air density due to higher mean air temperatures [89–91]. Yet total wind resources (measured as multi-year annual mean wind power densities) are projected to remain in the ±50% interval of current values in North America and Europe. Changes in interannual, seasonal and diurnal variability are unclear [89, 92], but they are likely to differ by locale; hence, there is a substantial uncertainty in quantifying the resources or the associated power changes. The only adaptation option is to improve wind resource assessments and select sites for wind parks accordingly.

Overall, gradually increasing mean temperatures imply lower air density that leads to reduced power generation. There is nothing designers and operators can do to mitigate this physical law. Extreme weather episodes do not affect the resource base but can severely impact the operation of wind energy facilities.

6.3.2. Power generation

In the wind power sector, interannual, seasonal and diurnal variability of wind determines the timing and amount of electricity generation. Given the current status of global climate and regional meteorology models, changes in these aspects of variability are difficult to project. Accounting for random variability in energy planning and installing sufficient reserve capacities are the main adaptation options until more knowledge becomes available.

Gradual changes in precipitation, temperature and near surface humidity will affect icing frequency on turbine blades in both onshore and offshore wind power. Icing reduces power output, but proper blade design as passive or blade heating as active adaptation measures can reduce this impact. Onshore wind power will be affected by on average drier air that produces more wind blown dust. Dust deposition on blades reduces power output, but improved blade design and coatings and increased blade maintenance can mitigate this impact. Wind parks established in permafrost regions may be affected by permafrost melting that would destabilize the foundations and make access to affected regions for construction, maintenance and repair difficult.

At offshore wind power sites, changes in wave activity and wind–wave coupling are highly uncertain [93], but they may generate additional load and cause structural damage and failure. This possibility should therefore be considered in the design specifications [94]. On the positive side, sea ice is likely to decline in a warmer climate, which would decrease the loading on turbine foundations.

Wind turbines are vulnerable to wind speed extremes, especially gust, direction change and shear [95, 96] because they can drastically increase turbine load. Extreme winds threaten the structural integrity of towers and blades and can cause fatigue and damage to turbine components, thus reducing output [97]. Maintenance of wind turbines is also a problem during windstorms. Improved turbine design [98] and light detection and ranging (LIDAR) based protection are examples of adaptive measures. The forward pointing LIDAR technology can be used to trace gusts at 300 m distance before they reach the turbines. This technical supplement can increase power generation by 5–10%. LIDAR technology would increase the cost of a typical turbine by about 10%, but this additional investment can be recovered in two to three years [99].

Extreme low and high temperatures affect physical properties (expansion/contraction) of solid materials and fluids; therefore, the selection of turbine types and lubricants is important. Lightning can damage the blades and other mechanical and electrical components; therefore, adequate lightning protection is needed [100]. Table 6 summarizes the most important impacts of climate change and extreme weather on wind power generation, together with the related adaptation options.

6.4. SOLAR ENERGY

6.4.1. Resource base

Changes in insolation and cloudiness are the main effects of GCC on the resource base for all types of solar energy: solar heating, photovoltaic and concentrated solar power (CSP). Increasing cloudiness will reduce output from all three, but evacuated tube collectors for solar heating are less vulnerable because they can use diffuse light; this is in contrast to CSP, which cannot [101]. Technological adaptation is possible by applying a rougher surface on photovoltaic panels to use diffuse light better [102]. Optimizing the fixed mounting angle and applying a tracking system to adjust the angle for diffuse light conditions should also be considered [103, 104]. Increasing the storage capacity for CSP would lengthen the power generation time but not the total output [105].

6.4.2. Power generation

An increasing mean temperature improves the performance of solar heating (especially in colder regions) but reduces the efficiency of photovoltaic conversion and the efficiency of CSP operating with water cooling. Solar photovoltaic efficiency is estimated to drop by about 0.5%/°C temperature increase for crystalline silicon [101] and thin film modules [106] as well, but performance varies across types of module [107], with thin film modules performing better. In addition, long term exposure to higher temperatures causes faster ageing of sensitive material.

In solar energy, hot spells may cause material damage to photovoltaic equipment, reducing its output [108]. Adaptation may involve cooling

TABLE 6. IMPACTS OF CLIMATE CHANGE AND EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR WIND ENERGY

Impact	Potential vulnerabilities	Examples of adaptation options
Change in windiness (wind power density)	Windiness determines wind power potential, so any change may modify wind resources	Enhance resource assessment and site selection according to changing conditions
Interannual, seasonal or diurnal variability	Variability determines the timing of power availability	Consider intermittency in energy system planning Build and maintain reserve capacities
Changes in precipitation, thermal regime and near surface humidity	These changes affect the frequency of icing, which causes operation problems and can reduce power output	Account for icing in blade design Install blade heating
Lower air density due to higher air temperature	Lower air density reduces power generation	No adaptation option
Dryer air, causing more wind blown dust	Dry air and wind cause dust deposition on blades, which reduces power output	Modify turbine design and blade coatings Increase the frequency of blade cleaning and maintenance
Changes in wave activity and wind–wave coupling	Loads from wind, sea currents, waves and sea ice can cause structural damage to offshore foundations and towers, leading to failures	Adjust design specifications and construction schemes according to projected wave and wind conditions
Changes in sea ice	Formation of sea ice increases the load on offshore turbine foundations	Reinforce support structure Use robust construction material
Wind speed extremes, e.g. sudden change in direction, gust and shear	Wind extremes increase structural load and threaten the structural integrity of wind turbines, and can cause fatigue and damage to turbine components, leading to reduced output	Improve turbine design and apply reinforced structures to withstand extreme wind conditions Install light detection and ranging based technologies to increase protection

TABLE 6. IMPACTS OF CLIMATE CHANGE AND EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR WIND ENERGY (cont.)

Impact	Potential vulnerabilities	Examples of adaptation options
Extreme low and high temperatures	Temperature extremes can modify the physical properties (expansion and contraction) of materials and fluid	Consider extreme temperature ranges in turbine material and lubricant selection
Changing lightning frequency	Lightning can damage blades and mechanical and electrical components	Apply enhanced lightning protection and grounding

photovoltaic panels passively by natural air flows or actively by forced air or liquid coolants [109].

Most CSP plants these days are operated in dry regions, and most of them use wet cooling systems, requiring significant amounts of water (more per unit of power output than thermal power plants with recirculating cooling systems [110]). This makes CSP plants rather vulnerable to water supply. The choice between water and air cooling is heavily influenced by the site conditions and involves various trade-offs. Air cooled systems use only a small amount of water for steam generation and some auxiliary activities, which matches dry conditions nicely. However, the performance of air cooled systems declines considerably as ambient air temperature rises to 37.8°C and above. Owing to the decreased performance on hot summer days, the amount of electricity generated by an air cooled CSP parabolic trough plant can be about 5% lower in a year than the output of a similar water cooled plant [111]. Air cooling also requires more energy to produce the same unit of electricity, with an energy penalty of 7–9% compared with the CSP parabolic trough using wet cooling. Beyond the impact on the income of the generator due to the energy penalty and the loss of energy on hot summer days, the relative cost effectiveness of air and water cooled systems also depends on the cost of water and differences in investment, maintenance costs and other factors.

Extreme cold conditions will reduce the efficiency and output of solar heating because unglazed collectors would suffer heat loss when the ambient temperature becomes lower than that of the liquid inside the plate collector. An ambient temperature 50°C below the inlet fluid temperature decreases efficiency by more than 50% in flat plate collectors and up to 20% in evacuated tube collectors [112]. All this assumes that current technologies are being used; however, such technologies may become more weather resilient in the future.

In cold regions, antifreeze chemicals can be applied in solar heating systems to reduce vulnerability to low temperature extremes, but such a system needs a heat exchanger and secondary cycle for clean water [113].

All types of solar technology are vulnerable to windstorms, which may cause material damage through wind load and would therefore necessitate strengthened mounting structures. Hail could cause material damage to solar photovoltaic panels, although the resilience has improved significantly (see Fig. 14). The same damage can apply to solar heating, as evacuated tube collectors are more vulnerable than flat plate collectors; therefore, reinforced glass is needed to withstand larger hailstones up to 35 mm or even 45 mm [114]. Fracturing of glass plate cover and damage to photoactive material can be reduced by increasing protection standards for future equipment. Lightning can damage the inverter in photovoltaic panels; therefore, adequate lightning protection is required. Table 7 summarizes the most important impacts of GCC and EWEs on solar energy, together with the related adaptation options.

6.5. SUMMARY

The three main renewable energy technologies (hydropower, wind and solar) use rather different environmental resources and hence are sensitive to changes in different climatic attributes and EWEs. The resulting advantage is

FIG. 14. Just one photovoltaic panel out of more than 3000 was damaged at Golden, Colorado, United States of America, after the hailstorm on 8 May 2017. (Reproduced with permission courtesy of the National Renewable Energy Laboratory.)

TABLE 7. IMPACTS OF CLIMATE CHANGE AND EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR SOLAR ENERGY

Impact	Potential vulnerabilities	Examples of adaptation options
Higher mean temperatures	Average warmer temperatures improve the efficiency of solar heating (especially in colder regions) but reduce the conversion performance of photovoltaic modules Thermal and cooling efficiency declines in water cooled CSP systems Solar photovoltaic efficiency decreases by ~0.5%/°C temperature increase for crystalline silicon and thin film modules Exposure to heat over the long term causes faster material ageing	Depending on the ratio of value of lost electricity and the costs of alternative cooling options, install cooling facilities to reduce efficiency losses
Changing cloudiness	Increasing cloud cover degrades the performance and reduces the output of all types of solar technology, so evacuated tube collectors are less affected because they can use diffuse insolation CSP plants are more vulnerable because they cannot use diffuse light Decreasing cloud cover is beneficial (increased output)	Cover photovoltaic panels with a rough surface so that they can use diffuse light better Adjust the angle of fixed mounting to improve the use of diffuse light Install tracking systems to optimize the angle for diffuse light conditions Extend storage capacity for CSP plants
Hot spells	Extreme hot temperatures cause material damage to photovoltaic panels and reduce power generation in photovoltaic panels and CSP plants	Install passive cooling (natural air flows) for photovoltaic panels or apply active cooling by forced air or liquid coolants
Extreme cold periods	Extreme cold conditions reduce output from solar heating owing to heat loss in unglazed collectors	Install a heat exchanger and apply antifreeze chemicals

TABLE 7. IMPACTS OF CLIMATE CHANGE AND EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR SOLAR ENERGY (cont.)

Impact	Potential vulnerabilities	Examples of adaptation options
Windstorms	High winds can cause material damage through wind load for all solar technologies Debris carried by wind can impair collector surface areas	Reinforce mounting and supporting structures Fortify sensitive collector surfaces
Wind and sandstorms	Storms can carry and deposit dust and sand on collector surfaces and thus reduce power output Higher humidity can make this impact worse	Install a tracking system to rotate panels out of wind Clean collector surfaces Apply elastomeric coatings instead of glass At CSP plants, turn the mirrors upside down (trough) or out of wind (tower) and use thermal storage to continue operation during sandstorms Clean mirrors after storms
Hail	Depending on the size of hailstones, solar heating can suffer material damage, so evacuated tube collectors are more vulnerable than flat plate collectors Hail can also fracture glass plate cover and inflict damage on photoactive material	Use reinforced glass for flat plate collectors to withstand hailstones Strengthen the surface of evacuated tube collectors Increase protection of all solar equipment beyond current standards
Lightning	Lightning can damage the inverter in photovoltaic panels	Increase lightning protection of the site and the panels

Note: CSP — concentrated solar power.

that the technologies can complement each other in an energy system because different types of weather catastrophe will affect the technologies differently and unlikely simultaneously.

The changing volume and possibly increasing variability of precipitation are the main sources of climate related vulnerability of hydropower, both dam based and run-of-river types. Enlarging dam storage capacities would reduce the vulnerability of the former if geographical conditions and available capital allow this option. Modifying management schemes and water release schedules can be effective adaptation measures at low cost. There is little room for adjustments to changes in water flows in run-of-river plants. Floods caused by extreme precipitation events are the main EWE hazards for hydropower. Increasing storage capacity or adjusting water resource management are the main adaptation options to mitigate the impacts of such events as well.

Changes in wind power potential will be driven by several atmospheric processes in a warmer climate. Despite considerable uncertainties surrounding wind resource projections, it is highly probable that the various types of wind power generation (onshore or offshore; horizontal or vertical axis) will remain a viable technology in this century. Ironically, the major weather hazard for wind energy installations is too much wind. Extreme high wind conditions (direction change, gust or shear) can destroy the structural integrity of wind turbines and damage various turbine components.

Insolation and cloudiness are projected to change in a warming world, but the magnitude of changes across geographical regions is somewhat uncertain. More atmospheric moisture and increasing cloudiness are the main factors that can reduce the conversion efficiency and electricity output in all main solar technologies (solar heating, solar photovoltaic and CSP). Several EWEs (extreme heat and cold, strong winds, sandstorms, hail and lightning) can impose damage on solar energy installations, but material and technologies are available to reduce their vulnerability to these events.

7. ELECTRICITY TRANSMISSION AND DISTRIBUTION

7.1. INTRODUCTION

The electricity grid system provides the vital link between power generators and customers. Its reliable operation is of key importance for producers and consumers of electricity. In grid system interruptions, all power generation facilities can discontinue operation and stay put until their connections are restored. Preferably, nuclear plants need electricity from the grid system even when they are shut down, although locally installed diesel generators can provide the required amount of power for some period of time. On the consumer side, power supply disruptions longer than a few hours can cause some damage to households beyond the obvious inconveniences, but real harm would really hit industrial plants, service outlets and office buildings that would need to close down entirely in the absence of their own emergency power generation equipment (see selected cost estimates of unserved power in Section 4.5.1.)

The importance of a reliable power supply is widely recognized by governments and regulators. Clearly specified reliability standards guide the operation of grid systems in many countries. They prescribe the required level of redundancy (allowing power to be re-routed in cases of line failure) in the grid system to prevent the interruption of the power supply under specified fault conditions when a power circuit or equipment switches out for an unspecified reason. Historical records show that about half of the loss of supply and about two thirds of the largest blackout events (with over a million customers affected) in North America between 1984 and 2006 were caused by weather events [115, 116]. Extreme weather was found to be the major cause of interruptions in distribution networks in the United States of America [117] and in Finland [118].

Owing to its very function to transmit electricity from power plants to end users, the bulk of the grid system components (overhead lines, substations and transformers) are located outdoors and exposed to the vagaries of weather. The power industry has developed numerous technical solutions and related standards to protect those assets and to secure a reliable electricity supply under prevailing climate and weather conditions worldwide. Most components of the electric grid system are designed for an economic lifetime of 30–50 years or longer. They will need to be reviewed and adjusted to the changing climatic conditions and weather events over this time horizon.

This section provides a short overview of the most important impacts of GCC and EWEs on the transmission network (transferring great volumes of electric power over large distances at very high voltage, usually over 100 kV) and on distribution networks (delivering smaller amounts of electricity to shorter distances at lower voltage to consumers). Section 7.2 presents vulnerabilities to and adaptation options for GCC parameters. An assessment of the impacts of and adjustment possibilities to a diverse range of extreme weather episodes follows in Section 7.3. The main points are summarized in Section 7.4.

7.2. GRADUAL CLIMATE CHANGE

There are two main implications of increasing average ambient temperatures on the transmission and distribution of electricity. The first is the reduced maximum power rating of the equipment and the increasing energy loss in the grid system due to greater electrical resistance as a result of increasing temperature. Estimates in the United Kingdom show that in the transmission network, 8°C higher summer mean temperatures would decrease the capacity of overhead lines by 3% and of underground cables and transformers by 5%.

TABLE 8. IMPACTS OF GRADUAL CLIMATE CHANGE ON AND ADAPTATION OPTIONS FOR THE GRID SYSTEM

Impact	Potential vulnerabilities	Examples of adaptation options
Higher mean temperatures	Warmer temperatures cause increased transmission line losses and the extension of transmission line cables	Consider higher temperatures in the rating calculations for new lines and adjust them in existing lines Manage underneath vegetation to keep it at a distance from cables Consider placing cables underground

The capacity drops by 10% in overhead lines, 4% in underground cables and 7.5% in transformers in the distribution net [119, 120]. The increase in electricity lost owing to rising temperature is estimated at about 0.4%/°C for aluminium and copper conductors [121]. These increasing transmission losses under a changing climate will need to be included in the design calculations for maximum temperature or rating for upgraded and newly built transmission and distribution lines [116].

The second implication of increasing mean temperature is the extension of transmission line cables, which reduces the distance to trees underneath. With warmer and, in many regions, wetter climate, this risk will increase owing to faster vegetation growth. In general, the sag on the overhead line determines its rating; hence the maximum temperature of the line is limited by the minimum safety clearance distance below it [117, 122]. Larger sag due to higher temperatures can cause a high voltage electric short circuit made through the air between conductors and trees (flashover). Distribution networks have lower voltages and traverse at lower height; therefore, they are less exposed to this type of risk. Cutting back vegetation below and near the conductors is the obvious adaptation option. In forested areas, replacing overhead lines with underground cables could also be an option [123, 124], albeit a rather expensive one because underground cables are more difficult to install and maintain and because they cost about ten times as much as overhead lines [125]. The cost difference is smaller for lower voltages, yet the bulk of distribution networks consist of overhead lines except in urban areas.

Table 8 presents the most important vulnerabilities and options for adaptation to GCC conditions in the electric power grid system.

7.3. EXTREME WEATHER EVENTS

The most frequent and most severe impacts on the electricity grid system are instigated by wind storms, hurricanes and tornadoes. The frequency and intensity of extreme wind episodes are projected to increase in many regions, and peak wind speed is the main factor responsible for the magnitude of damages. High winds and storms can cause mechanical damage to overhead lines, towers, poles and substations directly and by blowing debris against exposed grid system components indirectly. In transmission lines, high winds may lead to flashovers caused by live cables galloping and thus touching or getting too close to each other. Strong winds can blow trees over overhead lines and short circuit lower lying distribution grid system cables [126]. Designing transmission towers and substation structures to withstand the highest projected wind loadings, more frequently inspecting and maintaining their integrity, rerouting lines alongside roads or across open fields, more frequently and drastically trimming trees, and more effectively forecasting storms and hurricanes are examples of a wide range of already established adaptation options that may need to be increasingly used in the future [116, 122].

Owing to the technical nature of the electric power grid system, lightning is of special importance among the EWEs. The height of transmission towers supporting overhead power lines makes them particularly vulnerable to lightning strikes. Lightning risk to distribution lines situated at lower elevations is smaller but not negligible. Lightning close to or directly on line conductors produces ionized gases that can cause a short circuit fault as the electrical protection disconnects the affected circuit. Such flashover faults may increase in many regions owing to greater lightning frequency. Vulnerability can be reduced by adding earth wires above live conductors and to substations, and fitting spark gaps and surge arresters [115]. These are widely used techniques, but more will be needed in the affected regions in the future.

Losses in transmission efficiency due to gradual warming are relatively small compared with the physical and monetary damage to power transmission networks that can be caused by hot weather conditions. Transmission losses increase far beyond the level caused by the higher average temperatures: expanding cables might trigger flashover to trees underneath, and extreme high temperatures can make lines and transformers overheat and trip off. Adaptation can include a mix of measures, like enhancing system capacity, increasing the tension in the line to reduce sag and adding external coolers to transformers [117, 122].

Extreme low temperatures are likely to become less frequent, but precautions will still be needed because low temperatures may cause flashover by ice and snow building up on insulators, switchgear and transformers. This can bridge the insulators and open a conducting path, triggering a short circuit in the end. Vulnerability to such events can be reduced by improved insulator designs [127].

Similarly, a combination of low temperature, wind, rain and ice storms will probably occur less frequently in a warming world, but when they come, they could inflict physical damage on overhead lines and towers (including collapse) caused by the excessive weight of ice buildup. In addition, the ice layer will expand the cross-sectional area of the conductors and increase the exposure to wind, thus heightening the threat of collapse in strong winds (see Fig. 15). The weight of snow and ice accumulating on trees may cause trees to break and collapse on power lines. Enhanced design standards to withstand the largest projected ice and wind loading, and improved forecasting of ice storms, are the main options to reduce vulnerability [122]. Rerouting lines across less exposed regions is another option to consider (see the Slovenian case study in Section 10).

Increasing heavy rain may cause flashover faults across high voltage insulators and short circuits in high voltage circuit breakers [128]. The improved design of insulators, careful siting and enhanced maintenance can mitigate vulnerability to these impacts. Flooding caused by heavy rains and storm

FIG. 15. Damage caused by glaze ice on the 400 kV Beričevo-Divača power line, Slovenia, February 2014. (Courtesy of the Slovenian transmission network operator, ELES.)

surges would damage equipment at ground level (substations and transformers). Improving insulator design, siting ground installations outside hazard zones and reinforcing supporting elements can help reduce these impacts. Landslides or avalanches caused by heavy rain or snow would damage overhead lines, underground cables and substations. Reinforcing structures and siting ground installations out of the hazard zones is the solution here as well.

At the opposite extreme, prolonged low precipitation periods lead to drought and cause the land surface to dehydrate. This can affect underground lines and equipment. The thermal conductivity of dry ground is lower than that of wet ground, and this reduces the rating of subsurface cables, making the impact of the anyway warmer temperature worse [118]. Electrical conductivity in dry soil would also decrease, which may necessitate uprating of the earth wires.

Drought conditions are particularly dangerous when vegetation close to overhead lines dries out. The dry undergrowth can be ignited by flashover if it comes into contact with line conductors [129]. Ionized air in the resulting smoke and combustion particles may turn into an electricity conductor that would cause multiple luminous electrical discharges (arcs) on the overhead line. Forest or bush fire caused by drought can also damage overhead lines directly by damaging conductors and insulators and by burning wood poles. Trimming back vegetation to a safe distance within and along the borders of transmission corridors is the most obvious way to reduce vulnerability to this type of weather hazard. Depending on regional circumstances, routing transmission lines to areas without high growing flora may also need to be considered [116]. Table 9 presents the most important vulnerabilities of the electric grid system to EWEs and the related adaptation options.

7.4. SUMMARY

GCC parameters are projected to impose only modest impacts on the electric grid system. Increasing mean temperatures will cause more transmission losses, but the amount of lost power is rather small compared with the large increases in electricity demand and hence in power generation and transmission over the next few decades in most countries. Warmer temperatures in regions with sufficient water supply will nurture progressively more thriving vegetation, which will require more frequent trimming of trees growing too close to overhead lines.

Various kinds of extreme weather phenomena cause significant damage to the transmission and distribution networks already, under the present climate. High winds, storms, tornadoes and hurricanes are projected to remain the major cause of grid system faults owing to the exposure of various grid system components to these kinds of events. Combinations of low temperature, intense rain or snowfall

TABLE 9. IMPACTS OF EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR THE TRANSMISSION AND DISTRIBUTION OF ELECTRICITY

Impact	Potential vulnerabilities	Examples of adaptation options
High winds, storms, tornadoes, hurricanes	Extreme peak wind speed can cause direct mechanical damage to overhead towers, lines and poles Galloping live cables can cause flashover Trees falling over and debris flying to power lines can cause indirect mechanical damage and short circuits	Adjust wind loading standards to projected future conditions Re-route lines across open areas or along roads Cut back vegetation regularly to safe distance Invest in better storm and hurricane forecasting tools Consider placing cables underground
Lightning	Increasing lightning frequency may cause more flashover faults	Add earth wires above live conductors and to substations Fit spark gaps and surge arresters
Extreme heat	Hot ambient air will further increase transmission losses Expanding cables increase the risk of flashover to trees underneath Lines and transformers may overheat and trip off	Upgrade system capacity to account for losses Increase line tension to reduce sag Enhance passive or add active coolers to transformers
Extreme cold	Ice accumulating on insulators, switchgear and transformers may cause flashover	Improve insulator design
More frequent and intense rain	Heavy rain can trigger flashover faults across high voltage insulators and cause short circuit in high voltage circuit breakers	Improve insulator design Enhance maintenance of components at risk

TABLE 9. IMPACTS OF EXTREME WEATHER ON AND ADAPTATION OPTIONS FOR THE TRANSMISSION AND DISTRIBUTION OF ELECTRICITY (cont.)

Impact	Potential vulnerabilities	Examples of adaptation options
Simultaneous extreme cold, high winds, heavy rain or snow, and ice storms	These combinations may cause snow and ice buildup, and wind load may buckle, break and even collapse transmission towers and overhead lines Snow and ice accumulating on trees can break them over distribution lines and damage the underlying lines	Enhance design standards according to greater ice and wind loading Re-route lines across less exposed areas Improve ice and storm forecasting in vulnerable regions
Flooding caused by heavy rain or storm surge	Floods can damage equipment at ground or subsurface level (substations, transformers)	Site ground installations outside hazard zones Improve insulator design
Landslide or avalanche caused by heavy rain or snow	Land and snow slides can damage overhead lines, underground cables, substations and other components	Site ground installations outside hazard zones Build avalanche protection Develop mesh configuration of the grid system in hazardous regions
Forest or bush fire caused by drought	Fire can damage overhead lines and wooden poles Smoke and combustion particles may cause flashover	Consider risks in routing transmission lines Enhance vegetation control in the vicinity of transmission and distribution lines

and high winds strike less frequently, but their simultaneous occurrence may cause severe damage and longer interruptions in grid system services.

A variety of methods are known and already used to reduce the exposure and decrease the vulnerability of the electric grid system to EWEs. They span from simple precautionary measures — like considering higher transmission losses in upgrading existing and rating new transmission lines, routing long range transmission connections to areas less exposed to weather hazards and enhancing vegetation management under and along transmission cables — to engineering options, such as adjusting design standards to endure larger expected loads of various kinds (wind, snow, ice or flood), improving insulator design to prevent flashover and installing additional earth wires above line conductors for lightning protection.

8. ADAPTATION TO CLIMATE CHANGE IN THE ELECTRICITY SYSTEM IN ARGENTINA

8.1. INTRODUCTION

This section assesses the vulnerability of the electricity sector to climate change in Argentina. It draws on many studies prepared by researchers in Argentina and other South American countries. Preliminary documents prepared for the Third National Communication of Argentina to the UNFCCC were also used. Observed climate trends and regional projections of climate change have been considered to identify the main vulnerabilities of and the potential hazards for the electricity system.

The country level data compilation available in the disaster information management system DesInventar [130] was used to evaluate the effects of EWEs on the electricity system. The EWEs considered included droughts, floods, frosts, hailstorms, heatwaves, heavy rain and snowfall, storms, thunderstorms and wind storms. Landslides and earthquakes have also been taken into account, although the latter are unrelated to climate or weather. The DesInventar database compiles damage to different components of the energy system, such as dams, distribution systems, fuel stores, gas pipelines, power plants, substations and transmission lines.

To describe the historical and current impacts of climate factors on the electricity system, its responses to extreme temperatures, floods, flash floods, high winds, tornadoes and droughts were examined. The analysis contains a description of the national electricity system and highlights the infrastructure built in recent years.

The recent and expected evolution of climate and the main features of the power sector in Argentina are presented in Section 8.2. Section 8.3 discusses climate and weather related risks and summarizes the main vulnerabilities of the Argentinian electricity system. A case study of climate change impacts and adaptation options in hydropower generation is presented in Section 8.4, followed by a short summary in Section 8.5.

8.2. CLIMATE CHANGE AND THE ELECTRICITY SECTOR

8.2.1. Observed and expected climate change

Argentina has a predominantly oceanic climate, except in its northern part. The Andes mountain range on the western border, with an average height of about 4000 m from the 40° S latitude to the north, completely blocks air exchange in the lower atmosphere, preventing the movement of humidity from the Pacific Ocean to the country. As a result, the climate in north-western Argentina is dry and continental. On the basis of these atmospheric circulation patterns, two large regions are distinguished: north and south of the 40° S latitude.

Climatic and hydrological trends in Argentina over the last 30–40 years that are potentially associated with climate change and are likely to affect the electricity system include the following:

(a) Increasing mean annual precipitation in almost the entire country, especially in the north-east and in the marginal western zone of the humid Pampas [131]: This explains the increased frequency of flooding and why some areas are becoming almost permanent lagoons [132].

(b) Increasing frequency of extreme precipitation in most of the central and eastern regions of the country since the late 1970s: The frequency further increased in the 1990s and probably intensified in the first decade of this century [133].

(c) Increasing river stream flows and floods in the whole country, except in Comahue, Mendoza, San Juan and northern Patagonia: The stream flows of major rivers of the La Plata basin show strong interannual variability [134]. The increase in rainfall in southern Brazil and north-east Argentina has not been accompanied by significant warming that could increase evaporation and compensate higher levels of precipitation. The increased precipitation resulted in more runoff into rivers, and stream flows have increased since the mid-1970s [135].

(d) Decreasing trends in stream flows, which have been recorded since 1980 in rivers of the regions Cuyo (provinces of Mendoza and San Juan) and Comahue (provinces of Neuquén and Rio Negro) [136].

(e) Rising mean minimum temperatures and decreasing mean maximum temperatures north of the 40° S latitude. The analysis of temperatures in recent decades shows that warming in southern South America has been much less than in the northern hemisphere. These trends varied spatially between 1°C and 3°C during the twentieth century [137].

(f) Increasing temperatures in the Andean region of Cuyo and Patagonia, resulting in glacier retreats. A different trend has been observed north of the 40° S latitude. This region shows an increase in the number of warm days and nights in winter and a decrease in the number of cold days and nights in summer. Summer maximum temperatures have increased. Thus, a significant increasing trend in mean temperatures has been observed, with larger increments (>1°C) towards the south. Most glaciers (48 out of 50) of the South Continental Ice Sheet, located in southern Chile and Argentina, have been receding for decades [138, 139].

Regional projections of climate change in Argentina that may have an impact on the electricity system concern increasing temperatures in all seasons, both in the near (2015–2030) and distant (2075–2099) future. The biggest changes are projected for tropical and subtropical latitudes and the Andes, with values for the near future of 1.5°C and more than 3°C for the distant future. The smallest increases are projected for the central and south-eastern zones in winter [140].

Changes in precipitation vary substantially from season to season and across regions in response to changes in large scale circulation. Therefore, this assessment considers projections made for Argentina and for a larger geographical region, including neighbouring countries. The seasonal patterns are as follows [140]:

- Summer: Most projections indicate increases in most regions, except for southern Chile.
- Autumn: Increases are expected for central and northern Argentina by the end of the century, and large decreases are expected for the southern and central areas of Chile.
- Winter: Projections indicate less precipitation in the entire continent. By the end of the century, increases for the south of Chile and decreases for central Chile are projected.
- Spring: Models project increases in south-eastern South America in the distant future.

8.2.2. Overview of the electricity sector

The Argentine Interconnection System (SADI, Sistema Argentino de Interconexión) is divided into eight regions (see Fig. 16). The total national electricity demand in 2012 was 121.2 TW·h, with a maximum power demand of 21.9 GW. Most of this demand is concentrated in the metropolitan area of the City of Buenos Aires and the province of Buenos Aires, representing 50.9% of the national demand.

The electrification rate is close to 100%. A diversified supply portfolio consisting of fossil thermal (65.8%), hydropower (29.2%), nuclear generation

FIG. 16. Argentine Interconnection System, mainland only. Note: artographical data were obtained from Compañía Administradora del Mercado Mayorista Eléctrico [141]. BSAS — Province of Buenos Aires; GBA — City of Buenos Aires; NEA — North-east Argentina; NOA — North-west Argentina.

(4.7%) and non-conventional renewable energy (0.3%) (mini hydro, solar and wind) met the demand in 2012. While fossil based generation remains the largest source because of historically available national resources, the Government is seeking to change this by increasing the contribution of other sources. Fuel consumption (in TW·h) in 2012 was the following: natural gas (136.7), fuel oil (32.6), uranium (20.9), gas oil (18.1) and coal (6.1). The consumption of natural gas and liquid fuels varies significantly across seasons, particularly because the residential and commercial sectors have priority in using natural gas in winter, imposing supply constraints on industry and electricity generation, which meet their demand with imported natural gas and by switching to liquid fuels.

Power distribution is operated by a company that manages the wholesale electricity market. A combination of technologies supplies the amount of electricity to satisfy the demand. Run-of-river hydro and nuclear power plants are the first to be dispatched to satisfy the daily minimum or the baseload demand, which does not vary on an hourly basis. Conventional thermal generation, mainly combined cycle and steam turbine plants, meet part of the baseload demand and supply peak demand in high consumption periods. Reservoir hydropower plants and gas turbines complement the generation in times of peak demand. Owing to the random nature of their availability, renewable technologies benefit from a special scheme that allows them to supply power to the grid system whenever they are operational.

The electricity transmission networks are operated by national carriers (extra high voltage) and regional carriers (high and medium voltage). In recent years, major expansion of the 500 kV network has taken place, expanding the interconnection between different regions of the country to increase the security of supply and the quality of service.

8.3. CLIMATE RELATED RISKS FOR THE ELECTRICITY SECTOR

Water availability in the rivers of Argentina depends mainly on rainfall, which means that a drought period might result in a significant drop in hydropower production. As hydroelectricity accounts for almost a third of the electricity supply, a drop in hydropower production, particularly in the regions of Cuyo and Comahue, can cause major shortages. So far, a decrease in hydropower generation has been in general balanced by other generating sources, particularly thermal power.

Large amounts of water are also required for thermal power generation whether conventional or nuclear. The availability of water is therefore an important factor in the decision about the location of power plants. The Argentinean nuclear power plants are strategically located near ample natural water sources; thus, climate change does not seem to jeopardize their water supply. Nevertheless, decreases in the efficiency of thermal electricity generation can occur under extended periods of high temperature. Likewise, transmission and distribution losses might increase in times of overload owing to the higher temperature of the lines and can further increase if the ambient temperature is high.

According to the DesInventar database [130], the EWEs that most affect the electricity system of Argentina are storms (48%), followed by floods (25%), wind storms (17%), heatwaves (5%), snowfall (3%), hailstorms (1%) and other events (<1%). On the basis of the information compiled in the disaster information management system DesInventar [130], of the about 20 000 EWEs that have had disastrous consequences in Argentina, more than 3000 affected the energy sector, out of which 1764 events affected various components of the electricity system. The vast majority (1194) of these events caused power outages. This was followed by 453 events affecting different components of the distribution system: damage or breakage of poles (272), damage or fall of cables and lines (158) and breakdown of substations at processing centres (23). The transmission system was affected 105 times by either the breakage of power towers (73 times) or the

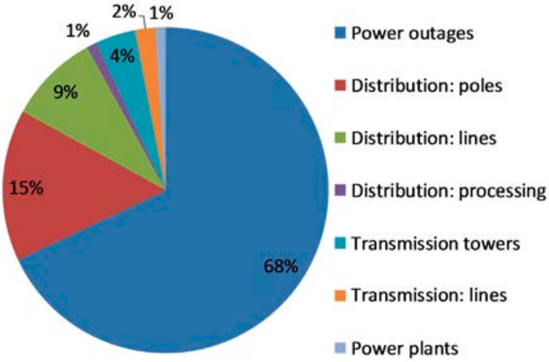

FIG. 17. Impacts of extreme weather events on the electricity system in Argentina [130].

cutting or falling of high voltage lines (32 times). Power plants were affected only by 11 events (see Fig. 17).

Under flood conditions, a few problems in supplying fossil fuel to conventional thermal plants have been registered. The adaptation measure may envisage increasing the storage capacity of fuels at power plants located in flood prone areas. The current vulnerability of electricity generation from biofuels as a result of floods affecting plantations is negligible because most of the biofuel production is destined for transport fuel and only a minor amount is used for electricity generation. This situation might change in the long term if the nationwide support for biofuels in electricity generation continues. However, the shortage of biofuel produced electricity, if any, might also be compensated by conventional thermal plants. In the case of nuclear power, the methods of site selection in Argentina consider possible flooding, including the surrounding water sources used for reactor cooling. In addition, safety measures for normal operation include systems that address this type of climate contingency.

Strong winds and tornadoes have caused damage to power lines and breakage of towers and poles of the transmission and distribution systems, leading to power outage at demand centres. The continuing expansion of the electricity transmission network in recent years has strengthened the security of supply by multiplying the connecting lines between nodes, resulting in a mesh configuration. Furthermore, strong winds and tornadoes can affect wind generation and cause the collapse or partial destruction of wind turbines. For safety reasons, the rotation of the blades is stopped when wind speed exceeds 25 km/h. In addition to these findings, the most relevant risks to the Argentinean electricity system and the related adaptation options are summarized in Table 10.

TABLE 10. CLIMATE CHANGE VULNERABILITY OF THE ELECTRICITY SYSTEM

Risk	Vulnerability before adaptation	Adaptation strategy and options
Hydropower		
Decreases in mean rainfall and discharges in certain rivers in the Andean region, north-western Patagonia and the Comahue region	Decreasing river stream flows, which cause less hydropower generation. However, in the last 20 years, records do not show a decrease in the load factor of the Comahue reservoir hydropower plants under regular hydraulic conditions. Potential water crisis in the Andean foothill oases (Cuyo and Comahue).	Win–win/technical — diversification of power generation Compensate decreasing hydropower generation with conventional thermal power Incorporate energy planning sources independent of reduced rainfall in the mountains (such as renewable and nuclear power) Incorporate future climatic conditions into the design of new power plants and ancillary structures
Increase in the mean annual precipitation, except in the areas mentioned above, especially in the north-eastern and central regions	Increased flows in the three main rivers of the La Plata basin (Paraná, Paraguay and Uruguay). Despite their high interannual variability, increasing average flows have been observed since 1970. Electricity output of run-of-river plants has not increased. An increase in stream flows may result in increased hydropower generation if plants are able to handle higher levels of stream flows.	Low regret/informational — risk assessment for siting Add more turbines in the case of sustained increase in river flows

TABLE 10. CLIMATE CHANGE VULNERABILITY OF THE ELECTRICITY SYSTEM (cont.)

Risk	Vulnerability before adaptation	Adaptation strategy and options
Steady rise of the 0°C isotherm in the Andean area, reaching 120–200 m by midcentury	Continuing retreat of glaciers. Snow accumulation and the regulation capacity of glaciers are affected. Glacier melting influences river stream flows, and spring flooding would not be dammed by hydropower plants. The retreat of glaciers can also lead to a minor and transient increase in mean stream flows of rivers feeding hydropower plants and a corresponding increase in power generation. By contrast, higher temperatures increase evaporation and decrease mean stream flow, consequently reducing generation by the reservoirs' hydropower plants.	Win–win/technical — higher and more robust dams and/or small upstream dams, diversified power generation Improve regulating capacity of hydropower plants Build taller and more robust dams depending on the level of the effect Diversify power generation when the retreat of glaciers commences
Hydropower: electricity demand		
Increasing temperatures, which affect the entire country, especially the northern and Andes region	Increased water stress throughout the northern and western parts of the country due to warming. The central and Litoral regions located in the affected area concentrate 60% of the electricity demand.	Low regret or win–win/technical — diversified power generation Build riverine defences Review the design of hydropower plants located near mountain ranges

TABLE 10. CLIMATE CHANGE VULNERABILITY OF THE ELECTRICITY SYSTEM (cont.)

Risk	Vulnerability before adaptation	Adaptation strategy and options
Hydro and thermal power plants		
Rise of sea level and water level in Rio de La Plata	Uncertainty in the availability of water resources in the La Plata basin. Impact on some parts of the sea coastline and on the banks of the La Plata River.	Low regret/informational — risk assessment for siting Monitor progress of water level in the La Plata River and changes in wave conditions Use records to update maintenance policy to respond to the gradually changing conditions
Electricity transmission and distribution		
Increasing frequency of heatwaves	Increased cooling requirements caused by extreme temperatures, which will cause greater electricity demand with overload on transmission and distribution lines. When these lines approach maximum transmission capacity, resistance to electric current flow increases exponentially, generating a proportional increase in losses and temperature. High ambient temperature decreases the possibility of dissipating excess heat and strongly increases the occurrence of failures (blackouts). Similar impacts disturb voltage transformers.	Low regret or win–win/technical — improved maintenance and renovation of infrastructure Maintain, repair and renovate components of the transmission and distribution systems* Manage temperature related limitations on generation by improving cooling capacity through design modifications

TABLE 10. CLIMATE CHANGE VULNERABILITY OF THE ELECTRICITY SYSTEM (cont.)

Risk	Vulnerability before adaptation	Adaptation strategy and options
Electricity transmission and distribution: fuel pipeline transport and biofuel		
Increase in river stream flows and floods in the whole country, except in San Juan, Mendoza, Comahue and northern Patagonia	Floods in waterways, which can affect energy infrastructure that crosses or runs parallel to them, such as high voltage and/or distribution lines and underground pipelines (gas and oil transport).	Low regret or win–win/technical — verification of designed excess flow and plant capacity, and risk assessment for siting high voltage lines and fuel transport routes Verify and expand the designed excess flow discharge and/or augment the plant capacity by increasing the number of turbines Re-route high voltage transmission lines and natural gas and oil pipelines (may be advisable under persistent adverse conditions)
Increasing frequency of extreme precipitation in most of the central and eastern regions of the country	Prolonged flooding, which can reduce soybean harvest, the main feedstock for biodiesel production. The vulnerability of electricity generation to this shortage is minimal because only a marginal share of biodiesel is used in electricity generation. Heavy rainfall and flooding, which can undermine tower structures through erosion. Flooding can damage underground cables and infrastructure in general.	Low regret/informational — risk assessment for siting Replace biodiesel by with gas oil Relocate cropland to non-flooded areas, and use other biofuel crops that are suitable for production in these new areas Increase power generation from sources that do not depend on fossil fuels or biodiesel Reinforce the structure of towers in high voltage transmission lines Put distribution lines underground

* Currently, no records are available about the effects of high temperatures on thermal power plants in Argentina.

8.4. CASE STUDY: ADAPTATION TO THE IMPACTS OF CLIMATE CHANGE ON HYDROPOWER PLANTS

Analysis of the electricity system in Argentinia indicates a significant degree of vulnerability of hydropower in the Comahue and Cuyo basins. To address this, different water supply scenarios representing potential decreases in stream flows of the rivers in both regions were explored by using the IAEA energy planning tool MESSAGE — Model for Energy Supply Strategy Alternatives and their General Environmental Impacts. The model identifies the best technology mix to increase the security of energy supply for cases of reduction in river flows.

Table 11 summarizes the existing and projected hydropower capacities in each region. They include Comahue (37.8% of the total hydropower capacity in the country), north-east Argentina (25%), the City of Buenos Aires, the Province of Buenos Aires and Litoral (15.2%), Cuyo (8.6%), the central region (7.4%), Patagonia (4.2%) and north-west Argentina (1.8%). Power plants in north-east Argentina are run-of-river type, and those in the other regions are reservoir type. Most of the projected hydroelectric projects were designed in the 1970s and 1980s and many have been revised and updated in recent decades and are presently at different stages of development. Type 1 projects have at least a basic engineering design, type 2 projects have the pre-feasibility study concluded and type 3 projects are listed as likely investments. The existing capacity and the various projects envisaged for the Cuyo and Comahue regions indicate their importance in the Argentinean electricity system: currently they account for 51.9% of the hydroelectric capacity of the country and 18.3% of the total installed generation capacity at the national level.

To assess the adaptation of the system to climate change over the period 2014–2040, two basic trends were considered: (i) the expansion plan of the national electricity system; and (ii) the evolution of the Argentinian river flows. The collected historical information in the Comahue and Cuyo regions shows a general decreasing trend in river flows and considerable interannual variability. Given the variability and periodicity of rivers flows, the scenarios of their future behaviour were modelled according to the average flows in recent decades. These trends were consistent with the prospective analysis included in Ref. [142].

High and low scenarios of electricity demand growth were considered in this study. These demand scenarios did not take into account the effects of climate change, but rather represented the reference for the analysis of these effects. Energy demand in the low scenario was projected by considering the growth rate in Latin America until 2040; the growth rate of energy demand in Brazil until 2040 was taken into account for the high scenario [143].

For hydro, wind and solar power plants, as well as for nuclear, up to 2040, the expansion was based on the planned schedule as indicated in the strategy for the national electricity system. The evolution of hydropower capacities was found to be gradual, and by 2040 they would reach 1969 MW in Cuyo, 6917 MW in Comahue, 3603 MW in north-east Argentina and 2505 MW in Patagonia in both scenarios. Wind and solar capacities were projected to reach 4980 MW and 116 MW, respectively, in both scenarios by 2040. For the other renewable technologies, both scenarios took into account the following considerations:

- The capacity factor for wind turbines depends on the region in which they are located, reaching about 40% in Patagonia.
- The generation of solar panels is modelled according to the time of day, because it is driven by the sunlight cycle.

A scenario of thermal plant retirement was formulated according to plant depreciation starting in 2020 and reaching a cumulative retired capacity of 5189 MW in 2040. Beginning with an installed capacity of 1755 MW in 2014, nuclear power plants were found to reach a capacity of 8425 MW in 2040 as per firmly and tentatively planned projects.

TABLE 11. CAPACITY (MW) OF EXISTING AND PROJECTED HYDROPOWER PLANTS

Plant status	Plant type	North-west	North-east	GBA+ BSAS+ LIT	Central Region	Cuyo	Comahue	Patagonia
Existing	Large & medium	131.1	3100	1890	835	987.4	4647	518.8
	Small	86.1			82.6	83.4	33.7	
Projected	Project type 1		1240	500		1681	1681	1842
	Project type 2	190	1440			750	2162	309
	Project type 3	110				185	4142	34

Note: BSAS — Province of Buenos Aires; GBA — City of Buenos Aires; LIT — Litoral.

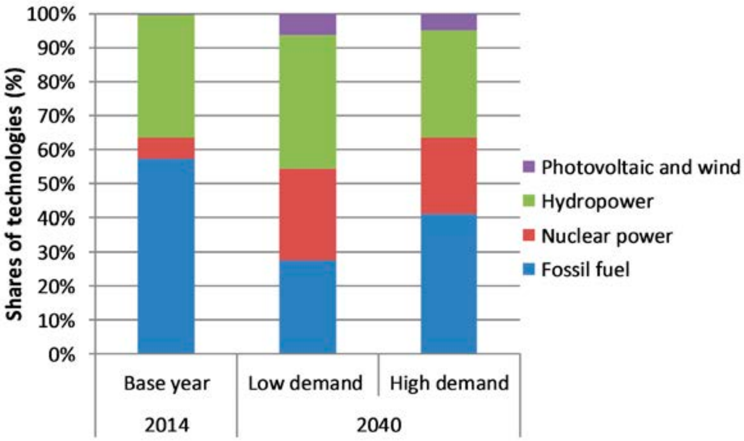

FIG. 18. Shares of technologies in electricity generation in the reference low and high demand scenarios.

Results of the reference scenarios under low and high electricity demand are shown in Fig. 18. The main difference is in electricity generation from fossil fuels, which increase by 35% more by 2040 in the high demand scenario than in the low demand scenario.

Three scenarios were used to explore the potential impacts of climate change (scenario H1) and EWEs (scenarios H2 and H3) on water resources for hydroelectric plants:

(1) Scenario H1: Gradual decrease in river flows in the Comahue and Cuyo basins.
(2) Scenario H2: Drought affecting the Comahue and Cuyo regions.
(3) Scenario H3: Drought affecting the generation of the Yacyretá and Salto Grande hydropower plants in north-east Argentina, plus the same assumptions as for scenario H2. Although projections indicate increases in the mean annual precipitation in north-east Argentina, droughts have occurred and may still occur because of climate variability. This scenario considers the implications of such an extremely adverse situation for the national electricity system, which are highly unlikely to occur.

Scenario H1 projects that the generation of hydroelectric plants in the two regions will decline gradually and that in 2040 it will reach the lowest historical ratio between the installed capacity and the generated electricity of the last 30 years. The intent of this scenario is to estimate how much installed capacity would be required to cover the shortfall in hydroelectric generation.

Scenarios H2 and H3, on the other hand, are meant to assess how the electricity system would react during the years of drought by using different technologies (mainly fossil based thermal generation) and potential electricity imports. For these cases, the lowest value of the capacity versus historical generation ratio is adopted over the entire scenario horizon. These are extremely negative scenarios, with negligible probability of occurrence. They are analysed to explore worst case conditions. Power plants burning fossil fuels are the adjustment variables in the system to meet electricity demand in all scenarios.

The results of scenario H1 indicate that:

(a) Under low electricity demand, 1840 MW of new capacity would be needed to cover the shortfall in hydroelectric generation and would be needed in the following sequence: 240 MW in 2032 (gas combined cycle and/or turbines), 800 MW in 2038 (gas combined cycle and/or turbines and/or nuclear) and 800 MW in 2039 (gas combined cycle and/or turbines and/or nuclear). As a result, fossil fuel consumption would increase in the period 2014–2040, the cumulative consumption for the period would increase by 11%, and the annual consumption in 2040 would increase by 30%.

(b) Under high electricity demand, 2400 MW of new capacity would be needed in modules of 800 MW (gas combined cycle and/or turbines) in 2020, 2030 and 2032. In this case, cumulative fuel consumption throughout the study period would increase by 9% and the difference in annual fuel consumption would amount to 18% in 2040.

Contrary to scenario H1, no new investments in power plants have been included in scenarios H2 and H3 because the study conceived drought as an unpredictable EWE. Therefore, these two scenarios are meant to explore how the electricity system (already installed generation capacity in reference low and high scenarios, plus imports) reacts to the conditions of drought. Under these circumstances, the system dispatches all available power to meet the energy demand. In scenario H2, drought is assumed to occur in any randomly selected year. The results show how thermal electricity generation, and consequently fuel consumption, increase under scenario H2 in the low and high demand cases (Figs 19 and 20, respectively) and similarly under scenario H3 in the low and high demand cases (Figs 21 and 22, respectively).

Figure 19 depicts thermal electricity generation (red line) under scenario H2 over that of the low demand case (blue line) and the corresponding increase in fuel consumption (green line). Given that throughout the entire study period the hydropower capacity in Comahue and Cuyo is growing, the gap between demand and unavailable hydropower increases as well. This gap is covered by thermal power plants.

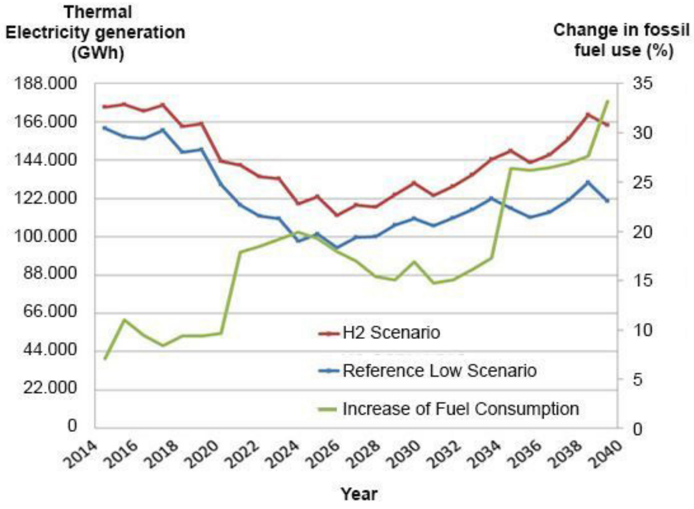

FIG. 19. Thermal electricity generation in the reference low demand and H2 scenarios (left axis) and the associated increase in fuel consumption (right axis).

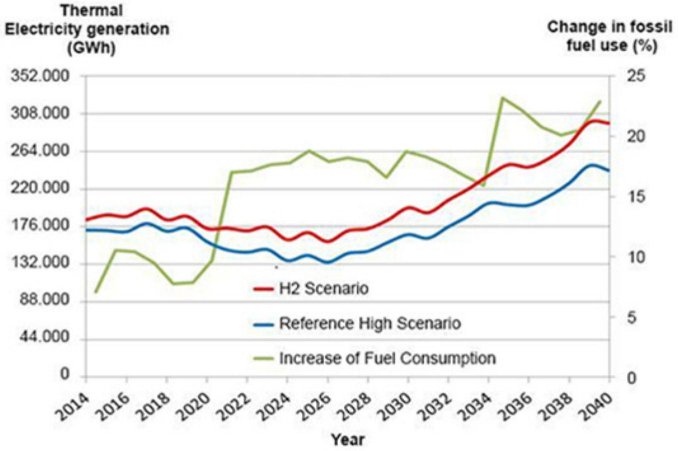

FIG. 20. Thermal electricity generation in the reference high demand and H2 scenarios (left axis) and the associated increase in fuel consumption (right axis).

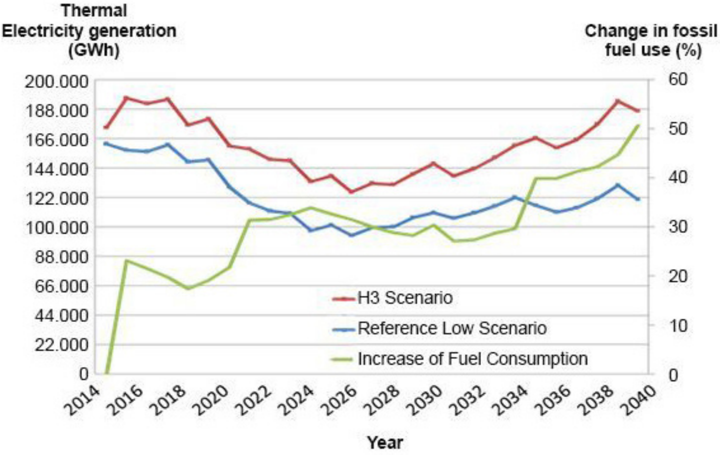

FIG. 21. Thermal electricity generation in the reference low demand and H3 scenarios (left axis) and the associated increase in fuel consumption (right axis).

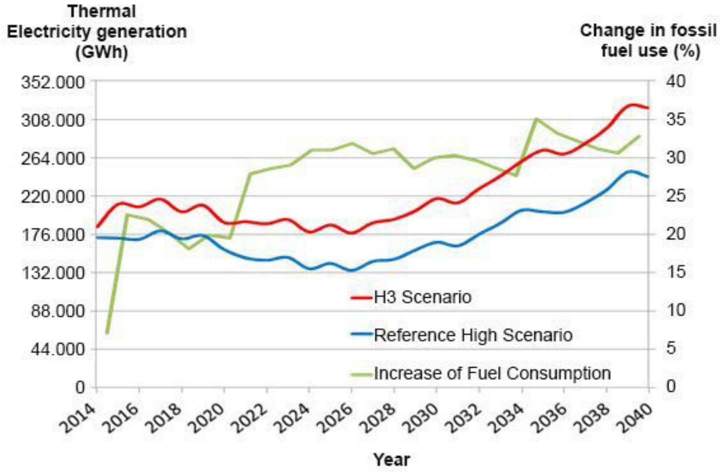

FIG. 22. Thermal electricity generation in the reference high demand and H3 scenarios (left axis) and the associated increase in fuel consumption (right axis).

Figure 20 shows the results when scenario H2 is combined with the high electricity demand scenario. Since fuel consumption is higher in the reference scenario, the percentage increase in fuel consumption is lower. Under drought conditions, the system would usually first dispatch all available power to meet the demand. If this power is not sufficient, electricity would be imported; if the amount imported is insufficient, power outages would occur. However, this is not likely to happen because the scenario of domestic natural gas production is rather optimistic, so that demand can be satisfied and electricity imports will not be needed. In fact, in the reference scenarios, part of the installed capacities is not fully utilized; therefore, under a drought scenario in the Comahue and Cuyo regions, thermal power using domestic natural gas would cover the shortage in hydropower generation.

When the low demand scenario is combined with extreme drought (scenario H3), whereby generation of the Yacyretá and Salto hydropower plants decreases by 20% in addition to the drought in the hydropower plants of Comahue and Cuyo, annual fuel consumption increases by up to 50% to satisfy demand in 2040 (see Fig. 21).

Only in the worst case (scenario H3, with high electricity demand), would the system need to import electricity to meet the demand (see Fig. 22). However, the amount of imported electricity would be very small (0.03–0.09 TW·h) in the last three years of the study period.

The main conclusions of this study are as follows. Scenario H1 shows that when river flows decline, a decrease in the generation of hydroelectric plants can be expected and, therefore, extra power capacity should be installed to meet the demand. In the case of the H2 and H3 drought scenarios, the hypothesis was refuted that under these circumstances the electricity generation system would be pushed to the limit, electricity imports would be needed and power outages may occur. The results show that with the increasing dispatch of combined cycle and gas turbines burning abundant domestic natural gas, demand under the drought scenarios can be satisfied.

8.5. SUMMARY

Water resources in Argentina may be subject to significant risks owing to climate change. The major power generating technologies of the national electricity system — namely thermoelectric power plants (fossil fuel and nuclear plants) and hydropower plants — rely on water availability. Thus, vulnerabilities of water resources and electricity generation in a changing climate must be taken into account to ensure security of supply to meet the needs of a growing population and the demands for economic development. Declining hydropower generation caused by decreasing river stream flows in certain regions of the country would be compensated mainly by thermoelectric power as an adaptation option that may be in conflict with national GHG mitigation plans. On the other hand, higher rainfall levels leading to increases in stream flows and possibly to floods would require diversified technical strategies to achieve a resilient power generation, transmission and distribution infrastructure.

The increasing frequency of heatwaves, strong winds and tornadoes is expected to mostly affect transmission and distribution. Maintaining and reinforcing existing infrastructure and renovating ageing assets are the key measures to cope with the stress posed by these EWEs. The impact of changes in cooling water temperature on the thermal efficiency of fossil fuel and nuclear power plants should also be accounted for.

9. ADAPTATION OPTIONS FOR NUCLEAR AND OTHER ENERGY INFRASTRUCTURE TO LONG TERM CLIMATE CHANGE IN PAKISTAN

9.1. INTRODUCTION

After 2007, the energy crisis coupled with EWEs (devastating floods and rains) slowed down annual economic growth in Pakistan to 0.4% in 2009 (years refer to financial years; e.g. 2009 indicates the period from 1 July 2008 to 30 June 2009). During 2011–2015, the average annual economic growth rate was 3.9%, an improvement compared with 2008–2011, when this rate was 2.2% [144]. To keep pace with this revival in economic development and to meet the needs of the growing population, massive amounts of energy and electricity will be needed. There is a need for strategies to deal with the growing energy demand along with the multifaceted challenges of climate change threatening water, food and energy security in the future.

This study was conducted under the IAEA Coordinated Research Project on Technoeconomic Evaluation of Options for Adapting Nuclear and Other Energy Infrastructure to Long Term Climate Change and Extreme Weather, using the IAEA energy and electricity planning tools MAED (Model for Analysis of Energy Demand) and MESSAGE. The study assesses the adverse impacts of climate change on energy and electricity demand and the power generation system during the period 2014–2050. Adaptation options to minimize these impacts on the energy and electricity system are also analysed.

9.2. ENERGY AND THE ENVIRONMENT IN PAKISTAN

9.2.1. Energy and the electricity sector

Per capita primary commercial energy supply in Pakistan is only 0.37 tonnes of oil equivalent (toe), which is one fifth of the world average of 1.78 toe/person [144–146]. In 1972, the combined share of coal and oil was more than 50% in the primary energy supply. It declined to 44% by 1982 as coal and oil were replaced mostly by natural gas. Since 1982, cleaner energy sources (i.e. gas, hydropower and nuclear energy) have provided more than half of the energy supply. The share of low carbon energy sources (hydropower and nuclear energy) varied between 10% and 16% in the total primary commercial energy supply over the last 40 years. One quarter of primary energy is imported oil, which adversely affects the balance of payments.

As of 30 June 2014, the total installed power generation capacity was 23 535 MW, comprising 29.3% hydropower, 66.9% oil and gas, 3.2% nuclear energy and 0.6% coal fired power plants. In 2017, installed electricity generation capacity was about 27 000 MW, with new capacities of gas fired (1890 MW), nuclear (340 MW), renewable (806 MW) and hydropower (130 MW) plants added in recent years. Natural gas, hydropower and oil are the main sources of electricity generation (see Fig. 23). In 2015, grid system supplied electricity was 107 408 million kW·h, encompassing 36.7% oil, 30.2% hydropower, 26.4% natural gas, 5.4% nuclear energy, 0.7% renewables, and 0.5% coal and imported power [145].

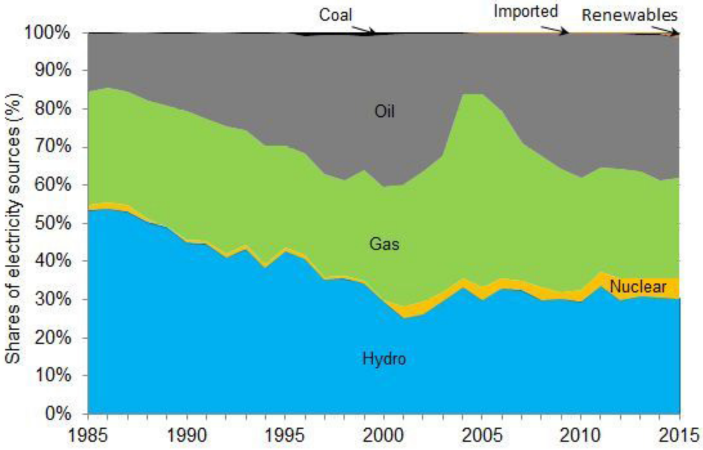

FIG. 23. Electricity generation mix in Pakistan [145].

During the last four decades, electricity consumption in Pakistan has grown from 5.3 billion kW·h to 85.8 billion kW·h, at an average annual growth rate of 7.0%. At present, per capita electricity consumption is 451 kW·h, which is about one seventh of the world average [145, 147].

9.2.2. Future energy supply options

Total proven fossil fuel reserves in Pakistan as of June 2014 were 3874 million toe, comprising 343.56 million toe gas, 51.57 million toe oil and 3479 million toe coal [145]. In addition to these conventional resources, the country has around 1600 million toe technically recoverable shale gas and 1875 million toe shale oil [148]. Total coal resources (including measured, indicated, inferred and hypothetical) are about 186 Gt, of which measured reserves are 7.78 Gt. The hydropower potential is about 55 000 MW, of which 7030 MW (13%) has already been exploited [145]. A total of 25 000 MW hydropower projects are at different stages of implementation [149].

According to the IAEA's Power Reactor Information System (PRIS) database, the installed nuclear energy capacity of 1318 MW generated 6.8% of the total electricity produced in 2018. The energy security plan of the Government of Pakistan envisages a nuclear power capacity of 8800 MW by 2030. Construction of two 1100 MW nuclear power plants has started at Karachi.

The exploitable wind potential of Pakistan is about 50 000 MW. Two commercial scale wind power plants (50 MW and 56.4 MW) are in operation. Four more wind power plants of similar capacity were commissioned in 2015 [150]. The solar energy potential is quite high as most of the country receives clear bright sunlight. Areas with average insolation of 2 MW·h/m^2 receive sunshine for 3000 h/year [149]. The Government plans to expand the first large solar park from 100 to 1000 MW in the coming years. Pakistan has been importing electricity from the Islamic Republic of Iran since 2002. In 2015, 443 million kW·h of electricity was imported.

In 2008, the estimated GHG emissions of Pakistan were 309 Mt CO_2-eq, of which the share of energy and agriculture was 90%. Annual emissions in 2035 are estimated to reach 1.65 Gt CO_2-eq [151] — 2.6% of the total world emissions.

9.3. IMPACTS OF CLIMATE CHANGE ON THE ENERGY SYSTEM

9.3.1. Extreme weather events and future threats

Pakistan is highly vulnerable to climate change. On the basis of the climate risk index of Germanwatch [152], Pakistan was ranked third in 2012 and sixth in 2013 among the most affected countries. During 2010, Pakistan faced several EWEs: a drought at the beginning of the year, a heat spell in March that reduced wheat production, a tropical cyclone in June, a heatwave with a temperature of 53.7°C at Mohenjo Daro (the fourth hottest ever recorded in world history) and severe floods in August. Around 1980 people lost their lives, and the economic damage was estimated at US $10 billion [153].

A report of the Government of Pakistan on climate change concludes that one of the most threatening effects of climate change on the country is the likelihood of increased frequency of occurrence and greater severity of extreme events such as floods, droughts and cyclones [151]. The average temperature rise in Pakistan during 2020–2050 is projected in the range of 1.45–2.75°C relative to 1990 [151].

Energy is a key input for socioeconomic development. Some likely impacts of climate change on the energy sector of Pakistan include [154]:

- Reduced reliability of hydroelectricity supply due to seasonal water flow variations in rivers, reduction in water resources and increased sedimentation resulting in reduced reservoir capacity;
- Direct damage to energy and electricity infrastructure due to extreme events;
- Sharper peak electricity demand spikes caused by increased demand for space cooling and water pumping for irrigation;
- Reduced efficiency of fossil fuel and nuclear power plants due to lesser quantity and higher temperature of intake water during extreme heatwaves;
- Higher risk cover for extreme events resulting in higher energy prices (e.g. sea transport of oil).

9.3.2. Impacts on energy demand

Over the last two decades, demand for energy in Pakistan has been increasing at almost the same pace as economic growth. Socioeconomic development of the fast growing population with income below world average will increase the demand for energy and electricity. Global warming will increase demand growth even further. The IAEA model MAED was used to build two electricity demand scenarios for this study: the baseline scenario and the climate change scenario.

The baseline scenario depicts the period 2013–2050 without considering the effects of climate change. It assumes an average annual economic growth rate of 6%, in line with the targets set by the Government of Pakistan [155]. The climate change scenario adopts a projected temperature rise in Pakistan of 1.08°C by 2020 and 2.38°C by 2050, relative to 2012 [151]. Electricity demand in the climate change scenario is assessed to be higher than in the baseline scenario owing to increased demand for air-conditioning (space cooling) and water pumping for irrigation.

The energy demand projection reveals that final commercial energy demand in the baseline scenario increases sixfold, while electricity demand increases sevenfold, during the period 2014–2050. The share of electricity in the total final commercial energy demand increases from 19% in 2014 to 21% in 2050. Space cooling and heating in the residential and service sectors are sensitive to changes in atmospheric temperatures, as modelled in the climate change scenario. Higher average surface temperature increases air-conditioning requirements in summer and decreases the need for space heating in winter. Higher temperatures also result in higher levels of evapotranspiration and an overall greater demand for water in agriculture.

Compared with the baseline scenario, electricity demand for air-conditioning in the residential and service sectors increases by 11% in 2020 and by 25% in 2050 in the climate change scenario. In space heating, substitutable fossil fuel demand decreases by 25% in 2020 and by 51% in 2050. This is where climate change is actually saving fuel.

Presently, the agriculture sector consumes around 92% of the total freshwater supply in the country. In water consumption for irrigation, 34% is groundwater pumped using electricity and diesel fuel. With global warming, demand for irrigation will increase owing to enhanced evapotranspiration. Water demand in agriculture will increase in proportion to the change in evapotranspiration (ignoring changes in cropping patterns and increased water supply due to glacier melt). Water demand in the climate change scenario is projected to be 6% higher in 2050 than in 2012; hence, more energy will be needed for water pumping. By 2050, a significant amount of additional electricity, 717 million kW·h, will be required to meet the increased water needs of crops.

Figure 24 shows the total electricity demand in the two scenarios. The increase in electricity demand in the climate change scenario, due to enhanced air-conditioning in summer and water pumping for irrigation, will be 1.4% (2.0 billion kW·h) in 2020 and 3.2% (22.5 billion kW·h) in 2050, relative to the baseline scenario.

9.3.3. Impacts on electricity generation technologies

9.3.3.1. Thermal and nuclear power plants

Many climate parameters, such as temperature, precipitation, wind speed and direction, have impacts on electricity production from power plants. Their output and efficiency is closely related to ambient temperatures. Global warming

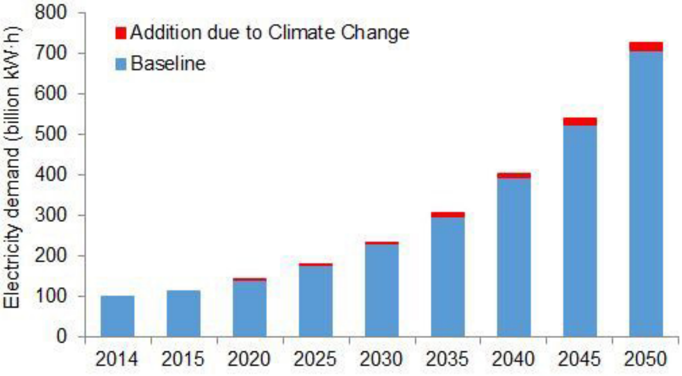

FIG. 24. Additional electricity demand due to climate change.

will increase air and water temperatures, which will reduce the output of existing thermal and nuclear power plants.

Studies reviewed by the Asian Development Bank [156] reveal that with each 1°C rise in (air) temperature above 30°C, the power output of gas turbines declines by 0.50–1.02%, while efficiency drops by approximately 0.24%. Steam turbine power output and efficiency are not significantly altered by changing air temperatures, but the net power output from combined cycle gas turbines drops by 0.3–0.6% and net efficiency declines by approximately 0.01% with each 1°C rise in temperature. An adverse impact of warmer cooling water is expected on the efficiency and output of steam power, fossil fuel fired and nuclear power plants. The turbine entry temperature for a typical nuclear power plant is about 300°C, and the condenser temperature is about 30°C. An increase in the ambient temperature by 1°C above 30°C is estimated to reduce the output of nuclear power plants by 0.37–0.72% [30]. A study of the European Commission estimates that a rise of 1°C in cooling water temperature decreases the output of nuclear power plants by 0.2% [157].

Owing to the impacts of climate change, the mean annual temperature in Pakistan is likely to increase by 1.08°C by 2020, 1.42°C by 2030, 1.85°C by 2040 and 2.38°C by 2050 relative to 2012. The estimated output decline of existing thermal and nuclear power plants for these years is modelled by changing the plant factors.

9.3.3.2. Hydropower plants

Pakistan has three main rivers: Indus, Jhelum and Chenab, also called the Western Rivers. They are predominantly fed by the

Himalaya–Karakoram–Hindukus glaciers. Water flows reach their peak in midsummer. The catchment areas of these rivers receive heavy summer monsoons; therefore, rainfall also contributes to their flows. Water flows are lowest in winter.

Pakistan lies in a region where temperature increases are expected to be above the global average. The country has greater risks of variability in monsoon rains, large floods and extended droughts. The Himalaya–Karakoram–Hindukus glaciers are predicted to recede rapidly owing to global warming. The Tarbela and Mangla storages are essential for supplying irrigation water; therefore, electricity generation from these power plants depends on the need for irrigation. Climate change will affect the flow of these rivers [151]. During the next few decades, flows will increase as average temperatures rise and then decline as the glacial stocks shrink [158].

Declining efficiency and reduced output of thermal and nuclear power plants due to global warming will require more fuel and augmented system capacity. Under drought conditions, additional system capacity is required to compensate reduced hydropower availability. The frequency of heatwaves hitting the country during the summer is expected to increase in the future. These extreme events will change the load curve of electricity demand and require more capacity for peak hours.

9.4. IMPACTS OF CLIMATE CHANGE ON ENERGY SUPPLY

9.4.1. Method and main assumptions

The IAEA MESSAGE model was used to analyse adaptation options in the energy system of the country. It is an optimization model that minimizes the total system costs by obtaining the least cost composition of energy sources and technologies subject to infrastructure and policy constraints, such as market penetration rates for new technologies, fuel availability and environmental emissions.

Total system costs include investment costs, operating costs (domestic and imported fuel costs, variable and fixed operating and maintenance costs) and additional penalty costs to be paid for violating limits, bounds and constraints set on certain activities (e.g. environmental emissions). All costs being incurred at any point in time are calculated by discounting them to the base year of the case study (2014). The sum of all discounted costs is used to find the optimal solution. The discount rate is an important parameter. In energy sector decisions, a higher discount rate discourages plants with high capital costs but with no or low fuel costs, such as hydroelectric and nuclear power plants. An annual discount rate of 10% is used in this study.

Key constituents of the energy industry of Pakistan include oil refineries, gas processing plants and electric power plants. Under global warming conditions, it is assumed that demand for additional electricity will prevail from May to September and that the seasonal load curve is adjusted accordingly from 2030. On the basis of the increase in cooling degree days, it is assumed that more than 0.2 percentage points of the total electricity demand is required for additional air-conditioning during heatwaves. The load curve during the ten day heatwave in June increases by 0.2 percentage points and then decreases by the same ratio in the next period.

The output from hydroelectric plants depends on the seasonal flow of water in rivers. This seasonal variation of hydropower generation is modelled in the study. Water flows of the three main rivers (Indus, Jhelum and Chenab) reach their peaks in the monsoon season. Snowmelt and rainfall in the monsoon season are the main sources feeding these rivers. Water flows are lowest in winter. Currently, there are two hydropower plants with reasonable water storage. They are essentially for supplying irrigation water; hence, electricity generation depends on the need for irrigation water. Power generation of these plants varies greatly across seasons.

Wind and solar sources supply energy intermittently. Their availability varies over seasons and hours of the day, but they save fuel costs and do not contribute to GHG emissions. The annual capacity factors assumed for wind and solar power are 30% and 20%, respectively. The inclusion of wind and solar energy in the electricity system requires additional investments because they need backup supply to make up for the shortage when they are not available.

9.4.2. Reference energy system and supply scenarios

The reference energy system of Pakistan formulated for this study represents the flow of domestic energy resources and imported energy to meet the demand. Its salient features for addressing climate change are as follows:

(a) The study period stretches to 2050 to analyse the impacts of climate change on electricity generation technologies. To model seasonal variation in hydropower and wind generation, and impacts of extreme weather conditions on electricity demand, a year is divided into 25 parts: five seasons in a year, one type of day and five parts of a day.

(b) The energy system is depicted in five components: resources, primary energy, secondary energy, distribution and final demand.

(c) Presently, indigenous fossil fuel resources (oil, gas and coal), hydropower, nuclear energy, renewable energy, as well as imported oil and petroleum products, coal and electricity, meet the energy demand of the country. In the future, domestic shale oil and shale gas resources and imported piped and liquefied natural gas are also expected to contribute to the energy supply.

(d) The power sector of the country is modelled in detail. More than 60 electricity generation plants based on hydropower, nuclear energy, oil, gas and coal are part of the existing system. Future options for system expansion include hydropower, coal (imported and domestic), nuclear energy, liquified natural gas, solar and wind energy.

(e) The total demand for all types of substitutable fossil fuel is divided into two end use categories — manufacturing and the household and services sectors:

  — In the manufacturing sector, furnace oil, coal and natural gas can replace each other for thermal uses depending on their availability and costs.

  — Fuel substitution is limited in both the household and services sectors. Natural gas remains the main fuel; kerosene and liquified petroleum gas have limited use.

(f) Non-energy uses include natural gas in the fertilizer sector for ammonia production and coke for steel production.

(g) In addition to commercial energy supply, large amounts of traditional fuels are also used for cooking, water and space heating in most of the rural areas and small towns.

Four energy and electricity supply scenarios (baseline, global warming, extreme weather and hydrological drought) have been developed and analysed in the context of long term socioeconomic developments, projected climate changes, drought conditions and heatwave extremes.

The baseline scenario assumes business-as-usual socioeconomic development. Compared with the baseline scenario, the global warming scenario includes additional electricity requirements for more space cooling in buildings and more water pumping in agriculture, reduced output of thermal plants due to temperature increase and increased hydropower output due to glaciers melting. Plant factors are adjusted to incorporate water inflow impacts on hydropower plants. The extreme weather scenario assumes worse conditions than the global warming scenario: in addition to higher average temperatures, heatwaves are also considered. Heatwaves typically last for ten days, during which electricity demand for space cooling and water pumping increases, which changes the load curve as well. The last ten days of June are defined as a special season for analysing the impacts of heatwaves. In the hydrological drought scenario, hydropower output is assumed to decrease by 5% relative to baseline conditions after 2030 owing to lower flows in rivers. Optimistic assumptions have been made about the development of indigenous coal, wind and solar power in all the scenarios.

9.5. ADAPTATION IN THE ENERGY SYSTEM

9.5.1. Primary commercial energy supply mix and installed capacity for electricity generation

The total primary commercial energy supply in the baseline scenario increases more than five times during the study period, from 66.85 million toe in 2014 to 373 million toe in 2050. The share of low carbon energy (hydropower, nuclear energy and renewables) in the primary commercial energy supply increases from 13% in 2014 to 33% by 2050. Though the share of natural gas decreases from 46% in 2014 to 27% by 2050, it remains the largest contributor to primary commercial energy supply until 2050. The share of coal (local and imported) increases from 5.4% in the base year to 21.2% by 2050. Oil consumption during 2015–2020 remains almost at the level of 2014 owing to the import of liquefied natural gas, but its share continues to decline from 35% in 2014 to 18% by the end of the study period. The share of nuclear energy increases from around 2% in 2014 to 19% by 2050. Patterns of primary commercial energy supply do not deviate much across the scenarios. In the global warming scenario and the extreme weather scenario, 1–2% additional commercial energy is required to meet the increasing electricity demand for adapting to climate change impacts.

Total installed capacity is expected to increase from 23 535 MW in 2014 (base year) to 139 967 MW in 2050 to meet the growing energy demand. Hydropower, nuclear energy and coal dominate the future expansion of the power system with shares of, respectively, 27%, 29% and 31% in total generation capacity in 2050. Renewable capacities are also expected to contribute 10% in 2050.

Total electricity generation capacities required in alternative scenarios are shown in Fig. 25. The global warming scenario needs around 9000 MW additional capacity to meet the increase in electricity demand, especially in summer when warmer temperatures increase air-conditioning requirements and water pumping in agriculture. Adverse impacts of higher ambient temperatures on the performance of hydropower and thermal electricity production technologies will also require additional capacities. In the extreme weather scenario, an additional capacity of around 17 000 MW will be needed by 2050 relative to the baseline scenario. Electricity demand in the extreme weather scenario and the global warming scenario is the same, but 7700 MW additional capacity is required in the former to cope with the impacts of heatwaves. During the period 2040–2050, gas

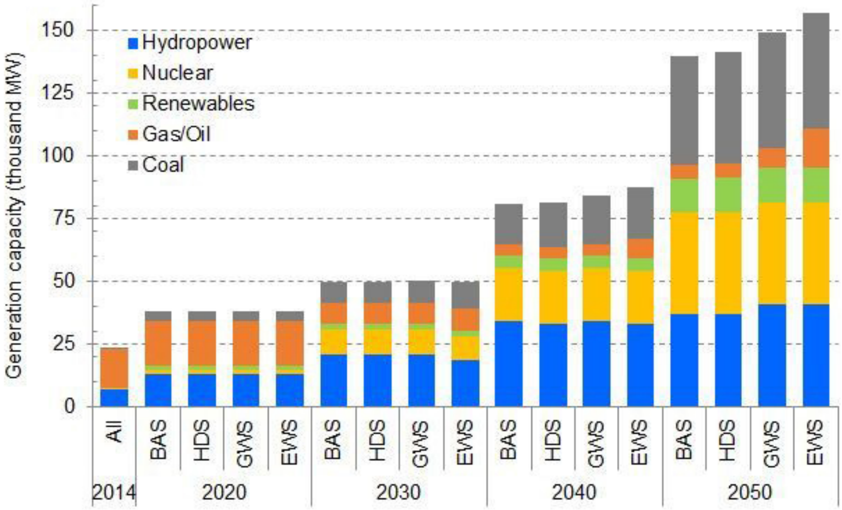

FIG. 25. Installed electricity generation capacity in alternative scenarios. Note: BAS — baseline scenario; EWS — extreme weather scenario; GWS — global warming scenario; HDS — hydrological drought scenario.

and oil (including gas turbine) based capacities in the global warming scenario and the extreme weather scenario are greater than in the baseline scenario (see Fig. 25). The incremental capacities are required to meet the peak load in June under climate change conditions, especially the impacts of heatwaves.

9.5.2. Electricity generation in alternative scenarios

Table 12 shows the electricity generation mix in all four scenarios. In the global warming scenario and the extreme weather scenario, additional electricity demand for enhanced cooling and irrigation is met mainly by hydropower and coal based generation. In the hydrological drought scenario, reduced hydropower production is compensated by coal based generation and renewables.

Table 13 compares annual electricity generation costs in the extreme weather scenario (the worst case) with those in the baseline scenario. The annual additional costs in the electricity sector amount to more than US $1.1 billion by 2040 and reach US $2.2 billion by 2050. The annual increment in GHG emissions goes up to almost 18 Mt CO_2-eq by 2050, and total additional GHG emissions in the period 2020–2050 are around 350 Mt CO_2-eq.

Total additional costs of electricity generation in the extreme weather scenario amount to US $27 billion during 2020–2050; in the global warming

TABLE 12. ELECTRICITY GENERATION (BILLION kW·h) IN ALTERNATIVE SCENARIOS

Year	Scenario	Hydro	Nuclear	Gas/oil	Coal	Renewables	Total
2014	All	31.9	5.1	66.6	0.2	0.0	104
2015	All	32.5	5.8	67.7	0.1	0.8	107
2020	BAS	67	9	66	24	5	171
	HDS	67	9	66	24	5	171
	GWS	67	8	69	24	5	173
	EWS	67	8	69	24	5	173
2030	BAS	101	71	43	54	6	275
	HDS	101	71	43	54	6	275
	GWS	103	70	45	58	6	282
	EWS	94	70	42	71	6	283
2040	BAS	175	155	20	106	12	468
	HDS	163	155	23	115	12	468
	GWS	178	152	12	127	12	481
	EWS	175	152	7	135	12	481
2050	BAS	190	300	4	284	33	811
	HDS	181	300	4	293	34	812
	GWS	207	295	4	297	34	837
	EWS	207	295	5	297	33	837

Note: BAS — baseline scenario; EWS — extreme weather scenario; GWS — global warming scenario; HDS — hydrological drought scenario.

TABLE 13. IMPACTS ON ELECTRICITY GENERATION COSTS AND GREENHOUSE GAS EMISSIONS

Year	Electricity generation costs (US $million)		Annual additional burden in the EWS compared with the BAS		
	BAS	EWS	Generation costs (US $million)	Increase (%)	GHG emissions increment ('000 t CO_2-eq)
2020	7 509	7 756	247	3.30	2 241
2025	10 592	11 004	412	3.90	2 958
2030	14 490	15 230	741	5.10	12 696
2035	19 854	20 353	499	2.50	12 515
2040	24 464	25 581	1 116	4.60	20 344
2045	33 923	35 254	1 331	3.90	10 799
2050	48 256	50 455	2 199	4.60	17 830

Note: BAS — baseline scenario; EWS — extreme weather scenario; GHG — greenhouse gas.

scenario, they are around US $20 billion in the same period. Between 2020 and 2050, GHG emissions increase in the extreme weather scenario relative to the baseline scenario owing to additional power generation to cope with warmer conditions. Annual increments in emissions increase until 2050 and approach 18 Mt CO_2-eq in the extreme weather scenario in that year. This means that adaptation efforts contribute to the increase of global surface temperature, worsening the climate change problem. There is a need to combat this situation. An analysis of mitigating GHG emissions in the extreme weather scenario relative to the baseline scenario explores the impacts of renewables being substituted for coal based generation during 2030–2050. An additional 5000 MW capacity is required owing to the lesser availability of renewables compared with coal based plants. Additional renewable capacities required to mitigate incremental GHG emissions are around 9000 MW, increasing the investment costs by US $10 billion compared with the extreme weather scenario. The incremental costs of electricity generation spread over the whole study period correspond to a

GHG mitigation cost of US $25/t CO_2-eq. Substituting renewables with nuclear energy reduces these investment costs by 50% in the period 2020–2050.

9.6. SUMMARY

Climate change results in a net increase in electricity demand by 1.4% (2 billion kW·h) by 2020 and 3.2% (22.5 billion kW·h) by 2050 for enhanced space cooling in the summer and water pumping for irrigation in agriculture. Although space heating requirements in winters decrease significantly (60% by 2050), the energy saved is not sufficient to compensate the increased demand for electricity.

This study shows that, relative to the baseline scenario, an additional capacity of 9000 MW will have to be installed to offset the adverse effects portrayed in the global warming scenario (from 140 000 MW to 149 000 MW); around 17 000 MW will be needed in the extreme weather scenario. As a result, the economic burden is high in the global warming scenario and even higher in the extreme weather scenario. Additional investments reach US $14 billion in the global warming scenario and US $18 billion in the extreme weather scenario. They are 4.4% and 5.4% higher, respectively, than in the baseline scenario. The analysis shows that adapting to temperature changes and heatwaves in Pakistan will increase the total costs of electricity generation by US $27 billion in the period 2020–2050.

GHG emissions from the energy sector increase to about 775 Mt CO_2-eq/year by 2050 in the baseline scenario owing to increased coal use. In the extreme weather scenario, annual GHG emissions in 2050 are 18 Mt CO_2-eq higher owing to greater electricity demand, reduced efficiency of thermal power plants and reduced output of hydropower plants. Total additional GHG emissions from the energy sector in the extreme weather scenario are about 350 Mt CO_2-eq during the study period compared with emissions in the baseline scenario.

The increased electricity generation in the extreme weather scenario is environmentally not sustainable because it leads to increased GHG emissions. To keep emissions in the extreme weather scenario at the level of the baseline scenario, additional investments of US $10 billion will be required to replace coal based power with renewable electricity. This will also increase the overall electricity generation costs. The average avoidance cost of these incremental GHG emissions is around US $25/t CO_2-eq.

Annual GHG emissions from the energy sector are about 775 Mt CO_2-eq, despite the increasing share of low carbon technologies in power generation (hydropower, nuclear energy, solar, wind) from 36% in 2014 to a staggering 64%

by 2050. Should this share decline, it will increase GHG emissions and worsen the global warming problem.

10. ADAPTING TO CLIMATE CHANGE IN THE ENERGY SYSTEM IN SLOVENIA

10.1. PAST AND FUTURE CLIMATE IN SLOVENIA

10.1.1. Observed climate change

As in other parts of the world, indications of changing climate have been detected and confirmed in Slovenia, especially changes in temperatures and in the precipitation regime [159]. The most significant changes have been observed since 1990 as air and soil temperatures have increased significantly and the water cycle has been altering [160–162]. The Slovenian Ministry of Agriculture and the Environment [163] analysed trends in temperature and precipitation in the period 1961–2011. Results show that the annual mean temperature rose by approximately 0.33°C per decade. Since 1961, Slovenia has on average become 1.7°C warmer. The average annual precipitation has decreased by 32 mm/decade (±30 mm). Average precipitation in spring decreased by 16 mm/decade (±16 mm); trends in the other seasons are not statistically significant.

Owing to its geographical location, intense meteorological processes occur often in Slovenia. They cause storms with hail, strong winds, floods and droughts. Long lasting rain causes landslides, which can damage houses, roads and other infrastructure. Accidents related to EWEs have caused significant damage in recent years, and the threat of wildfires has increased as well. Between 1995 and 2005, weather related accidents caused more than €80 million loss annually, mostly (around 60%) in agriculture [164]. Changing precipitation patterns, more vigorous and frequent long droughts and more intense rainfall increase erosion noticeably. The average annual variability of precipitation is high. There has been no significant change in the amount of precipitation in recent decades, but a greater intensity of showers and fewer days with snow cover have been observed.

10.1.2. Expected gradual climate change

Regional scenarios of GCC predict an increase in mean temperature [165]. The magnitude of the temperature change highly depends on the chosen emissions scenario. According to one set of scenarios, mean annual temperature is expected to increase by 0.5–2.5°C by 2030, while the amount of precipitation in summer may decrease by up to 20% [166].

Other projections involve slightly different ranges: in comparison with the baseline period (1961–1990), mean temperatures show an increase of 0.7–2.4°C by 2030, 1.4–4.2°C in the period 2031–2060 and 2–8°C in the period 2061–2090. Climate change projections (especially at the local scale) are plagued with several types of uncertainty; therefore, the mean value and both extremes should be taken into account.

Precipitation projections show greater uncertainty. Precipitation in spring and autumn may increase or decrease in the future. The amount of precipitation is expected to increase in winter and decrease in summer (at least in the southern part of the country).

10.1.3. Expected changes in extreme weather events

Future EWEs are difficult to predict precisely. Both the intensity and frequency of such events are expected to increase as a result of climate change. The resulting risks are expected to increase [13, 22, 167]. The number of days with extremely high maximum temperature (above 30°C) will increase in Slovenia. Ljubljana had on average 11 such days per year in the period 1961–1990. A rise in mean temperature by 2.5°C would lead to 31 hot days per year [168].

Water deficit in Slovenia is expected to increase by 50–100 mm in spring and by 230–280 mm in summer. Potential evapotranspiration is not expected to change as drastically as water deficit and the number of dry days in the vegetation period because changes in precipitation do not affect them that much. Three scenarios of climate change (low, middle and high) were used for projections of droughts. In the Murska Sobota region, the probability of occurrence of more than 35 dry days per year is 3% in the low scenario, 6% in the middle scenario and 23% in the high scenario. In Ljubljana, there is zero probability of such events in the low scenario, 3% in the middle scenario and 15% in the high scenario [169].

Regional scenarios of future climate change predict more intensive precipitation and more frequent and intense EWEs, such as droughts, floods and thunderstorms, during the time when soil is without plant cover and more exposed to erosive forces [165, 170]. Model simulations of maximum discharges of the Sava River at gauging stations Šentjakob and Čatež were made with 20 year and 100 year return periods based on precipitation forecasts for three periods (2011–2040, 2041–2070 and 2071–2100) [171]. By 2070, discharges with a return period of 20 years at the gauging station Šentjakob on the middle section of the Sava are predicted to increase by 9.6%, and discharges with a return period of 100 years by 14.8% relative to 2010. By 2100, discharges with a 20 year return period will rise by 12.2% and discharges with a return period

TABLE 14. ELECTRICITY GENERATION (GW·h) PER TYPE IN 2014 [172]

Generation type	Electricity generated	Share (%)	Electricity generated (50% Krško)	Share (%)
Nuclear power plant	6 060	36.4	3 030	22.3
Thermoelectric power plants	3 328	20.0	3 328	24.5
Hydroelectric power plants	5 923	35.6	5 923	43.6
Other small generation facilities (connected to transmission lines)	138	0.8	138	1.0
Other small generation facilities (connected to distribution lines)	1 178	7.1	1 178	8.7
Total	16 628	100.0	13 597	100.0

Source: Table 16 of Ref. [172].
Note: 50% of the electricity generated at the Krško nuclear power plant belongs to Croatia.

of 100 years will increase by 12.8%. Today's discharge with a 100 year return period will become a 50 year event by 2070, and its return period by 2100 will be 40 years. The frequency of today's 1000 year discharge will become 200 years by 2070 and 125 years by 2100.

10.2. ELECTRICITY GENERATION IN SLOVENIA

All types of primary energy source are used for electricity generation. The bulk of electricity is generated in conventional power plants: thermal, hydroelectric and nuclear. These sources contribute almost equally to electricity generation (see Table 14).

For 2014, Ref. [172] states:

> "In Slovenia, 16,281 GWh of electricity were generated, 1325 GWh more than in the previous year. The structure of production is changing, the share of hydroelectric power plants is increasing, and, on the other hand, the share

> of thermal power plants decreased; the share of small producers is slowly growing. Domestic production sources covered 98% of consumption. In 2014, almost 42% of electricity was produced in hydroelectric power plants and plants using other renewable sources, plants using fossil fuels contributed 21%, and nuclear power plant 37% of electricity."

Electricity demand is expected to increase by 0.4–0.6%/year between 2015 and 2030.

10.3. STUDY METHOD

A geographical information system (GIS) supported tool was developed for assessing the vulnerability of existing and planned energy infrastructure to EWEs. It provides two types of result: (i) assessment and differentiation of the vulnerability of existing facilities to improve their resilience to EWEs by adaptation measures; and then (ii) assessment of vulnerability at different sites in Slovenia to guide future siting of new energy infrastructure.

In general, there are two approaches for avoiding or reducing major damage to the electric power infrastructure caused by GCC and EWEs. The first involves technical improvements of the mechanical components, making them more robust and resistant to physical stress. The second considers sites for new infrastructure where vulnerability to GCC and EWEs is reduced [173–175].

Studies integrating risk assessments into spatial planning have concentrated on developing a decision support system based on aggregated hazards or risks and not specifically on the use of risk assessment results for siting new facilities [176–179]. The aim of this study is to use a later approach, which builds on and extends the process developed by Kontić and Kontić [180]. It is illustrated by three case studies. Matko et al. [181] outline the method in four steps.

Step 1: Determination of geographical scope and intensity level of an extreme weather event from data on past occurrences

The scope and intensity level of an EWE provide an indication of the magnitude and spatial distribution of its consequences. The intensity level of each EWE (e.g. mass, force, temperature, burden due to glaze ice, strong wind, heavy snow, heavy rain storm) is depicted on GIS based maps in which each cell is evaluated on a scale from 1 (low) to 4 (high) of the physical burden on the electric energy infrastructure. Data are obtained from records of past EWEs.

Step 2: Analysis of the system’s vulnerability to an extreme weather event

Establishing the vulnerability of the system (e.g. electric energy infrastructure, its location and the environment in which the infrastructure is situated) determines whether it is able to withstand an EWE of a given intensity level. Vulnerability is expressed as the ratio of the expected level of damage or loss in the infrastructure to the maximum possible damage or loss measured between 0% and 100% and expressed on the scale 1–4. The results are represented on GIS based maps for different EWEs at specific locations. A particular EWE can cause direct, primary damage to the energy infrastructure as well as secondary damage arising from detriments in the environment (e.g. falling trees and erosion), which then cause additional damage or loss to the energy infrastructure. Thus, the overall vulnerability of the energy infrastructure needs to be evaluated. Vulnerability of infrastructure in terms of primary damage can be specified and evaluated by using construction and other engineering or quality standards. Vulnerability to secondary damage caused by environmental destruction is more complex because it is affected by several factors (e.g. damage to forests and susceptibility to erosion).

Step 3: Assessment of the probability or frequency of an extreme weather event where the energy infrastructure is located

The probability or frequency is calculated on the basis of historical data and the application of meteorological and other models.

Step 4: Integration of Steps 1–3 to determine physical, economic and health consequences to establish a risk index

The risk index combines the intensity level of an EWE and the vulnerability of a particular electric energy infrastructure or system by taking into account the frequency or probability of the occurrence of an EWE on the one hand, and the resulting consequences, damages or impacts on the other. It expresses the degree of damage to the infrastructure resulting from an EWE, together with the impacts of that particular damage on society (e.g. the costs of interrupting electricity supply). Risk indices are obtained by combining the intensity and vulnerability levels, frequency, and specific physical consequences. These combinations are similar to ordinary risk matrices, which combine the frequency or probability of an incident (event) and the severity of its consequences.

10.4. QUANTITATIVE ESTIMATES

10.4.1. Case study 1: Risk assessment of ice storms in planning transmission lines[1]

Matko et al. [181] report on the risks to electric power lines due to ice storms and damage caused by glaze ice, using data on the occurrence of damage to forests and electric infrastructure between 1961 and 2014 collected by the Slovenian Environment Agency and reports. Damage to forests was addressed separately and then aggregated to yield the final results in the form of risk maps. Matko et al. [181] categorize extreme events into four classes (where class 1 represented the lowest and class 4 the largest extent and intensity level of ice storm) based on financial damage to forests and to the electricity infrastructure. Financial damage was calculated from data on the physical damage to forests by using the average price of wood biomass in Slovenia over the last decade (€50/m^3) [182]. Financial damage to the power infrastructure was calculated according to the average prices of power grid system components [183]. The direct cost of €430 million of the ice storm in February 2014 was also taken into account [184].

Different approaches to classification (equal interval, quantile, percentile, natural breaks, geometrical interval, etc.) can be applied in a GIS [185, 186] or in multi-attribute decision support modelling [187] with different scopes and levels of expert judgement [188]. In this case study, a semi-quantitative approach was applied on the basis of the authors' experience and combined with the views of energy infrastructure operators and available published information on the annual maintenance costs of the infrastructure. Events were classified according to the calculated financial damage they caused and then transferred onto a GIS map. These maps were then overlaid to obtain the aggregated map.

The frequency of occurrence of ice storms of different intensities was categorized as follows: up to 0.02/year: class 1; 0.02–0.05/year: class 2; 0.05–0.2/year: class 3; 0.2/year and more: class 4. These classes were then combined with the consequence categories (scope and intensity level) and transferred onto a GIS map as risk indices, in which class 1 represents the lowest and class 4 the highest risk index.

During the observation period (1961–2014), ice storms caused damage to the power grid system seven times and to forest 18 times. There were seven events in which damage was caused to both energy infrastructure and forests. The Slovenian engineering standard SIST EN 50341-3-21/AC101 (2009) for overhead electric line exceeding AC 45 kV "divides Slovenia into three zones based on

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[1] This section is based on Ref. [181].

the burden [of glaze ice] that should be considered in designing power lines" in different regions (1 has the lowest burden; 3 has the highest burden) [181].

The zonal map was then compared with the map showing risks to the electricity infrastructure posed by ice storms. According to this analysis, the extension of zone 3 is proposed. Slovenian development plans for the energy sector include a proposal for upgrading existing high voltage power lines from 220 kV to 400 kV. In this case study, two alternatives of the Beričevo–Divača power line are compared. The proposed 100 m wide corridors were overlaid with the risk map of ice storms (see Fig. 26). About 24% (137 ha) of the northern corridor lies in areas with highest risk (risk index 4) and 52% (302 ha) in areas with relatively high risk (risk index 3). The southern corridor does not cross areas with highest risk (risk index 4); 29% of its track (212 ha) lies in areas with risk index 3. The transmission line would be less exposed to ice storms in the southern corridor because it mostly runs through areas of lower risk index.

10.4.2. Case study 2: Risks of ice storms to wind turbines

Burden due to glaze ice can cause damage to wind turbines. This analysis produced a map of spatial suitability for siting wind farms that takes risks due to ice storms into account (see Fig. 27).

For siting large wind farms of a minimum 10 MW of installed capacity, Matko et al. [181] report:

> "The total area of these territories (without consideration of risk) is about 31 km^2. Four hundred five sample turbines could be built there. Their total installed capacity would be 930 MW and their total annual electric energy production (assuming that they would operate for 1,800 hours per year) would amount to 1.68 TWh. If high-risk areas are excluded, there are altogether 17 km^2 suitable for building at least five wind turbines. These areas are presented in Figure [27], Two hundred fifteen wind turbines could be built there with a total installed capacity of 495 MW. Their total annual production of electric energy would be 890 GWh."

The comparison of costs and benefits included three site suitability models: the first ignoring risks, the second accounting for risks and the third considering risks and a system for de-icing. The cost–benefit analysis of different alternatives for siting shows that damage due to EWEs have a significant impact on the economic viability of a plan.

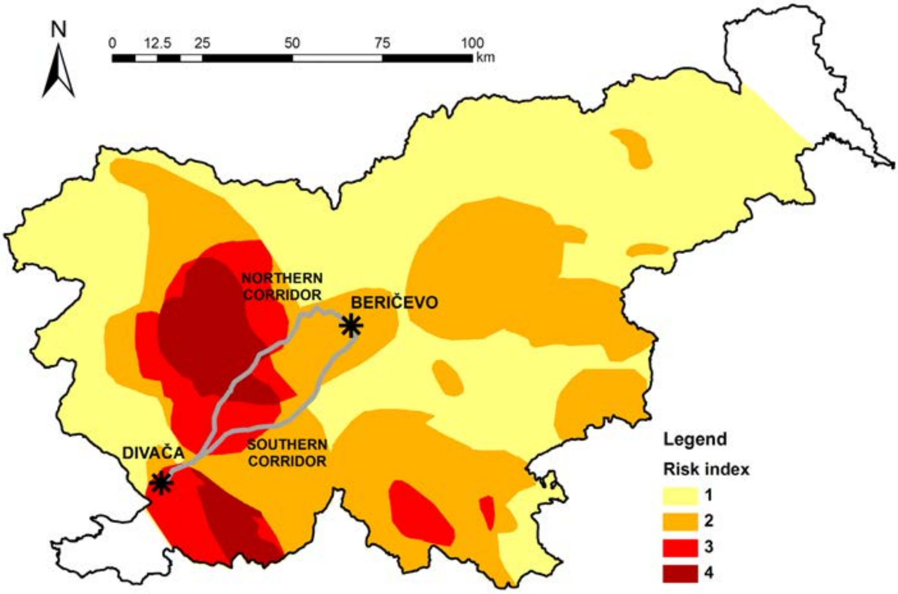

FIG. 26. Proposed corridors for the 400 kV Beričevo–Divača power line overlaid on the map of risk indices [189–191].

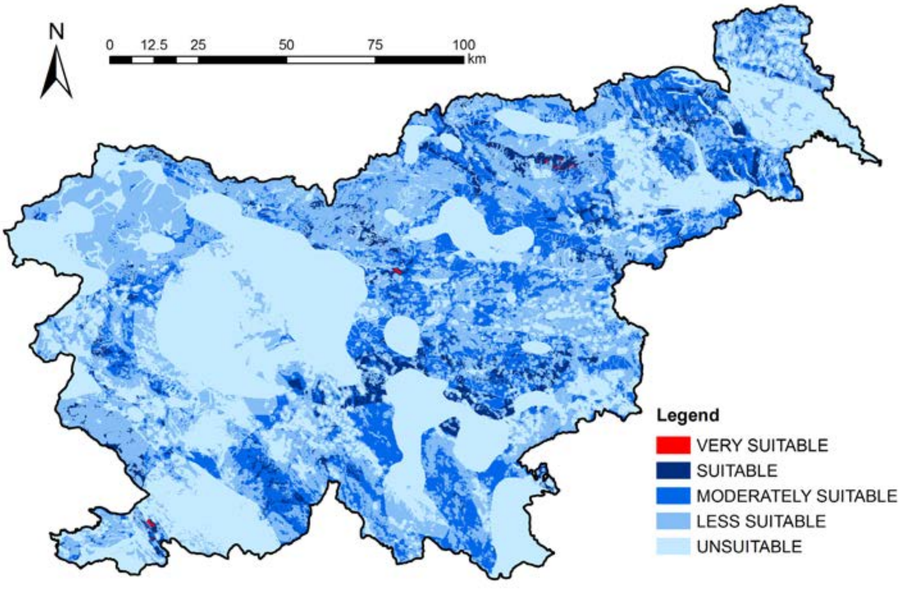

FIG. 27. Site suitability for wind farms considering the risk of ice storms.

10.4.3. Case study 3: Risks to hydropower plants on the Sava River due to heavy rainstorms

Heavy rain events in 2006, 2008, 2011, 2012 and 2014 caused significant soil erosion, floating trees and other debris and led to operation disturbances and shutdowns of hydropower plants on the Sava River. These events triggered the risk assessment presented here. To interpret these events in terms of actual risk assessment, an erosion vulnerability model was constructed for the Sava watershed to assess the vulnerability of hydropower plants on the river due to water erosion. The soil erosion model is based on the model developed for the Idrijca catchment in the EUROCAT project [192].

The amount of electricity not produced was calculated by using data about past operation interruptions of power stations on the Sava River due to heavy rain (high water level and/or too much suspended matter). The average planned electric output of the hydropower plants in a given month was used. The cost of interruptions was calculated on the basis of the price of electricity from different units (see Tables 15 and 16).

Locations of existing and planned power plants on the Sava River are shown in Fig. 28. There are three hydropower plants on the upper Sava River (Moste, Mavčiče and Medvode) that suffer minor interruptions because the size of the catchment area is relatively small. However, interruptions of the four hydropower plants on the lower Sava River (Vrhovo, Boštanj, Arto-Blanca and Krško) occur more frequently and are more intense. Of the various historical records of interruptions, data from energy production companies were used in calculations for this case study, on the assumption that they are more complete and accurate than the others. To calculate frequencies of interruptions transparently and consistently, data about actual interruptions and data about water discharges at three gauging stations (Šentjakob, Hrastnik and Čatež) have been used. Discharges at these stations during interruptions were audited and analysed systematically by focusing on high discharge values before 2000. Data from Šentjakob and Čatež were available from 1926 and data from Hrastnik from 1993. Data from the gauging stations Šentjakob and Čatež for the period since 1926 have been used as the basis. Discharges at Hrastnik (for the period between 1926 and 1993) were estimated by extrapolation. The overall length of the observation period for calculating the frequencies of events was thus almost 90 years. Calculated frequencies based on actual events and on extrapolation are presented in Table 17.

Frequencies were then categorized as follows: less than 0.1/year: class 1; 0.1–0.5/year: class 2; 0.5–2/year: class 3; and more than 2/year: class 4. Similar reasoning was applied in the categorization as in case study 1.

TABLE 15. COST CATEGORY AND COST OF INTERRUPTIONS OF HYDROPOWER PLANT EVENTS ON THE SAVA RIVER

Category	Cost (€'000)	Discharge, Šentjakob gauging station (m^3/s)	Discharge, Hrastnik gauging station (m^3/s)	Discharge,Čatež gauging station (m^3/s)	Suspended matter, Hrastnik gauging station (g/m^3)
1	<10	250–500	300–600	500–1000	<20
2	10–50	500–750	600–1000	1000–1500	20–100
3	50–100	750–1000	1000–1400	1500–2000	100–150
4	>100	>1000	>1400	>2000	>150

TABLE 16. COST CATEGORY AND ESTIMATES OF FUTURE RISKS BASED ON PREDICTION OF DISCHARGES

Category	No. actual events (2000–2014)	No. extrapolated events (1926–2000)	Extrapolated frequency (event/year)	Future risk (influence of climate change)* (event/year)
1	15	1374	15.4	
2	10	95	1.2	
3	4	24	0.31	
4	2	4	0.067	0.16

* As the frequency and intensity of high discharges are expected to increase, so does the possibility of interruptions of power stations along the Sava River. For the projection of future costs due to interruptions at power stations resulting from high levels of water and suspended material in the river, results of the simulations made by Kavčič et al. [171] were used to see which discharges would exceed specific damage levels. From 2040 onwards, the risk of costs due to interruption at hydropower plants caused by flood or high levels of suspended matter exceeding €100 000 is estimated to be around 0.16/year.

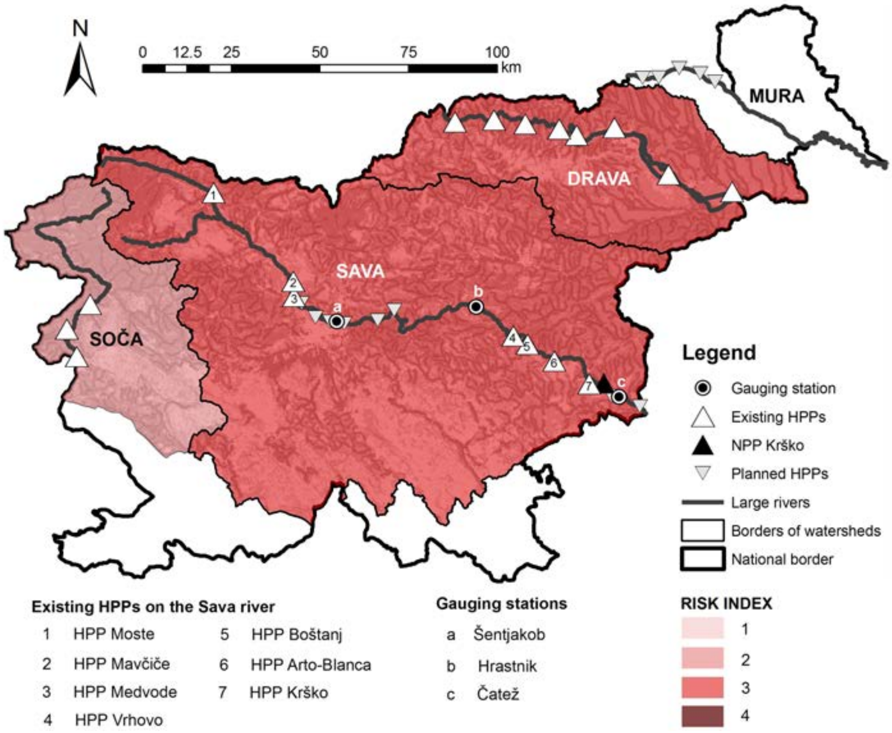

FIG. 28. Risk indices for the Sava, Drava and Soča river watersheds combined with results from the erosion models [190, 191].

TABLE 17. RISK INDICES DERIVED FROM COMBINING FREQUENCY AND CONSEQUENCES FOR HYDROPOWER PLANTS ON THE SAVA RIVER

Frequency class	Consequence (damage) category			
	1	2	3	4
1	1	1	2	3
2	1	2	3	4
3	2	3	3	4
4	3	3	4	4

In addition to hydropower plants, there is a nuclear power plant on the Sava River at Krško. Since the beginning of its operation in 1983, the nuclear power plant Krško has had to stop operation twice for several days (in 2003 and 2012) because large amounts of suspended and plant material were carried by the river. In both cases, the nuclear power plant's intake facility for cooling water was clogged after a sudden increase in river discharge due to the opening of dams at upstream hydropower plants in response to heavy rainfall [193]. Classes of frequencies of occurrence of events and classes of consequences (damage) were combined to obtain risk indices (see Table 16).

10.5. RISK ANALYSIS, UNCERTAINTIES AND FUTURE WORK

There are several aspects of applying the above results to optimize existing and future electric power infrastructures, both technically (mechanically) and spatially. In technical optimization, results of risk assessments can be used to revise building codes, making future facilities more resilient physically. Risk assessment results can also support investment planning for the upgrading or maintenance of existing infrastructure. In spatial optimization, the approach adopted here can be used to compare different alternatives of a proposed plan, as shown in case study 1 for transmission lines. It can also be integrated into developing the plan itself by searching for locations where damage will be reduced, as in case study 2 for siting wind farms.

These aspects have already been accepted as important factors in the framework of long term energy development planning in Slovenia. It is crucial to include risk assessment in the early stages of the planning process when alternatives are formed. Operationally, risk assessment is included into spatial suitability analysis as its third component (besides the spatial attractiveness and environmental vulnerability components). In the case studies presented, physical damage to power lines and financial damage due to loss of electricity production were analysed. However, energy not supplied to customers should also be included.

The application of the presented method raises several issues. One is the availability of historical data on intensities of and damage caused by extreme events. Monitoring of interruptions is in most cases not standardized, and data sets of operators are usually inconsistent. Proper assumptions and adjustments are therefore required before analyses can be undertaken. For example, data relating to the magnitude of damage and the length of power line interruptions recorded by transmission and distribution companies are not consistent. There are also inconsistencies between data about interruptions of power plant operation recorded by the national transmission network system operator Elektro

Slovenija and those recorded by energy production companies in charge of those hydropower plants. Available records about past interruptions also differ in the length of the observation period. Such differences may even occur within a single organization (e.g. data from the hydrological archives relating to observations at different gauging stations that did not start operation at the same time). The most important issue is the lack of data from production companies for the entire operating period of their facilities and the incompleteness, and therefore unreliability, of data from the transmission network system operator that makes it necessary to rely on hydrological data alone.

Appropriate caution is necessary when different types of facility (i.e. power units) are analysed. For example, damage caused by interruptions of the Krško nuclear power plant differ from those caused by interruptions of hydropower plants. The difference may be as much as an order of magnitude owing to differences in the nominal capacity of the plants. The risk index categories may be the same for various units, while damage in absolute terms (e.g. energy not delivered) may differ widely. Therefore, when interpreting risk indices and the related costs, the context and the energy infrastructure involved should be specified.

The definition of criteria for classifying costs, frequencies, damage and risk indices, among other things, is based on the authors' experience and expertise and on the value judgement of energy infrastructure operators. In real life, however, these categories are usually defined in an open, inclusive and participatory process that may be a spatial planning procedure, an energy policy development process, a top level managerial decision making activity related to the construction of a specific power plant, or some other process. In such cases, categories are subject to variations based on interests, goals and affordability (i.e. the value systems of the stakeholders involved). Therefore, the categories should not be perceived in absolute terms. Furthermore, proper sensitivity analysis may enhance the trustworthiness of results, especially in the context of operational decision making.

Other issues arise in the implementation of the risk assessment method. For example, how to assess risk for planned units on a river where no hydropower plant has been built yet (e.g. the Mura River in north-east Slovenia (see Fig. 28)). In such cases, data from other countries could be useful. In the case of the Mura River, data about interruptions at hydropower plants in Austria could be used to help to determine the risk index in Slovenia more accurately.

To reduce the degree of uncertainty, sufficient reliable data have to be obtained for different locations and infrastructures. In case study 3, gaps in records relating to interruptions were overcome by interpreting hydrological data from the three gauging stations. For better projection of climate change impacts, various combinations of climate change scenarios and projections of future energy and social development as well as details of planned infrastructure can be used.

10.6. SUMMARY

The purpose of this research was to test and verify the feasibility and benefits of integrating risk assessment results into spatial planning in order to reduce the damage to energy infrastructure caused by EWEs. The presented approach proved to be useful in spatial planning as well as in making decisions about enhancements of mechanical resilience, including decisions about the maintenance and reconstruction of electric power infrastructure. The developed approach was presented in case studies of ice storms and heavy rainstorms in Slovenia, but it can be applied to other types of EWE and their combinations on various geographical scales and in different regions. The application of the method is not limited to energy infrastructure; it can be used to assess risks to other critical infrastructures as well as other elements of the environment, both natural (e.g. forests, soil, watercourses) and anthropogenic (e.g. settlements, cultural heritage sites). Features of the risk assessment can be adjusted both in terms of geographical scale (size of the investigated area) and the level of detail of analyses.

In this research, the question arises of how to deal with so far unprecedented events. Using climate models that simulate changes in the frequency of occurrence and intensity of EWEs is one possibility. For better assessments of the impacts of climate change on electric power infrastructure, various combinations of climate change scenarios, projections of future energy and social development, and details of energy infrastructure development plans may be used. Some types of electric energy infrastructure (e.g. photovoltaic panels) are relatively new, and information about their vulnerability to different types of EWE is still advancing. There are also regions where infrastructure has been absent so far but might be located in the future. To reduce uncertainty, sufficient reliable data have to be obtained about different locations, infrastructure and other elements of the environment. Operators of electric power and other infrastructure should use a standardized system for recording data about the impacts of EWEs.

Additional tests are required to see how the method presented here can be applied in formal spatial planning procedures. This will require a consensus between spatial planners and other stakeholders. Agreement among experts is likely to be reached quickly; negotiations with administrative authorities may take longer. Integration of the presented approach into existing spatial planning procedures requires only minor adjustments to specific land use planning contexts, levels of detail and user requirements (expectations).

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ABBREVIATIONS

CMIP	Coupled Model Intercomparison Project
CSP	concentrated solar power
ENSO	El Niño–Southern Oscillation
EPRI	Electric Power Research Institute
EWE	extreme weather event
GCC	gradual climate change
GHG	greenhouse gas
GIS	geographical information system
IPCC	Intergovernmental Panel on Climate Change
IRS	International Reporting System for Operating Experience
MAED	Model for Analysis of Energy Demand
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
NAP	national adaptation plan
NDCs	nationally determined contributions
PSA	probabilistic safety assessment
RCP	representative concentration pathway
toe	tonnes of oil equivalent
UNFCCC	United Nations Framework Convention on Climate Change

CONTRIBUTORS TO DRAFTING AND REVIEW

Ahmad, I.	Pakistan Atomic Energy Commission, Pakistan
Athar, G.R.	Pakistan Atomic Energy Commission, Pakistan
Biscarra, M.A.	National Atomic Energy Commission, Argentina
Colace, S.	National Atomic Energy Commission, Argentina
Coppari, N.	National Atomic Energy Commission, Argentina
Gómez, D.	National Atomic Energy Commission, Argentina
Iglesia, M.	National Atomic Energy Commission, Argentina
Israr, S.	Pakistan Atomic Energy Commission, Pakistan
Jensen, S.	National Atomic Energy Commission, Argentina
Kilic, A.N.	International Atomic Energy Agency
Kontić, B.	Jožef Stefan Institute, Slovenia
Kontić, D.	Jožef Stefan Institute, Slovenia
Lodhi, M.H.K.	Pakistan Atomic Energy Commission, Pakistan
Matko, M.	Jožef Stefan Institute, Slovenia
Parera, M.D.	National Atomic Energy Commission, Argentina
Rey, C.	National Atomic Energy Commission, Argentina
Rössler, C.	National Atomic Energy Commission, Argentina
Santagata, D.	National Atomic Energy Commission, Argentina
Stankeviciute, L.	International Atomic Energy Agency
Zirulnikow Salmerón, F.	National Atomic Energy Commission, Argentina

This publication explores the diverse range of impacts on the energy sector resulting from gradual climate change and extreme weather events, and the potential ways to counter them. All elements of the supply chain are explored: resource base, extraction and transport of depletable energy sources, power generation, transmission and distribution. This publication includes three case studies which assess the energy sector vulnerability of Argentina, Pakistan and Slovenia.

IAEA
International Atomic Energy Agency